NOISE

A COMPREHENSIVE SURVEY FROM EVERY POINT OF VIEW

By

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With a foreword by
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FOREWORD

AT the end of Dr. McLachlan's book is a list of references to articles or books relating to or touching on the subject of noise. A glance at these will show that out of the references to articles, chiefly in English, 124 relate to papers written in or since the year 1930, i.e. during the last 5 years.

This raises in our minds two questions:

First, Why has so much been written on this subject recently? and:

Secondly, What is the necessity for another book?

With regard to the first the obvious answer is the great growth in importance of the subject. There are few of us upon whom it has not pressed heavily during the past few years and on whom the question has not increasingly forced its attention in one way or another. Much of this is due to the increase of mechanical transport on our roads and in the air. The advance in methods of silencing the total noise thus caused has not increased to the same degree.

With regard to the second question, the necessity of yet another book. This, I think, is self-evident from a glance at the list of books and articles. They deal with particular phases of the subject, and there is no short comprehensive book or article. Dr. McLachlan has dealt with noise from many if not all points of view, its causes, its measurement, and the remedies which at present exist. He gives, too, what will be of the greatest assistance to many of his readers, examples of the measurements of many common noises which trouble us. Much work is being done on the subject both by various societies and committees which have been formed, and by many who are carrying out research on the matter. To them, as well as to the ordinary man upon whom the subject is forced, the book should prove invaluable.

H. F.

PREFACE

NOISE is a ubiquitous accessory of the mechanical age in which we live. It has reached such proportions, metaphorically speaking, that steps must now be taken to reduce its intensity and arrest its further growth. To this end Mr. Hore-Belisha, Minister of Transport, has appointed a Technical Committee under the Chairmanship of Sir Henry Fowler, whilst the Anti-Noise League has been formed under the Chairmanship of Lord Horder. All concerned in these organizations are doing excellent work in taming the man-made acoustical medley. It is essential, however, to have the co-operation of the whole nation in this vast enterprise. Consequently, every one should understand what is meant by 'Noise', how it originates, and its detrimental effects. The purpose of this book is to inform the reader on such points. It is written in a form which should appeal equally to the lay and to the technical reader. The problems of noise and their methods of solution are discussed in general terms, without introducing intricate technical details. Those who desire to probe more deeply into the subject will find the bibliography comprising 140 references on pp. 139–45 of considerable use.[1]

The reader is earnestly requested to study §§ 2–5, Chap. 1, since they are of fundamental importance. Reference should be made to these sections from time to time, until the material facts have been memorized. Attention is directed to the method of expressing what is colloquially termed 'loudness', this being fully explained in § 4, Chap. 1. *Loudness is not measured in decibels.* It is incorrect to say that the *loudness* of traffic noise is 75 decibels.

The author has very great pleasure in acknowledging his indebtedness to: Sir Henry Fowler for writing the foreword; the Acoustical Society of America for permission to

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[1] Throughout the text the numbers in square brackets [ ] indicate the references at the end of the book.

reproduce Figs. 3, 4; Professor F. C. Bartlett for criticisms and suggestions regarding Chap. X; Commander T. R. Cave-Brown-Cave for permission to reproduce Figs. 48, 48*a*; Mr. B. G. Churcher and the Metropolitan Vickers Co. for criticisms and suggestions regarding Chaps. I and VIII, and part of Chap. II: also for permission to reproduce Figs. 11, 35, 55, 56; Mr. A. R. Cooper and the London Passenger Transport Board for permission to reproduce the information on tube railways in Chap. VI and the data in Table 6; the Editor of *Engineering* for the loan of blocks for Figs. 25, 28, 29, 32, 37, 48, 48*a*; the Institution of Electrical Engineers for permission to reproduce Fig. 5; Dr. G. W. C. Kaye and the Royal Institution for permission to reproduce Figs. 2, 31, 34, 38, 57; Dr. D. A. Laird and the Acoustical Society of America for permission to reproduce Figs. 2*a*, 59–61; the Editor of the *Listener* for the loan of the block for Fig. 43; the Noise Abatement Commission, Department of Health, City of New York, for permission to reproduce Figs. 10, 15, 16*a*, 26, 27, 30, 39–42, 58; the National Institute of Industrial Psychology for permission to reproduce Fig. 62 and for the loan of publications; the Physical Society of London for permission to reproduce Figs. 44–7; Mr. D. R. Pye (Air Ministry) for his criticisms and suggestions regarding Chap. VII; Dr. E. O. Turner (Lucas & Co.) for his criticisms and suggestions regarding § 5, Chap. III, and for permission to reproduce Figs. 25, 28, 29; Mr. S. S. A. Watkins and the Western Electric Co. for the photographs Figs. 12–14, particulars of their noise-measuring and analysing apparatus, and the data in Tables 3–6, 15, 16; the Editor of *World Radio* for the loan of the blocks for Figs. 8, 9, 17–24, 33.

N. W. M.

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I

GENERAL CONSIDERATIONS: BEHAVIOUR OF THE EAR

1. *Introduction.*

SOUND and, therefore, noise is sensed by the ear when the air particles constituting the atmosphere are in vibration. The frequency of the vibration in cycles per second (abbreviated $\sim$) must be within a certain range in order that the sound shall be audible. The motion of the particles to and fro along the path of the sound means that at any particular instant the air between an observer and, say, a ship's siren is compressed slightly at certain places and reduced equally in pressure at others. The rate of fluctuation in air pressure due to the sound corresponds to the pitch of the siren. The general result is what the mathematician is pleased to call wave motion, which means that the pressure disturbance at the siren travels outwards into the distance. The sound is gradually absorbed by the ground and by the atmosphere as the waves get farther and farther away from the source, and it ultimately reappears as an equivalent amount of heat. The sound power radiated by a siren is colossal compared with that used in normal conversation. For example, the power from a ship's siren might be $\frac{1}{7}$ horse-power or approximately 100 watts, which is ten million times the speech power in ordinary conversation. Putting the statement in another form, one-quarter of the population of England would have to talk simultaneously to generate the same sound power as the ship's siren. The small sound power necessary to stimulate the otic system is in great contrast with the relatively enormous power for heating purposes. This can easily be demonstrated by calculating the heat value in the gas supplied to a gas fire, when it will be found that several horse-power is required. As another example take the case of a 3-kilowatt (3,000 watts) electric radiator in a room of moderate size. Here the power consumed is thirty times that radiated by the siren or 300 million times that of the normal speaking voice. This comparison is based upon an output of 10 microwatts for the voice. In concert work a powerful bass singer may radiate 3,000 times this amount.

The outer ear, which is responsible for collecting the aerial vibrations, so to speak, consists of a canal approximately 2·3 cm. long having a volume of 1 cubic centimetre. At the inner end of this canal the ear-drum is situated, its area being about 0·65 sq. cm. It is nearly elliptical in form, having major and minor axes of approximately 1·0 and 0·85 cm., the latter axis being vertical. The drum can, therefore, be regarded as an elliptical membrane. Air-pressure waves reaching the drum, cause it to vibrate. The effect of vibration is perceived by the brain in a certain way, which we regard as the sensation due to sound. The character of the sound sensation depends upon three things, (1) pitch or frequency, (2) loudness (which depends upon the amplitude of the air particles), (3) quality or timbre, which is determined by the wave form, i.e. the relationship between air pressure and time. When a tuning-fork is struck and its stem pressed against the top of a piano, we hear a note having a certain pitch. If this corresponds to middle C, there are 256 complete vibrations every second. The nearer we approach to the fork, the louder it is, so that the amplitude of the air particles and, therefore, the sound pressure increases also. As we recede from the fork the air pressure becomes less, but the character of the sound is unaltered. If the fork is struck very violently, the note is impure at first but becomes pure as the amplitude of the prongs subsides. Consequently, the wave form changes. Under normal circumstances the sound wave form of a tuning-fork is the well-known sine curve shown in Fig. 1 (full line), whereas that of a violently struck fork consists of a sine curve on which small ripples are superimposed, as shown by the dotted curve. The ripples cause the sound to be impure, which suggests that the quality or timbre is dependent upon the wave form.[1]

When the wave form repeats itself periodically as in Fig. 1, the sound is sometimes regarded as musical. This, however, may be misleading, because continued depression of five consecutive notes on an organ manual could hardly be regarded as musical, although the sound wave form keeps on repeating itself. If sounds are irregular and the wave form is non-repetitive, they are sometimes regarded as constituting a noise. Neither of these definitions is rigorous, for in modern music there are many passages which seem to be mere 'noise', whilst there are 'noises' which are integral parts of the sounds from musical instruments [110]. According to the foregoing definition, the sounds of drums and cymbals can be regarded as 'noise'. Any precise definition of either music or noise would be cumbrous and protracted, which leads us to ask, 'When is a noise not a noise?' to which we reply, 'When it is in-

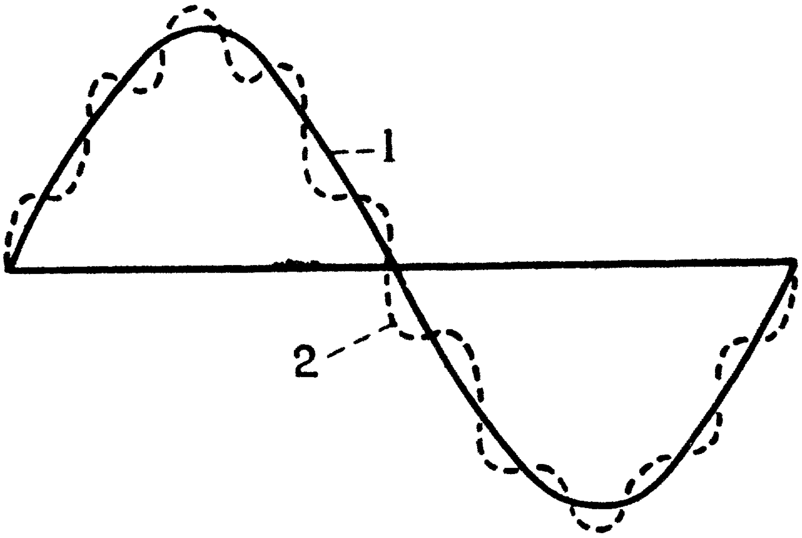

FIG. 1. Showing sound wave form due to tuning-fork struck normally (1).
Showing sound wave form due to tuning-fork struck violently (2).

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[1] Actually the quality of a continuous sound depends upon the component frequencies and their relative amplitudes irrespective of phase, so that many wave forms would sound alike. The above must, therefore, be interpreted in a broad sense.

audible!' Whether audible sounds constitute a noise or not depends upon circumstances. The ring of the blacksmith's anvil is music to the smith, but to the acoustical experimentalist longing for silence, it is a source of considerable noise. The lion's roar is not only a noise, but a harbinger of potential danger. It causes more fear than annoyance. The inconsiderate motorist who indulges in prolonged 'tooting', when almost on the heels of some unsuspecting pedestrian, causes far more fright than anything else. If one were made to dwell in a dungeon cell listening to perfect radio reproduction for weeks on end, it would ultimately become mere 'noise'. Consequently we are impelled to formulate some simple definition of noise such as, 'Noise is any undesired sound' or 'Noise is sound at the wrong time and in the wrong place'. Both definitions imply that the aerial vibrations cause distraction, fear, or annoyance.

2. *Characteristics of the Ear.*

We now come to the behaviour of the ear to sounds of different pitch and loudness. Much experimental work has been done to ascertain the influence of these factors on the average human ear. A large number of observers, whose ages are usually between 20 and 30 years, with normal hearing, are tested and the mean results of the tests are taken to indicate the performance of the ear under certain specified conditions. To gain the requisite information, the conditions are usually much simpler than those which obtain in practice. For instance, everyday sounds have an extremely complicated wave form, that is to say there is not one, but a myriad of different frequencies present. For test purposes, however, it is necessary in our present state of knowledge to experiment with one pure tone at a time. By doing so, characteristic curves of the ear for pure tones are obtained, and from these it is possible to infer, approximately, the behaviour of the ear under more complicated conditions.

There are two principal methods which have been used for testing the relationship between aural sensation and sound pressure. Tests are carried out in absolutely silent places, so that there is no interference from extraneous sources. To obtain the requisite degree of silence it is necessary to use a sound-proof studio, whose surfaces are lined with absorbent material. It is then possible to eliminate all noise except that due to heart-beats, breathing, and the like, which being part and parcel of the human body cannot be regarded as interference in a normal person. The first method is one in which a high quality telephone earpiece (with a uniform frequency response curve) is held to one ear. By aid of a microphone, a calibrated valve amplifier, and attenuator (intensity control), the intensity of the sound in the ear canal can be varied over a wide range, its value in dynes per square cm. being known accurately. Under such a listening condition, the sound is injected into the outer ear and modification due to external objects cannot occur [45*b*]. In the second method, a reference sound which spreads out equally in all directions from a small simple source is used [46] in an acoustically 'dead' room. The listener faces the source and the distance therefrom to the mid-point of the line joining his ears is 100 cm. Under this condition the sound distribution is modified by the body. Also a certain proportion of sound reaches the ears due to bone conduction through the head, whilst due to reinforcement the sound pressure in the ear canal exceeds that in the outer air [32]. At frequencies above 1,000 $\sim$ the sound reaching the ears is modified by the head, and curves showing the relationship between loudness and frequency differ from those obtained with a telephone earpiece. We may remark that the subject tested should not have defective hearing, whichever method is used.

There are two fairly well-defined boundaries of aural sensation, these being, (*a*) the threshold of hearing, (*b*) the threshold of feeling. We shall use the telephone method of test in dealing with these extremes. Let us select a frequency of 512 ∼, which corresponds to the fundamental of the octave above middle C on the piano. Seated in an acoustically 'dead' room with a telephone receiver applied to one ear, a very small current of 512 ∼ is passed through the winding of the 'phone. The sound is inaudible because the pressure happens to be below the threshold of hearing.

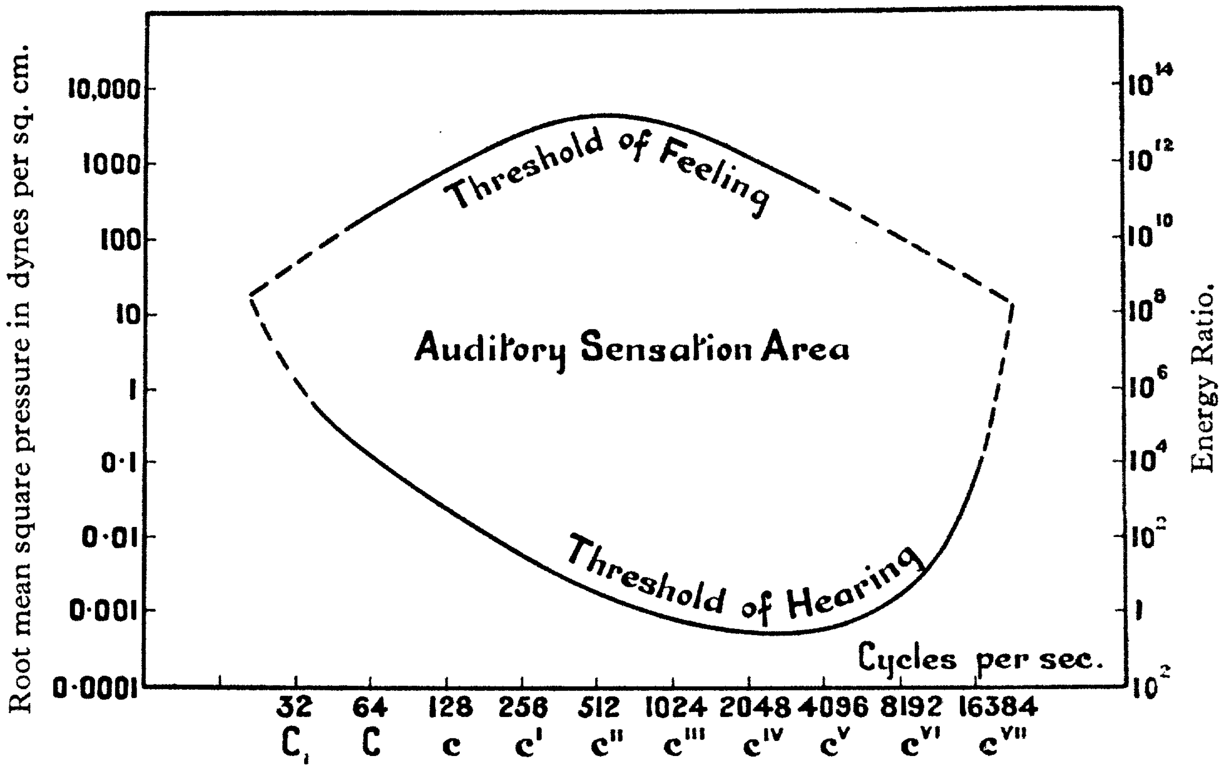


FIG. 2. Illustrating the thresholds of hearing and feeling for normal ears. Data obtained by telephone held to ear.

If the current is increased very slowly, a point is reached when the sound is just audible and no more. Since the apparatus is calibrated, the sound pressure in the ear is known from the reading of the attenuator. This is the threshold of hearing for 512 ∼. By conducting the same test at other frequencies, a threshold curve showing the relationship between sound pressure in dynes per square centimetre and frequency can be plotted. This would apply to the particular individual tested. As mentioned previously, it is customary to test twenty or more observers with normal hearing and take the average. The curve marked 'threshold of hearing' in Fig. 2 was obtained in this way [45]. It extends from about 20 to 20,000 ∼, these being approximately the lower and upper limits of audibility. Coming back to our tone of 512 ∼, if the sound pressure is increased beyond the threshold there is no sensation of additional loudness until the sound pressure has been increased by a certain amount. This can be found from the reading of the attenuator or device for controlling the alternating current supplied to the telephone. The increase in pressure required before the ear senses an increase in loudness depends upon the magnitude of the pressure. If the attenuator is adjusted accordingly, the sound is very intense and a tickling sensation is felt. At higher intensities the ear is actually pained. Between the threshold of hearing and that of feeling, the ear can distinguish about 270 degrees of loudness at 512 ∼. At other frequencies fewer degrees are distinguishable. To obtain some idea of the enormous difference between the intensities at the two threshold values at 512 ∼, we take a hypothetical example. Imagine that we are back many centuries ago when people believed that the earth was flat. We dig a subterranean chamber which is sound-proof, and we install therein apparatus for generating sound. The latter issues from a circular hole, say two inches in diameter, flush with the ground. If the power radiated at 512 ∼ is 10 watts, this being one-tenth of the output from the ship's siren quoted on p. 1, the sensation of pain will be felt when the ear is within a distance of 5 inches from the hole. Assuming this has not rendered our otic system *hors de combat*, we take a silent autogyro and soar up and up in an atmosphere of uniform density, until at an altitude of 260 miles a captive balloon awaits us. Having anchored the gyro, our head gear is removed, and we find that the tone of 512 ∼, due to the sound from the invisible 2-inch hole 260 miles beneath, is just audible, i.e. its pressure corresponds to the threshold of hearing, provided, of course, that there is neither transmission loss nor extraneous noise.

From Fig. 2 it is seen that the sound pressure at the threshold of hearing varies according to the frequency.

Starting at 20 ∼, the threshold pressure is relatively high, it falls to a minimum at 2,000 ∼, and rises thereafter to a large value as 20,000 ∼ is approached. Moreover, at the threshold, the ear is extremely insensitive to very low and very high frequencies, a point which is readily confirmed if we walk away from a band in the park. The fundamental tones of the low-pitched instruments and the higher overtones of the others soon become inaudible, whilst only the middle and the higher frequencies can be distinguished. The bass drum is audible at considerable distances, but this is due to the large power input by the drummer who 'beats' it. In fact the momentary or 'peak' acoustical power is of the same order of magnitude as that from a large pipe organ played fortissimo.

If a horizontal line corresponding to a pressure of 1 dyne per sq. cm., this being approximately one-millionth part of the normal steady atmospheric pressure, is drawn across Fig. 2, it intersects the threshold of hearing curve in two points. These tally roughly with the lowest C on the piano and that two and one-half octaves above top C. Thus when the sound pressure is 1 dyne per sq. cm., these two tones are just audible if sounded separately in a telephone receiver used in the manner described above, whilst tones of 256, 512, 1,024, and 2, 048 ∼, which correspond to middle C and the three octaves above it, would be quite loud. We also observe from Fig. 2 that the sound pressure required to cause pain at middle frequencies far exceeds that at very low and very high frequencies. At the extremities of the audible range, namely, 20 ∼ to 20,000 ∼, the thresholds of hearing and of feeling are coincident. The area included between the upper and lower threshold curves is usually regarded as the auditory sensation area.

3. *The Decibel.*

So far we have confined our remarks to sound pressure, which is measured in dynes per sq. cm. This is not a convenient unit where aural sensation is concerned, so it is essential to consider other units which are more, but not necessarily absolutely satisfactory. In telephone engineering, units are required to discriminate between various power levels. Suppose a loud speaker radiates 10 watts of sound at 512 ~, and by reducing the input this falls to 1 watt, the power levels are in the ratio 10/1. The logarithm, to the base 10, of this ratio is $\log_{10}10 = 1$, this being known as 1 bel, after Alexander Graham Bell the inventor of the telephone. A bel is rather too large for practical purposes, and it is customary to use the 'deci-bel', so we have $\log_{10}10 = 10$ db. More generally, if the power from a loud speaker is increased from P_0 to P_1, the level rises $10 \log_{10}P_1/P_0$ db. Since the decibel is merely the logarithm of a power ratio, it is devoid of dimensions, i.e. a numeric. The logarithmic scale was suggested by the Weber-Fechner law, which has a limited application to the organs of sense and touch. It is considerably in error for loud sounds [32].

One decibel is about the smallest change in power level which the ear can detect under ordinary conditions at frequencies between about 500 and 3,000 ~. When $10 \log_{10} P_1/P_0 = 1$, we have $\log_{10} P_1/P_0 = 0{\cdot}1$, and $P_1/P_0 = 1{\cdot}26$, so 1 db. corresponds to an increase in power of 26 per cent. On the average, an increase of from 2 to 3 db. is necessary in radio reproduction to make any appreciable difference in loudness, so almost double the power is called for. We have seen that there is an enormous variation in power level between the two thresholds at 512 ~. Expressed logarithmically this amounts to 130 db. Although the decibel is derived from a power ratio, it is frequently used in connexion with sound pressure. Since power depends upon the square of the sound pressure, the level in decibels of p_1 above p_0 is $20 \log_{10} p_1/p_0$, where p_1 and p_0 are sound pressures. The data of Table 1 put the above paragraphs in concrete form, and will be readily understood.

Experimental work in this country [32] and in America [46] shows that the threshold sound pressure at 1,000 ~ is approximately $2\times10^{-4} = 0\cdot0002$ dynes per sq. cm., i.e. 200 microdynes per sq. cm., and this will be taken as the datum or zero level from which all comparisons in this book are reckoned. This figure was obtained for free-air conditions, the observer listening with both ears, and facing a simple source of sound radiating equally in all directions [46].

TABLE 1. *Illustrating the decibel scale*

Ratio of sound power to that at threshold	*Decibels above the threshold*	*Sound pressure at 1,000 ∼ dynes per sq. cm.*	*Sound pressure ratio to that at threshold*
10,000,000,000 = 10^{10}	$10\times10 = 100$	2×10^{1}	10^{5}
1,000,000,000 = 10^{9}	$10\times9 = 90$	$2\times10^{0\cdot5}$	$10^{4\cdot5}$
100,000,000 = 10^{8}	$10\times8 = 80$	$2\times10^{0}=2$	10^{4}
10,000,000 = 10^{7}	$10\times7 = 70$	$2\times10^{-0\cdot5}$	$10^{3\cdot5}$
1,000,000 = 10^{6}	$10\times6 = 60$	2×10^{-1}	10^{3}
100,000 = 10^{5}	$10\times5 = 50$	$2\times10^{-1\cdot5}$	$10^{2\cdot5}$
10,000 = 10^{4}	$10\times4 = 40$	2×10^{-2}	10^{2}
1,000 = 10^{3}	$10\times3 = 30$	$2\times10^{-2\cdot5}$	$10^{1\cdot5}$
100 = 10^{2}	$10\times2 = 20$	2×10^{-3}	10^{1}
10 = 10^{1}	$10\times1 = 10$	$2\times10^{-3\cdot5}$	$10^{0\cdot5}$
Threshold 1 = 10^{0}	$10\times0 = 0$ zero level	2×10^{-4}	$10^{0} = 1$

Note that the number of decibels is ten times the *index* in column 1 but twenty times that in column 4.

The intensity level of a sound is defined to be the number of decibels it is above the reference level of 200 microdynes per sq. cm. For example, a sound pressure of 1 dyne per sq. cm. is $20 \log_{10} 1/0\cdot0002 = 20 \log_{10} 5{,}000 = 74$ db. above the datum level. More generally if p is the sound pressure in dynes per sq. cm., the intensity level is approximately $74+20 \log_{10} p$ db. above the datum level.

4. *Loudness.*

This is a very thorny topic, and discussions relating to it are apt to be polemical at times. Loudness cannot be defined in an absolute sense, so it is necessary to have a basis of comparison. Reverting to the experiment in an acoustically 'dead' room under free-air listening conditions, i.e. without the telephone receiver, suppose a tone of 512 ~ has a certain intensity level. It causes an aural sensation whose magnitude we desire to specify. This tone is replaced by a standard tone of 1,000 ~, and the intensity level is adjusted to a value such that when the tones are switched over, they are judged to be equally loud [46]. From the setting of a calibrated attenuator, used to control the intensity level, the value above the datum level of 200 microdynes per sq. cm. is known. We could, if we pleased, define this to be the loudness level of the 512 ~ tone. For example, suppose the intensity level of this tone is 25 db., then the intensity level of the standard reference tone of equal *loudness* is only 20 db., which shows that the ear is less sensitive at 512 ~ than at 1,000 ~ for the conditions in question. The loudness level of the 512 ~ tone is therefore 20 db. above the datum. If we accept this definition of loudness, it does not agree with experimental observation at high levels. For example, when the level is raised from 30 to 40 db. we should expect the increase in loudness sensation to be the same as that when the level is raised from 80 to 90 db. In practice this is not the case and for 10 db. change the increase in loudness sensation is greater the higher the level of the standard reference tone of equal loudness. Thus the decibel scale does not give a true index of loudness as we normally understand it. Consequently in using the decibel scale to express results, we do not propose to speak of loudness level, but of the intensity level of the equally loud reference tone of 1,000 ~ above the datum or threshold of 200 microdynes per sq. cm. For brevity this will be designated the 'iso-ref-tone level' or merely the 'reftone level' which is less of a mouthful!

The family of full line curves in Fig. 2*a* [66*a*] shows the intensity levels for equal reftone levels obtained by the telephone receiver method, whereas those of Fig. 3 are of a similar character found by the 'free-air' listening method [46]. The difference between the shapes of the two sets of

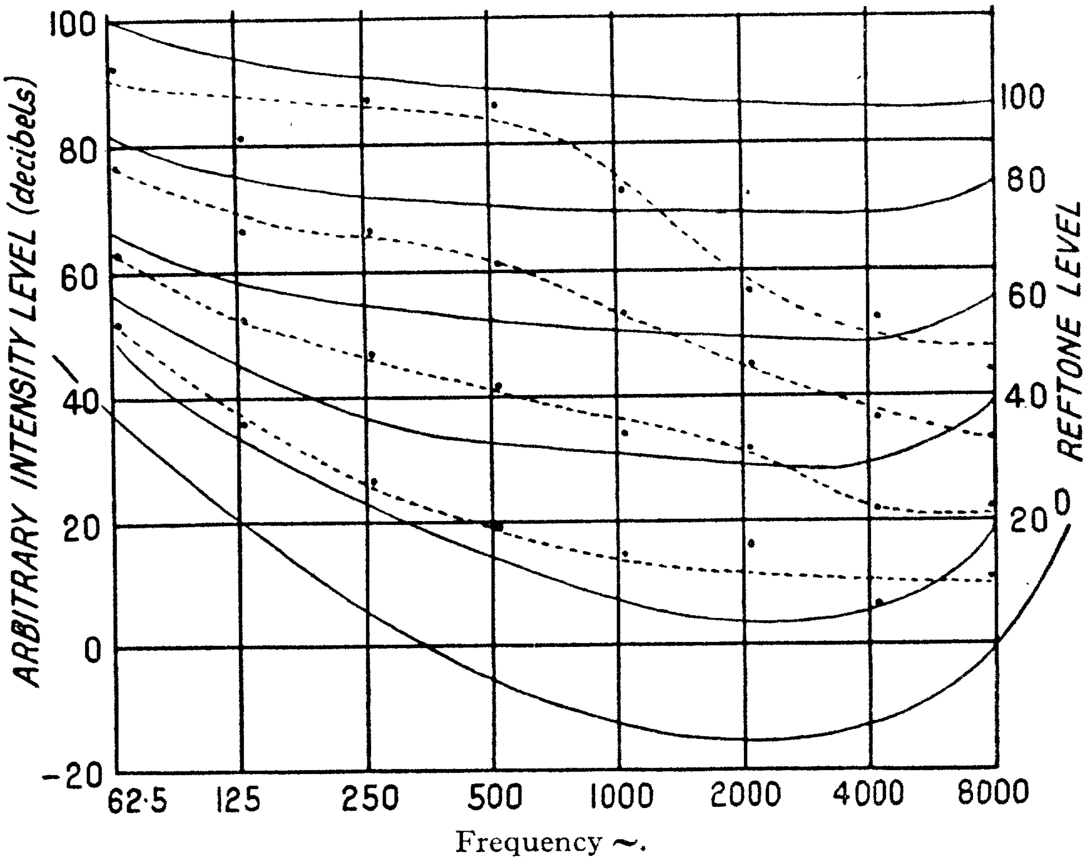


FIG. 2*a*. Full line curves show intensity levels for equal reftone levels, dotted line curves show intensity levels for equal annoyance.

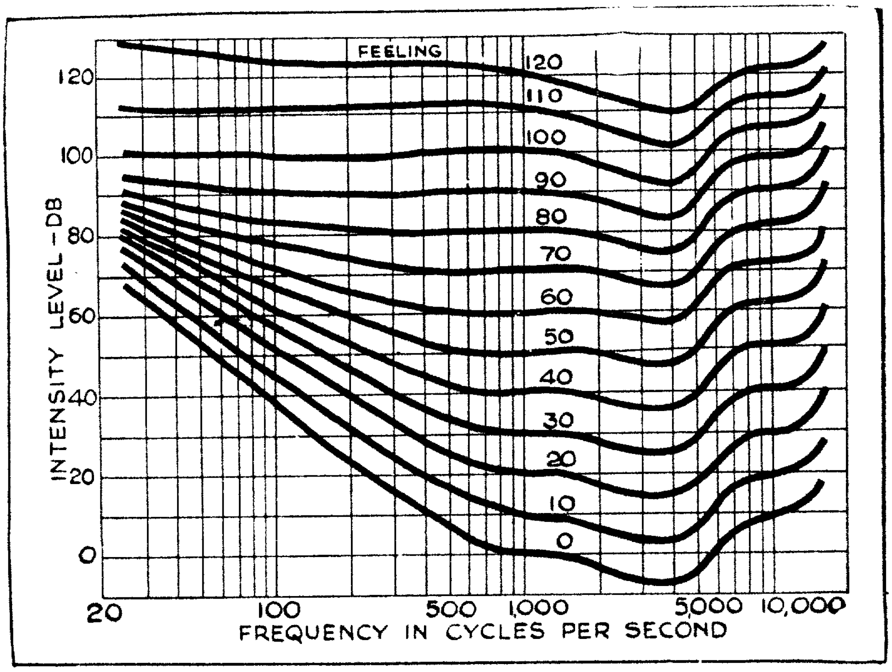


FIG. 3. Curves showing intensity levels for various reftone levels obtained under free air listening conditions.

curves above 1,000 ~ is due to the influence of the head in modifying the listening conditions, as mentioned previously. On each curve the reftone level is marked. To interpret Fig. 3 we choose the curve marked 70 db., which corresponds approximately to the reftone level of normal conversation. At 40 ~ the intensity level, this being a measure of the sound pressure, is 84 db. above the datum; from 500 to 2,000 ~ it is 70 db., whilst at 10,000 ~ it is 82 db. above the datum. Thus the sensitivity of the ear at a reftone level of 70 db. varies 14 db. between 40 and 500 ~, which represents a power ratio of 25/1. In other words if we listen to a non-directional loud speaker in the open air emitting two tones in succession, the power output at 40 ~ is 25 times that at 500 ~ for equal reftone level in both cases. At levels of 90 to 110 db. the power required is almost the same at 40 ~ and at 500 ~, since the ear is equally responsive over a wide frequency range at high reftone levels. On the other hand, at the lower threshold, the power ratio is half a million, i.e. 57 decibels, which illustrates how very insensitive the ear becomes at low levels. The crowding together of the curves below 1,000 ~ indicates that the sensitivity to low tones increases much more rapidly with rise in reftone level than it does at frequencies above 1,000 ~. These otic characteristics can be demonstrated qualitatively with a radio receiver and loud speaker capable of attaining a reftone level of 80 to 90 db. First of all set the volume control so that the reproduction or an orchestra, organ, or dance band, i.e. where there is sufficient bass, is just audible in a quiet room. Seated at the other side of the room, ask some one to gradually increase the sound output until it reaches a high value, so that normal conversation is drowned. The enormous increase in the relative strength of the lower register will be especially striking. The same experiment can be performed in the garden, to get free-air conditions, but it may not be so effective, since the relatively low room absorption for bass tones helps to raise the level relative to that of the upper tones. With certain loud speakers, which 'boom' due to diaphragm resonances and cabinets having flimsy sides, the lower register at moderate reftone levels is too pronounced, and one is glad to reduce the output to a point where the bass is more subdued. The ultimate effect of the reduction depends, however, entirely upon the diminution in sensitivity of the ear at the lower levels. Reproduction of speech at high reftone levels is a searching test for a loud-speaker system which covers a wide frequency range. If the speaker (or speakers) has conspicuous resonances in the lower and upper registers, they are then very noticeable and particularly offensive. The lower register is reproduced with a boom, whilst the upper register is accompanied by whistling and lisping of sibilants. A satisfactory system should have a good tonal balance at the reftone level of the original sound.

Additional information can be gleaned from the curves of Fig. 3 if they are plotted differently. Inspection shows that from the datum level upwards the intensity level is equal to the reftone level over the entire range from 800 to 1,800 ~. At other frequencies the intensity and reftone levels are unequal, the discrepancy near the extreme frequencies of the upper and lower registers being very marked. This information is delineated in Fig. 4 which serves to emphasize once more the great variation in sensitivity of the ear with variation in frequency.

It has already been remarked that the Weber-Fechner logarithmic law is inaccurate except at low intensity levels. In other words, the decibel scale based on the Weber-Fechner law is not in keeping with one's sensations of loudness when the level is fairly high [32]. The problem of what may be regarded as a true loudness scale, is one of considerable difficulty, owing to the purely subjective element involved. Where an objective scale, such as that of length, is concerned, there is universal agreement, excepting as to the units in which distances are expressed! Whatever units are employed, lengths can be added together, and the result is always the same, barring any minor corrections in virtue of relativity! Neither loudnesses nor reftone levels can be added, even at the same frequency. If the reftone level of a 64 ~ tone is 80 db. and that of a

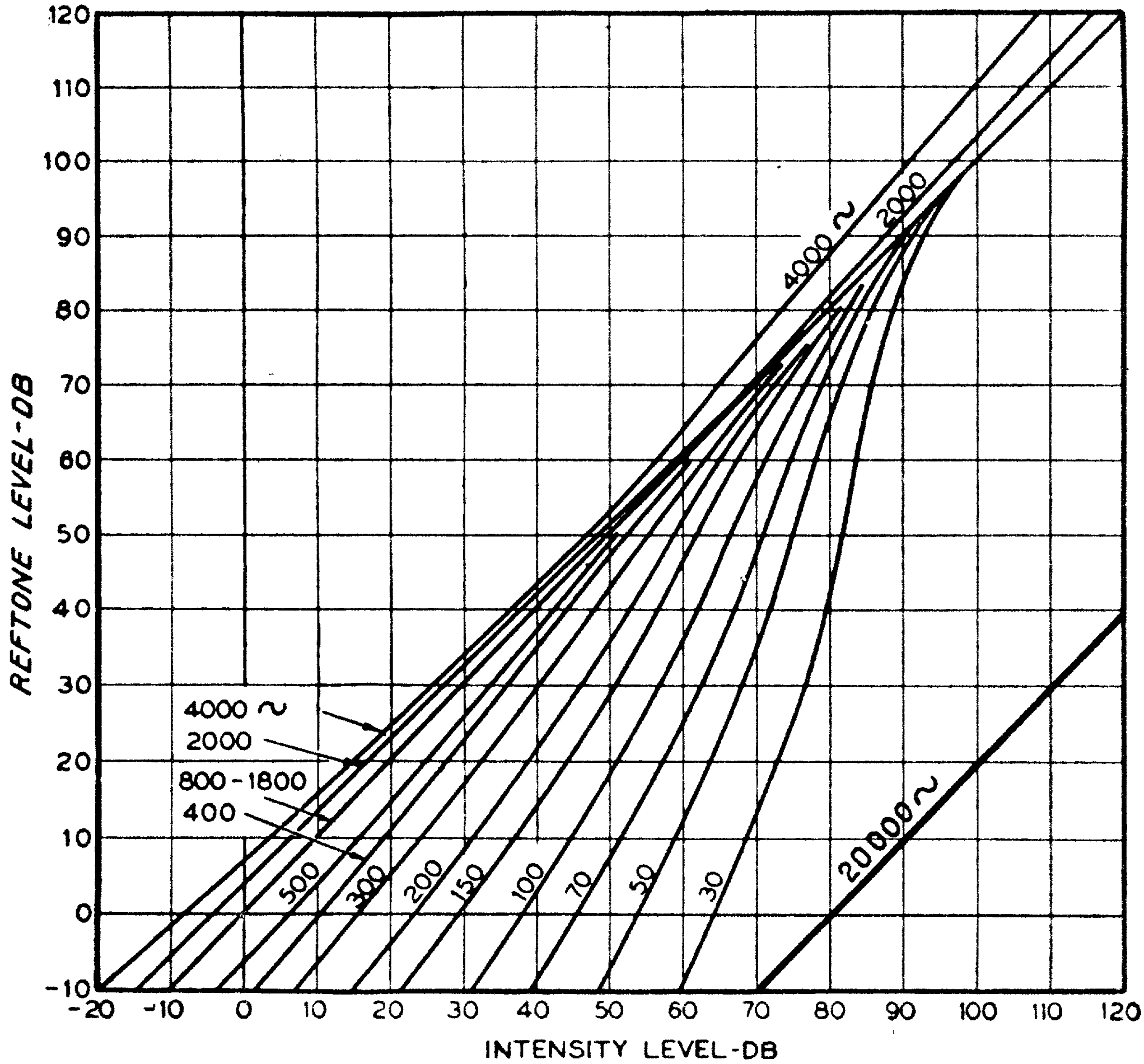


FIG. 4. Curves showing the relation between intensity level and reftone level for constant frequencies.

512 ~ tone is 40 db., the new reftone level is not 120 db. Actually it would be 80 db. since the 512 ~ tone would be masked and, therefore, inaudible. This, however, is not the place to discuss a thorny topic, so the reader who wishes to delve more deeply into decibels and their acoustical accomplices should consult [31, 32, 33, 37, 46].

It is easy by eye to judge when one line is half as long as another, but by virtue of the non-additive property of loudness one would expect judgement of half-loudness to be difficult. Nevertheless, experiment seems to indicate that it can be done, so the possibility of a 'loudness' scale arises [32]. If all ears had the same threshold curve and identical characteristics otherwise, the loudness scale would present little difficulty. Unfortunately, as we grow older, the characteristics of the ear change appreciably. To the average person 60 years of age, the complex sound of a large electric motor will not be so loud and penetrating as it will to a young person.

We shall now describe experiments from which a loudness scale has been constructed, since this is of considerable practical importance to engineers whose business lies in the design of new machinery to make 1/*n*th the noise of its forerunners, *n* being as large as possible [32]. The observer under test was provided with a pair of telephones mounted on a headband. His or her threshold of hearing was determined, and the intensity level of a 800 ∼ tone set 100 db. above this (the datum was about 200 microdynes per sq. cm.). By means of a change-over switch, the 800 ∼ tone was fed to the telephones either at full or at reduced intensity by way of an attenuator in the latter case. The observer adjusted the attenuator until on throwing over the switch the loudness was judged to be one-half that of the original at 100 db. level. The original was now reduced to the value judged to be one-half, and the loudness again halved by the attenuator, whose setting governed the 'original' for the next test, and so on down the scale. Thus the loudnesses were 100, 50, 25, 12·5, 6·25, 3·125, and 1·563 units respectively. This procedure was followed with 34 observers. Although there were deviations from the mean values determined for each step, when loudness is plotted against intensity level, the points give the curve of Fig. 5. This can be expressed mathematically by the simple formula, loudness $= 10^{-6}d^4$, where d is the reftone level above the threshold in decibels. From the curve it is found that if the intensity level rises from 40 to 50 db. the

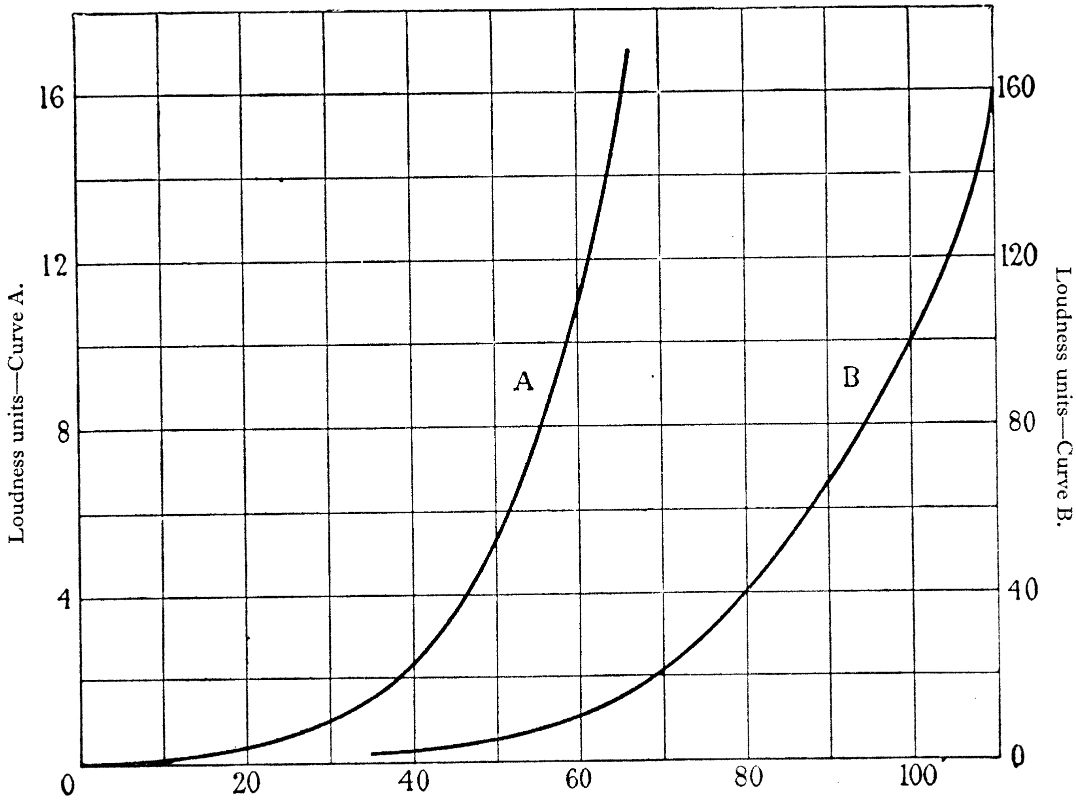
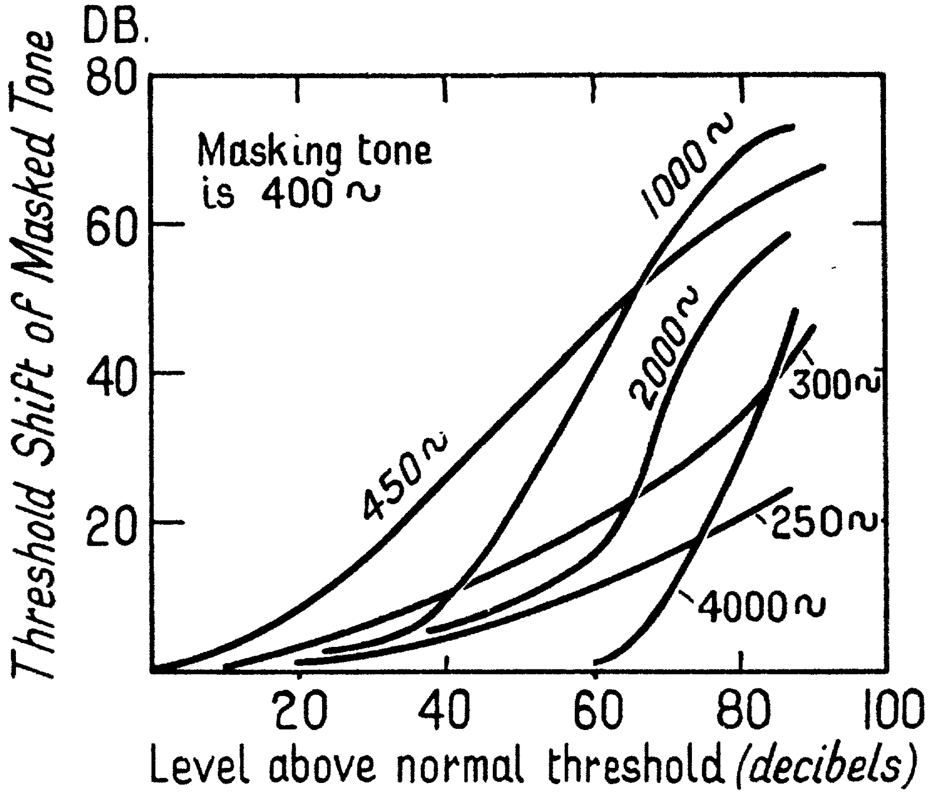


FIG. 5. Curve showing the relation between loudness and reftone level in decibels of an 800 cycle tone. 100 loudness units is taken as equivalent to 100 decibels. Curves obtained from the fractional loudness estimations of 34 persons with normal hearing. The equation to the curve is 'loudness' = $10^{-6}d^4$.

increase in loudness is 3·5 units, whereas a rise from 80 to 90 db. is accompanied by an increase in loudness of 26 units or about seven times as much. This latter figure is more in keeping with practical experience than the 10 db. rise on the logarithmic reftone scale. When the loudness is reduced to one-half, it falls from, say, 100 to 50, whilst the drop in intensity level is 95 db. These data illustrate clearly the great divergence between the loudness and the reftone level decibel scales.

5. *Masking of Sounds.*

In many vehicles of transport, conversation is carried on with difficulty owing to the high noise level. Speech at normal conversational level may be unintelligible in say an express railway train with the carriage windows open. This is due to the masking or deafening effect of the noise. It is necessary to increase the vocal output power from the normal value to one which outmasks the noise. This aural effect is of prime importance, since the perceived loudness of a sound depends upon the presence of other sounds. To obtain quantitative data relating to the masking of one sound by another, it is usual to deal with pure tones. Experiments have been conducted in an acoustically 'dead' room, using a telephone ear-piece as described on pp. 5, 6. Suppose a tone of frequency 300 ∼ is just audible. If another tone of 400 ∼ whose intensity level is well above the threshold is introduced into the ear, the first tone is completely masked, so that it is now inaudible. To render the 300 ∼ tone audible it is necessary to raise the intensity level by an amount known as the 'threshold shift of the masked tone'. Referring to Fig. 6 [45*b*], let the intensity level of the 400 ∼ masking tone be 40 db. above the threshold, then the threshold of the 300 ∼ tone must be raised 10 db. before it is audible. It should be observed that the threshold of the masked tone only rises 20 db. and not 40 db. In other words, it is possible to hear a sound in the presence of a much louder one, an effect we experience every day without recourse to scientific measurement. If the masked tone is 2,000 ∼, the threshold is raised only 4 db., whilst with a tone of 4,000 ∼ there is no perceptible rise in the threshold. The general conclusions which can be drawn from experiments of this nature are: (1) that a tone is most easily masked by another of nearly the same frequency, (2) when the intensity level of the masking tone is 70 db. or more above the threshold, tones of higher frequency are more readily masked than those of lower frequency. This conclusion requires to be modified for lower masking levels, as will be evident on inspection of Fig. 6 at say 20 db. In interpreting this diagram it should be remembered that the 'threshold' is that of audibility for the frequency of the tone under examination. It is not the arbitrary reference level of 200 microdynes per sq. cm. The loud speaker experiment described on p. 13 can be



(Masking tone.)

FIG. 6. Curves showing the shift of the threshold of hearing when one tone is masked by another. Masking tone is 400 ∼.

used to demonstrate the great masking effect of low tones at high output levels. In fact to obtain a good tonal balance in an orchestra, so that the violins, flutes, clarinets, and brass instruments are not overpowering, it is essential to introduce adequate power from the low-pitched units, e.g. double basses, trombones, drums. The same argument applies to the pedal organ, where powerful low tones produced by playing on the pedals are required to give a pleasing tonal balance.

6. *Annoyance.*

Every one is conscious of the annoyance created by a high-pitched intense sound. For example, few of us could tolerate the continuous blast of a policeman's whistle in the dining-room! By aid of the apparatus described hitherto, some idea of the relative degree of annoyance of pure tones can be obtained. So far it has not been possible either to define annoyance concisely[1] or to devise means of measuring the actual *degree* of annoyance. The full line curves of Fig. 2*a* are for equal reftone levels, whilst the dotted curves are for equal annoyance found by the telephone method, p. 6 [70]. Thus if we consider the uppermost dotted curve the intensity level at 62·5 ∼ is 90 db., whereas for equal annoyance at 4,000 ∼ it is only 50 db. This shows that high tones are much more annoying than low tones of the same intensity level. It ought to be mentioned, however, that some observers claim that prolonged listening to low tones is particularly troublesome. The data in Fig. 2*a* is the average for a number of trained acoustical observers. Amongst these it was found that pure tones of any frequency were annoying to certain observers.

So far as distraction is concerned, sharp intermittent sounds are much more disturbing than a continuous noise whose level is fairly high. In the former case we are in a state of continuous expectation and apprehension, whereas

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[1] It is sometimes difficult to discriminate between annoyance and distraction.

in the latter the ear adjusts itself to the new condition provided the loudness is not too great.

7. *Subjective tones.*

Where sound reproduction is concerned, whether it be the microphone, the radio transmitter and its associated valve gear, the loud speaker or even the medium itself (air), the designer aims to keep within the tenets of the law of linearity. That is to say, if the sound pressure on the microphone diaphragm is doubled, its amplitude of vibration will also be doubled; or if the voltage swing on the grid of any valve in the system is doubled, the corresponding current in its anode circuit is doubled too.

More generally if a variation in sound pressure occurs, the corresponding variation in voltage and current throughout the system is strictly proportional thereto. When money is no object, this ideal can be approached with adequate approximation. But what of the ultimate destination of the sound, namely, the human ear: is it linear in action? The amplitude of the otic system is proportional to the sound pressure at low intensity levels, but at moderate or high levels the law of proportionality is violated. From much experience in the use of thermionic valves, we are well aware that if a valve is worked on the lower curved parts of its characteristics, by applying too large a grid bias, the results are distinctly distressing. Pure tones are reproduced with a retinue of 'aliens', thereby introducing a raucous or harsh sound. This is particularly noticeable with power valves of high magnification factor, e.g. pentodes, since their characteristics have sharp lower bends. Owing to the asymmetrical mechanical construction of the ear [13], the characteristic showing the relationship between pressure and displacement, i.e. amplitude, will be curved. Thus the behaviour of the ear can be compared with that of the thermionic valve working on the curved part of its characteristics at high-power levels. If a pure tone is supplied to the ear at an adequate intensity, new tones will be created owing to the curved characteristic. For example, if a tone of 200 ~ is loud enough, it will give a subjective impression of 200 ~, 400 ~, 600 ~ and so on, according to the intensity level. Moreover, a pure objective tone may yield several subjective tones. Now let us suppose that there are two loud objective tones of 200 ~ and 300 ~, then there will be two sets of subjective tones, one corresponding to each frequency, namely, 200, 400, 600 ~, &c., 300, 600, 1200 ~, &c. To explain the combined effect of these tones we have recourse to Fig. 7, which shows an hypothetical curve which will be used in place of the actual pressure/amplitude characteristic of the ear. The point *P* corresponds to the middle of the swing of say the 200 ~ tone, and the sound pressure makes excursions on each side thereof. The amplitude of the ear drum, however, is greater in the positive than in the negative direction (signs purely conventional), i.e. *ST* is greater than *PR*. In thermionic valve terminology the otic system causes rectification, for under similar circumstances where sound pressure is replaced by applied grid potential variation, and amplitude by anode current, the unidirectional component of the latter would increase. If the 300 ~ tone is present the total amplitude is greater than before. With this tone the to and fro motion is executed in two-thirds the time taken by the 200 ~ tone. Consequently the portion of the

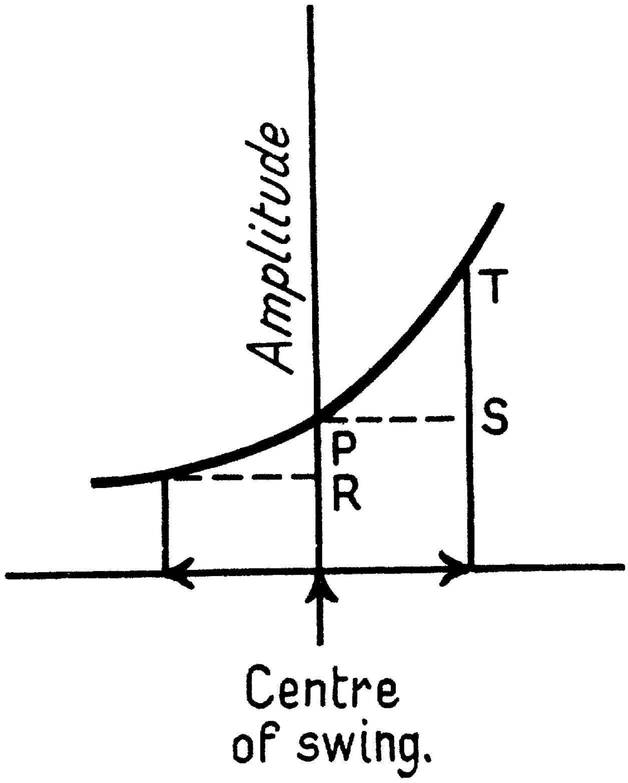

FIG. 7. Showing assumed curved amplitude characteristic of the ear. Abscissa represents sound pressure.

characteristic covered during operation varies, since one tone is on the top of the other, so to speak. The result is that one tone *modulates* the other, thereby creating sum and difference tones whose frequencies can be obtained by adding and subtracting the primary tones and their harmonics. Thus we get the following summation tones: $200+300 = 500 \sim$, $200+600 = 800 \sim$, $400+300 = 700 \sim$, $400+600 = 1{,}000 \sim$, and so on. The difference tones are $300-200 = 100 \sim$, $600-200 = 400 \sim$, $400-300 = 100 \sim$, $600-400 = 200 \sim$, &c. The effect of a non-linear aural characteristic is, therefore, to create *subjective* tones some of which are of lower whilst others are of higher frequency than either of the primary tones.[1] In the early days of broadcasting this non-linear effect of the ear in creating sub-frequencies was cited as an excuse for not having reproducing apparatus giving adequate reproduction in the bass register. In listening to a pipe organ or to an orchestra, both the subjective and objective low tones are present, so the latter must be supplied by the reproducer in order to create the sensation of naturalness. Although (so far as the author is aware) there are no published results showing the relationship between pressure and displacement of the ear drum, it is probable that as 'no two persons are alike', no two aural characteristics are alike. Moreover, the subjective tones will vary according to the individual, which taken in conjunction with other effects means that the musical or sound sensation is a purely personal matter, being different for each individual. This does not explain, of course, why certain people 'fit for treasons, stratagems and spoils', prefer noise to good music!

Finally we shall describe an experiment which, although performed on a cat, is of sufficient interest to warrant its inclusion here. The otic nerve of a cat was exposed and an electrode placed thereon, whilst another electrode made

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[1] In this discussion, for the sake of simple illustration, we have assumed the aural characteristic to be parabolic.

contact on the body. These electrodes were connected to a valve amplifier and loud speaker in an adjoining room. When the cat's ear was used as a microphone, the sounds were audible in the loud speaker. Low tones and high tones up to at least 5,000 ~ were reproduced in this manner, and speech was quite intelligible [2, 128].

8. *Summary.*

Since the behaviour of the ear is extremely complicated and as it is the court of appeal upon whose judgement all decisions respecting noise depend, we shall epitomize the salient points.

1. The character of sound depends upon three things, (*a*) pitch or frequency which determines the position in the musical scale, (*b*) intensity level, (*c*) wave form which in a broad sense determines the quality.

2. The audible frequency range extends approximately from 20 to 20,000 ~. On the average it is less than this, but it depends upon the individual and on his or her age.

3. When the power ratio of two sounds is P_1/P_0 the intensity level of one is defined to be $10 \log_{10} P_1/P_0$ decibels above that of the other.

4. The magnitude of sound sensation is specified in two ways, (*a*) it is the number of decibels above 200 microdynes per sq. cm. of a 1,000 ~ tone which sounds equally loud under free-air conditions. This is regarded as the reftone level in decibels; (*b*) it is the number of units above the same datum on a *loudness* scale in which 100 units represents the same magnitude of sound sensation as a reftone level of 100 decibels.

5. There are two thresholds, (*a*) that of hearing, (*b*) that of feeling. Under free-air listening conditions at 1,000 ~ they are 120 to 130 decibels apart, the latter representing a power ratio of ten billion to one. About 250 different degrees of loudness can be recognized in this interval at 1,000 ~.

6. At low *intensity* levels the ear is much more sensitive

to medium and high frequencies than to low frequencies. At moderate intensities the variation in sensitivity is less, whilst at high intensities it is negligible, under free-air listening conditions.

7. On the whole, high-pitched tones are more annoying than low-pitched tones of the same reftone level.

8. The action of the ear is not linear, so that a loud pure tone is heard as a complex tone, i.e. it is accompanied by subjective overtones. Several loud pure tones sounded simultaneously are accompanied subjectively by summation and difference tones, due to the ear acting as a mechanical rectifier.

II

MEASUREMENT OF NOISE

In Chapter I we outlined a method of measuring the reftone level of pure tones, where reference is made to a standard tone of 1,000 ∼ whose intensity level above an arbitrary datum is adjusted to give equal loudness sensation with the tone under test. This method is also used in measuring the reftone level of a noise, and the results are, of course, purely of a subjective nature. It is known as the balance or equality method. Now we have already seen that the influence of one sound is to mask that of another by raising the threshold of audibility. This can be regarded as a deafening effect. Thus, if the threshold of a 1,000 ∼ tone is raised 63 db. due to a noise, this can be considered to be the deafening effect of the noise. When the 1,000 ∼ tone is sounded at a higher intensity level in the presence of the noise, it will be audible, but not comfortably so. It is found by the equality method of experiment that in the range 750–1,500 ∼, the noise level of traffic is about 15 db. above the deafening or new threshold level. In the above case, therefore, the noise level was of the order 78 db., which is the average value at Ludgate Circus in London [124]. If a motor-horn is sounded in that neighbourhood to give a level of 67 db. at a distance of 100 feet, it will be just audible above the traffic din. This does not provide an adequate margin for warning purposes, and it is found that the reftone level at 100 feet should be equal to that of the noise itself, namely, 78 db. Where conversation is concerned in the presence of a noise level of 78 db., a conversation level of about 71 db. would probably suffice to obtain intelligibility.

The third method of noise measurement is an objective one and depends upon the reading of a direct current meter. A microphone picks up the noise which is amplified, then rectified, and passed on to the meter whose reading gives the intensity level in decibels above a selected threshold. No allowance is made for the variation in sensitivity of the ear at different frequencies. Consequently such readings would not be of much value as they stand. For example, suppose the meter reading corresponding to a noise were 70 db. This noise would be very annoying if the main frequency components were above 2,000 ~, but comparatively innocuous if below 600 ~, e.g. an aeroplane at a distance. An explanation of this partiality of the ear can be derived from the curves of equal annoyance given in Fig. 2*a*, where it is seen that above 2,000 ~ the annoyance increases rapidly with rise in frequency. To overcome this defect in the apparatus, a special network is incorporated in the amplifier to give it an ear-like response, i.e. to make it relatively insensitive to low tones, excepting at high reftone levels where there is little variation in aural sensitivity with frequency. This is usually accomplished by choosing one or more of the curves of Fig. 3, say that marked 60, and making the amplifier characteristic the inverse of this as shown in Fig. 8, curve 1.[1]

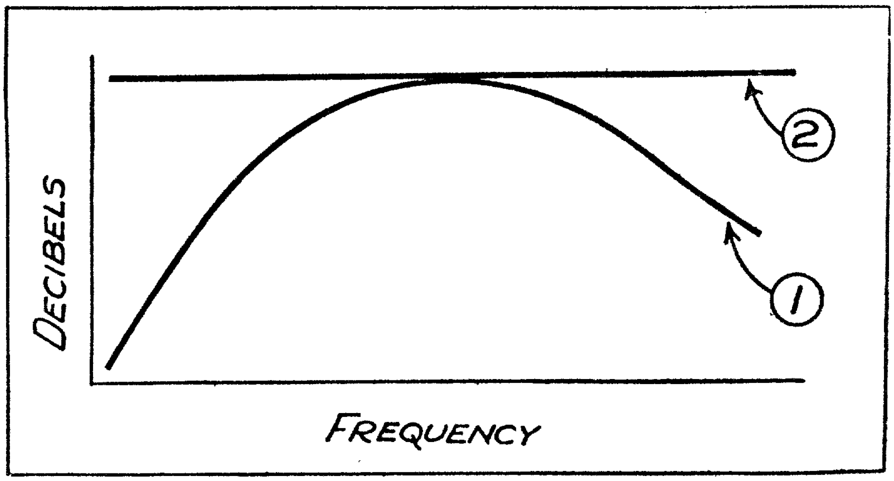

FIG. 8. Characteristic of amplifier with ear like response (1). Uniform characteristic amplifier (2).

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[1] No attempt is made to reproduce the rapid changes in curvature shown in Fig. 3, above 1000 ~. A mean curve is taken.

We see, therefore, that there are three principal methods of measuring noise: (1) by finding the deafening effect or increase in the threshold of hearing; (2) by judging when the noise is equal in loudness to a standard pure tone; (3) by using a microphone followed by an amplifier having an ear-like response curve and a direct current meter calibrated in decibels. Various forms of technique can be employed in cases (1) and (2), some of which have been mentioned, i.e. listening with a telephone receiver or listening under free-air conditions. In what follows it is proposed to describe the three methods in greater detail.

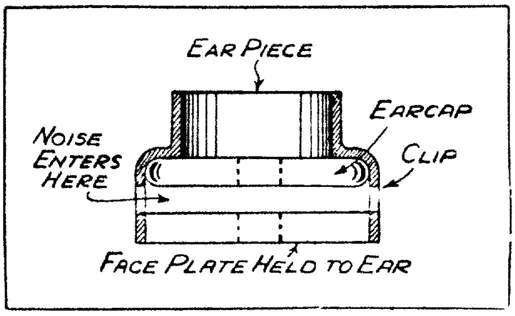

FIG. 9. Showing spaced telephone ear piece.

The instrument for measuring the deafening effect of a noise is called an audiometer. It consists of a gramophone turn-table and pick-up, used in conjunction with special records, each of which gives what is known as a 'warble' tone [90, 119]. This signifies that the pitch varies rapidly and continuously up and down over a specified frequency interval. Three records are used, one for each of the intervals: 250–750 ∼, 750–1,500 ∼, 1,500–5,600 ∼. The idea of the warble tone is to cover the band of frequencies in which the main components of the noise reside. The output from the pick-up is passed on to a valve amplifier, thence to an attenuator or special resistance network which is used to control the current supplied to a telephone receiver held to the observer's ear. The attenuator is calibrated in decibels above some selected datum. The telephone receiver is fitted with a special cap shown diagrammatically in Fig. 9. The cap holds the receiver about half an inch away from the ear, and the slots enable the noise to enter the ear, together with the warble tone from the gramophone record. The observer adjusts the attenuator until the warble tone is just audible in the presence of the noise. To obtain an accurate reading it is preferable to first set the attenuator until the warble tone is just inaudible, then to alter it for audibility and take the mean value. This procedure may be repeated with the other ear and the average value for both ears recorded. The attenuator reading is then the deafening effect of the noise above the reference datum. When deafening in decibels is plotted against frequency, the audiogram of the noise is obtained. Experimental data relating to street noises are illustrated diagrammatically in Fig. 10. Owing to the method of test, i.e. varying the pitch continuously over three selected bands, there is only one attenuator reading for each band. Thus the deafening effect of the noise is shown as a horizontal line throughout any particular range. This must not be interpreted to mean that the deafening effect is the same at all frequencies in the band, since it is only an average value indicative of the level throughout the range. It will be noticed that in all cases the deafening is greatest in the 750–1,500 ∼ range and least in the 1,500–5,600 ∼ range. The level of the middle

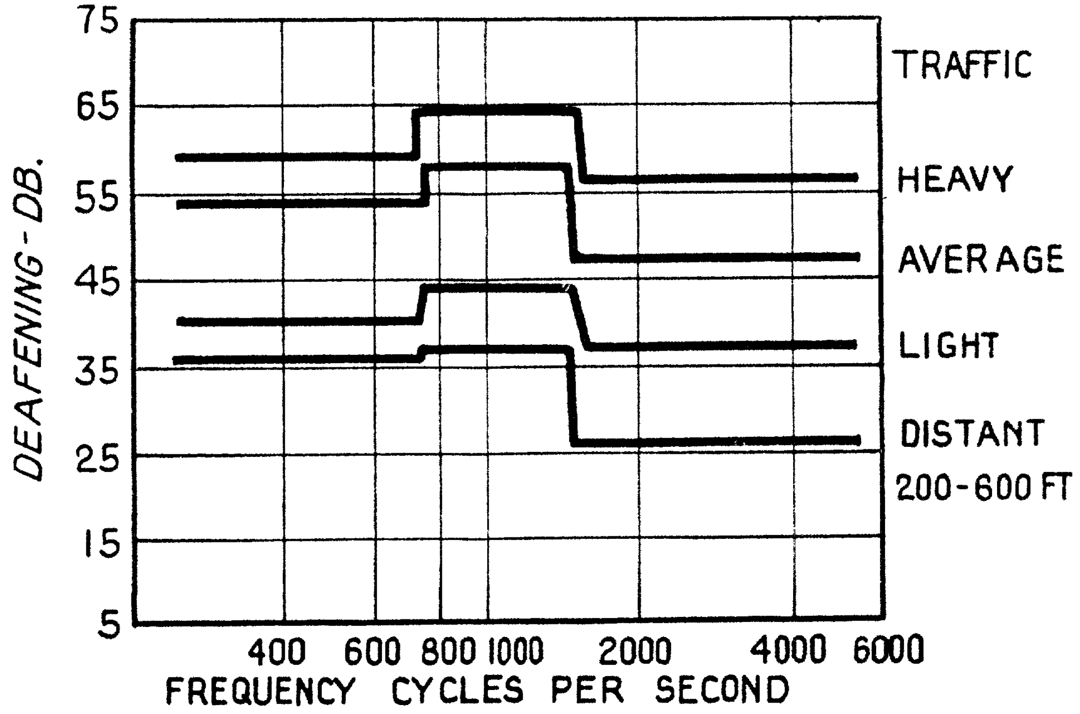

FIG. 10. Audiograms of traffic noise in New York.

range of record 2 for average traffic is 58 db., so that according to our previous data the reftone level is 58+15 = 73 db. The apparatus described above can also be used for equality tests, the attenuator being set so that the warble tone and the noise appear equally loud. In this respect, however, it is probably preferable to use a pure tone of 1,000 ~. The spaced telephone equipment (Fig. 9) has the disadvantage that the strength of the upper tones in the noise are reduced owing to a baffling effect. Hence, it is apt to give an under-estimate of either deafening or equality, particularly in cases where the noise has relatively large upper frequency components [32]. For equality tests, owing to the distance of the telephone receiver from the ear, a large current must be supplied to the winding to obtain a level of, say, 120 db., whilst the corresponding diaphragm amplitude will be adequate to introduce alien tones arising from non-linear action of the mechanism. This type of distortion is quite prevalent in modern sound reproducing apparatus, especially when the output is large.

For measuring the aural sensation of loudness direct, the equality method seems to be favoured most. Different investigators use different reference frequencies, but from various points of view, which need not be discussed here, 1,000 ~ seems to be preferable. A pure tone of this frequency is generated by a valve oscillator, the degree of purity being such that the fundamental is at least 40 db. above the level of the harmonics. This is passed to an attenuator for regulating the value of the current supplied to the telephone ear-piece. The latter is used with a rubber cap to make an effective seal thereby preventing leakage of sounds from outside to the ear. The noise enters by the other ear and the attenuator is adjusted until the 1,000 ~ tone is judged to be equally above and equally below the noise level, so that the mean represents the equality reading for that ear [32, 38]. The observations are then repeated using the telephone on the other ear and the average of the two is taken to be the reftone level in decibels. In each case the uncovered ear is presented to the noise, that is to say, the ear cavity is in a direct line with the source. Experiment shows that whilst it is advisable for the observer to have good hearing, fairly accurate results can be obtained even with a moderately deaf person or one whose two ears vary in sensitivity by as much as 50 decibels [32]. Two moderately deaf ears appear to give better results than one good and one bad ear. Apparatus of this nature is easily made in portable form and weighs about 16 lb. (see Fig. 11).

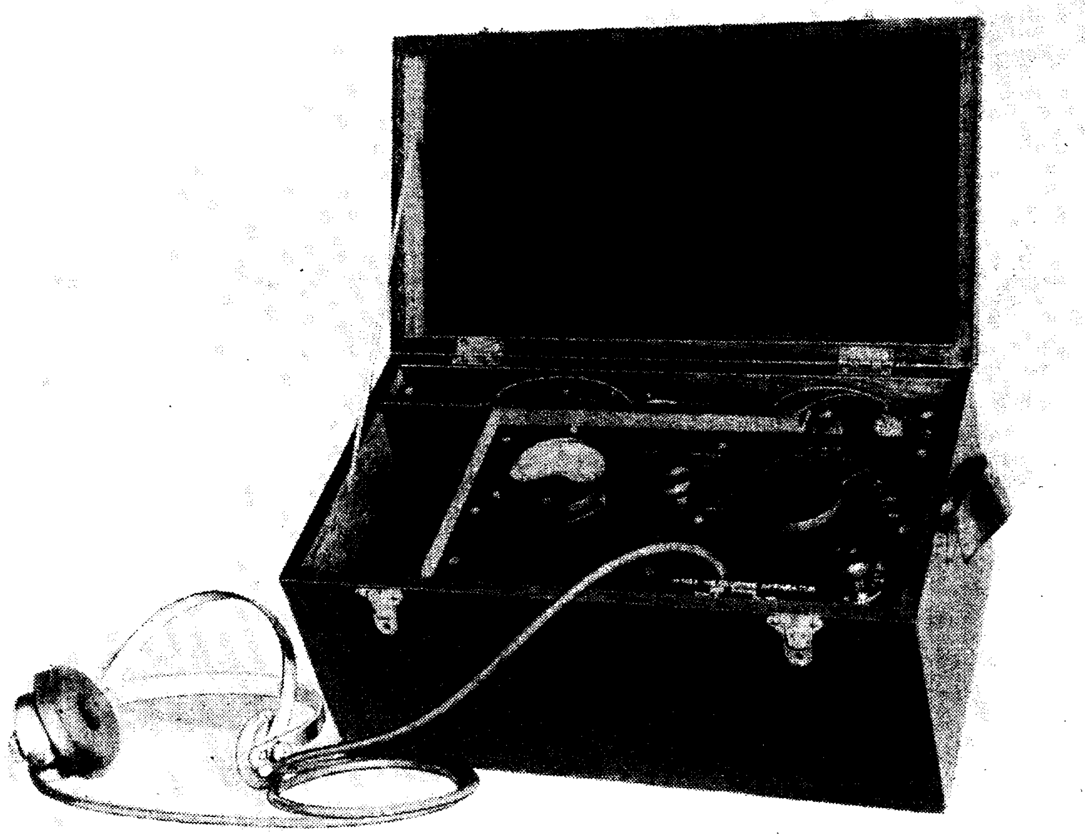

FIG. 11. Metropolitan Vickers portable noise-measuring apparatus.

Since an appreciable time is required to obtain a reading, the equality method cannot be used to study noises which are neither consistent in character nor constant in level. For this purpose, and also where accurate indications of small changes in noise level are desired, an objective noise meter should be employed. This instrument is used for the third method of measuring noise. Here the response of the amplifying apparatus is corrected to simulate the characteristics of the ear at certain reftone

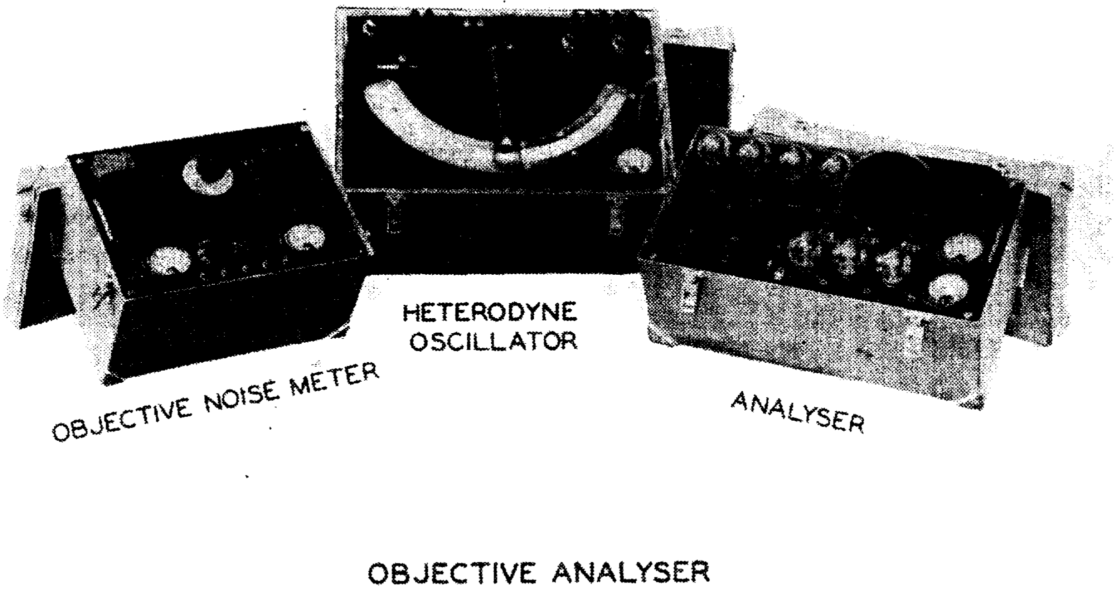

FIG. 12. Western Electric noise-measuring apparatus.

levels, as mentioned earlier on. Photographs of an objective noise meter are reproduced in Figs. 12, 13, whilst a schematic diagram of the apparatus is shown in Fig. 14. The microphone, which has a flat characteristic from 20 to 10,000 ∼, is located at a suitable distance from the noise source and pointed directly thereat. Its output is amplified and passed on to an attenuator calibrated directly in decibels. The current is then taken to one of three correction networks corresponding to the three reftone level ranges 30 to 50 db., 50 to 80 db., and 80 to 120 db. This gives a fair approximation to an ear-like response. Thereafter the current is amplified and rectified before being fed to the decibel meter. The zero of this instrument is at the centre of a scale which extends ±10 decibels. The reftone level of the noise is obtained by adding the meter reading to that of the attenuator.

FIG. 13. Western Electric noise-measuring apparatus in use.

In measuring the reftone level of pure tones, the instrument gives a fairly accurate subjective indication, but for complex noises the results will usually contain errors. This is due to the fact that the meter measures the total power of the constituent tones in the noise, whereas the magnitude of the auditory sensation differs from this owing to the masking effect of one tone on another. The range of the instrument shown in Figs. 12, 13, is from 35 to 165 db., or from 39 to 169 db., for reference levels of 300 and 200 microdynes per sq. cm. respectively. The battery supply unit contains standard electrical and acoustical sources by aid of which the calibration can be checked at any time.

In many noise investigations, e.g. in studying noise due to electrical machinery, it is essential to be able to assign to each component frequency a figure for the noise level it produces. This can be accomplished by aid of an objective noise analyser, one form of which is illustrated in Figs. 12, 13. The noise to be analysed (see Chap. III for noise analysis) is picked up by a microphone and amplified as already described. It can be passed through a correction circuit to give readings of reftone level, or the network

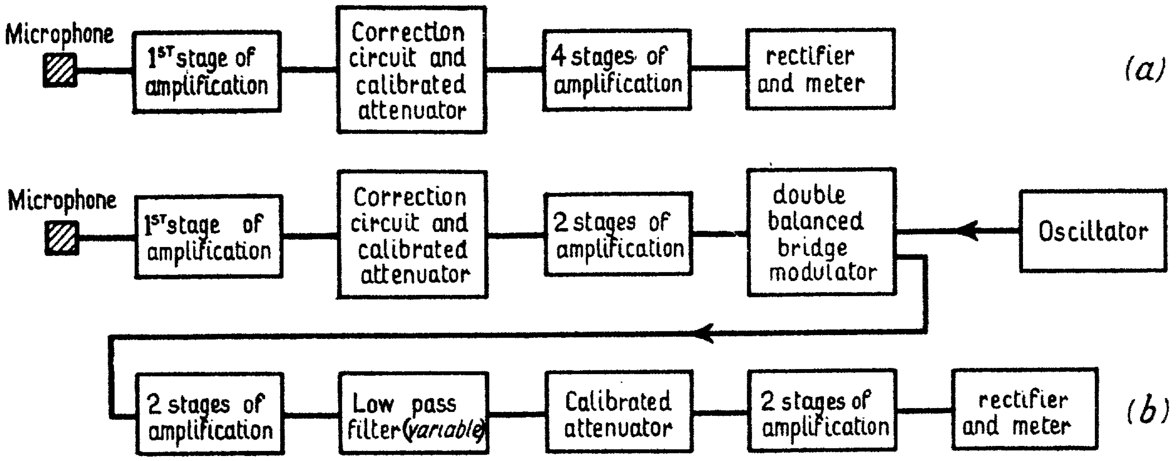

FIG. 14. Schematic diagram of Western Electric apparatus.

may be cut out, so that the readings represent intensity level above a prescribed datum. These readings give the actual sound intensity above the datum without reference to the ear. Suppose it is desired to know the intensity level of the component frequencies in the noise from 980 to 1,020 ∼. The central frequency is 1,000 ∼, so this (supplied by the oscillator Figs. 12, 14), together with the whole of the noise current, is fed to an electrical bridge arrangement followed by a double-balanced modulator. The latter produces two sets of frequency components. One set represents the differences between the noise components and 1,000 ∼, and the other represents their sum. The difference components only are accepted by an electrical filter, which cuts off all frequencies above a certain value specified above as 20 ∼ (1,000–980 or 1,020–1,000 ∼). Thence the current passes to an amplifier and thereafter it is rectified and fed to a meter reading ± 10 db. as described above. The amplification level in the band 0 to 20 ∼ is 60 db. greater than that outside this range, so the meter reading gives the level due to the noise components embodied in the range 980 to 1,020 ∼. By aid of a switch the band of frequencies can be adjusted to 40 ∼, 160 ∼ or 640 ∼.[1] Since the oscillator can be varied continuously from 50 to 10,000 ∼, the noise components in bands of the above widths can be found at any point in this range. Thus the apparatus enables a complete analysis of any noise to be made. Take the case of a motor horn whose main frequencies are 450, 900 and 2,700 ∼. If the oscillator were set at, say, 460 ∼ and the 20 ∼ filter used, the difference tone is 10 ∼, which gives a reading corresponding to the intensity of the 450 ∼ tone only. With the oscillator at 500 ∼ the reading would be negligible since the difference frequency is now 50 ∼, and this is well outside the 20 ∼ range of the filter. Similarly, to obtain a result at 900 ∼ the oscillator can be set to 910 ∼ and so on. The apparatus is designed so that the component frequencies in the noise cannot beat with one another and create difference tones which fall within the band of frequencies covered by the filter. Thus false readings are avoided. A feature of special interest is the use of transformers to transmit a frequency as low as 1 ∼ without attenuation.

A diagram illustrating analyses of typical noises is given in Fig. 15. In this case the measuring instrument differs from that just described. Band-pass filters covering the ranges to 500 ∼, 500 to 1,500 ∼, 1,500 to 3,000 ∼ and 3,000 to 7,000 ∼ are used. To determine the noise level in the 500 to 1,500 ∼ band, this filter alone is switched into circuit, and with a known adjustment of the attenuator, the output meter reading is taken in decibels. It will

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[1] It should be observed that the frequency band selected by the analyser is twice the range covered by the low pass filter. Thus for the above bands the filters cut off everything above 20, 80, and 320 ∼, respectively.

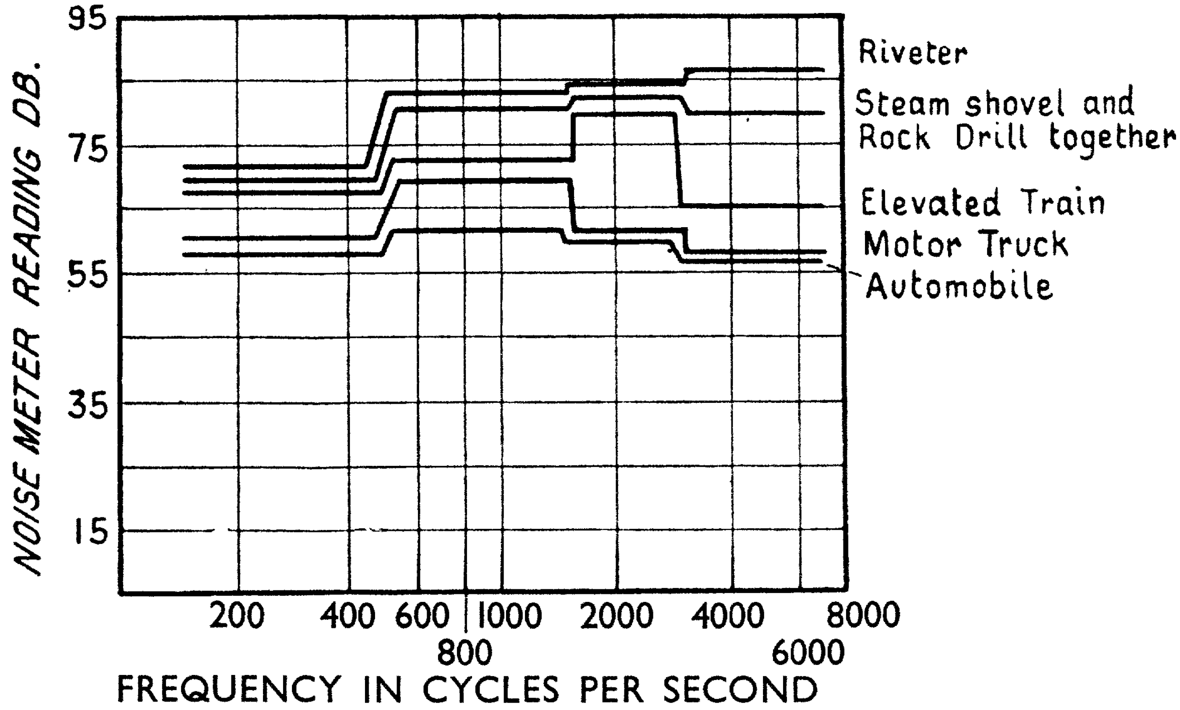

FIG. 15. Illustrating objective analyses of sounds in New York.

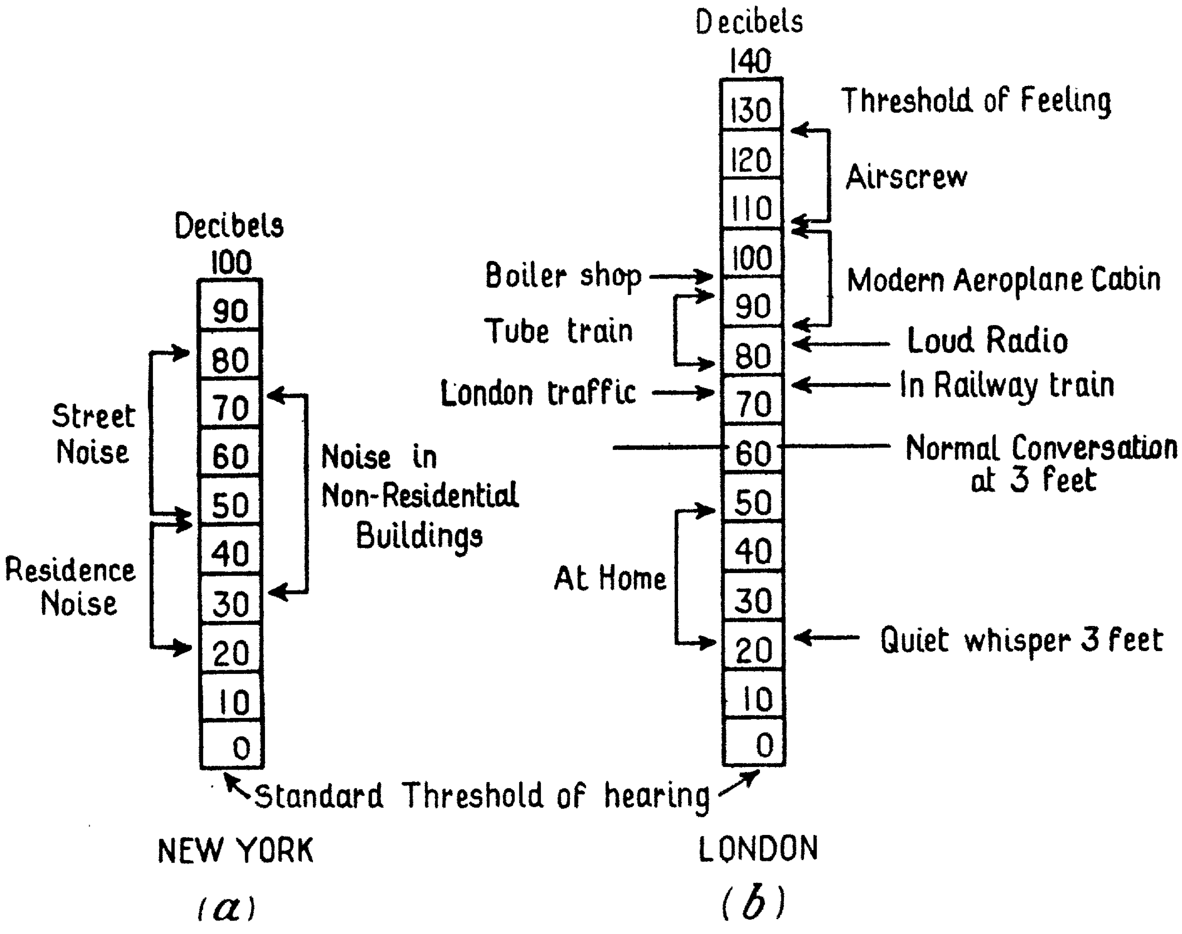

FIG. 16. Noise ladders.

be seen from Fig. 15 that, except in the case of a riveting machine, the reftone level is greatest in the 500–1,500 ∼ band. The increase in level at higher frequencies, with the riveter, is due largely to the natural oscillations of the steel structure. The analyses were obtained with the ear-like response curve and represent, therefore, the reftone levels under this condition, i.e. quasi-subjective. In the absence of a correction circuit, the *intensity* level would be greatest at the lower frequencies.

A selection of loudness and reftone levels due to sundry noises is given in Table 2 [32]. Column 2 represents loudness on the scale discussed in Chapter I, whilst column 3 refers to the reftone level in decibels above the average threshold of the individuals who made the tests, this being in the neighbourhood of 200 microdynes per sq. cm.[1]

Additional data are shown in what is perhaps a more spectacular form, by the noise ladders of Fig. 16, whilst a more complete selection of noise levels will be found in the tables on pp. 135–8.

TABLE 2. *Loudnesses and reftone levels of common noises* [32]

Datum level 220 microdynes per sq. cm.

Source of Noise	*Loudness (units)*	*Reftone level on decibel scale using* 800 ∼ *tone*
Two circular saws at 3 ft.	160	110
Motor-horn at 100 ft.	100	100
In suburban steam train, window open	50	84
Ordinary conversation at 3 ft.	20	69
In quiet saloon motor-car	10	59
Quiet electric motor (2 h.p.) at 3 ft.	5	49

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[1] The actual value was 220 microdynes per sq. cm., this being only 0·8 db. above the 200 level, which is a negligible amount.

III

FREQUENCY ANALYSIS

1. *Sound spectra.*

SOUNDS can be divided broadly into two classes: (*a*) those of a transient nature, (*b*) those which are steady whilst they persist. Speech consists mainly of transients, a number of consonants like *p* and *b* being highly explosive. The sounds start suddenly and die away quickly. In fact, speech is in the nature of a series of acoustical impulses, and for this reason it reveals resonances in loud speakers. There is no such thing as a continuous sound, in a rigorous sense, because it would last for ever. Nevertheless, it is customary to regard the pedal organ, violin, 'cello, cornet, and the like, as emitting continuous sounds of short duration. Each sound has to start and stop, but the transient states corresponding thereto are short in comparison with the duration of the note itself. Continuous sounds like that of an air-blown organ note, consist of a fundamental tone accompanied by a retinue of overtones of two, three, &c., times the fundamental frequency. To analyse any continuous sound into its constituents, it is merely necessary to use apparatus of the type described in Chapter II. In this way, what is known as the 'line spectrum' of the complex continuous tones is obtained. In the case of a transient, the matter is not so simple. When a note is struck on a piano, say middle C, whose pitch is 256 $\sim$, we infer that there are overtones having frequencies 512, 1,024 $\sim$, &c. Although the inference is justified by experimental evidence, there is more in it than this. There are two distinct epochs in the production of a piano tone: (1) the hammer travels with a certain velocity and deforms the string as shown in Fig. 17; (2) assisted by the string starting to move backwards towards its central position, the hammer rebounds and the string commences to vibrate at a number of its natural frequencies, whose values are given above. The effect of (1) is to introduce what is known as a 'band spectrum', whilst (2) gives both line and band spectra, the latter arising from decay in amplitude of the string. When an analysis is made, using apparatus different from that for noise measurements, the results depicted in Fig. 18 are obtained [84]. (1) and (2) represent the band spectrum, and the vertical lines the line spectrum. One may well remark, 'but the band of frequencies seems to extend from zero upwards, whilst the piano scale consists of separate notes one semitone apart'. To explain this apparent paradox we must digress a little. If a book is closed suddenly, the resulting sound is of a transient type, as also is the sound of a rifle shot. We know that audible sounds lie within the limits 20 to 20,000 ~, and as we heard the book close and the rifle go off, the

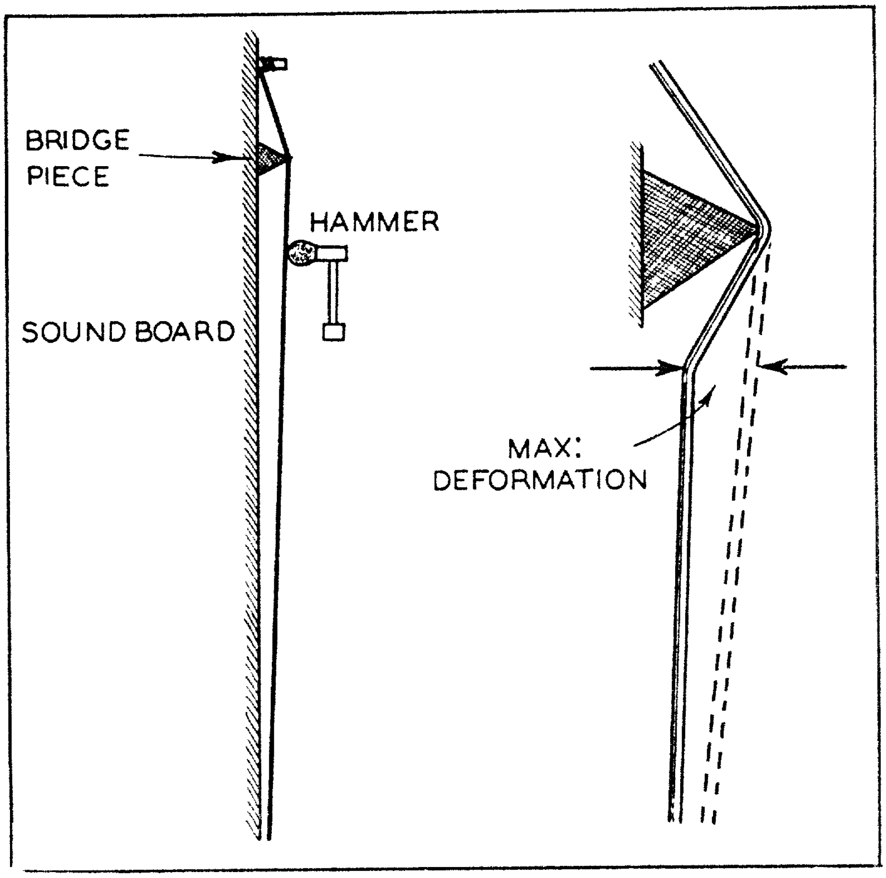


FIG. 17. Illustrating deformation of piano wire when struck by hammer.

audible component frequencies must be in this range. No particular tone is detected, because this is seldom possible where impulsive sounds are concerned. Let us cite another example in the realm of supersonics. Take two glass marbles each $\frac{3}{4}$-inch diameter, and in the open air, away from buildings, drop one on the other. There is a sharp sound of short duration. By mathematical calculation it is easy to show that the natural frequency of each marble exceeds 100,000 ~ and is therefore well above the range of audibility. Since we can detect sounds up to 20,000 ~ only, what is the explanation of the riddle?

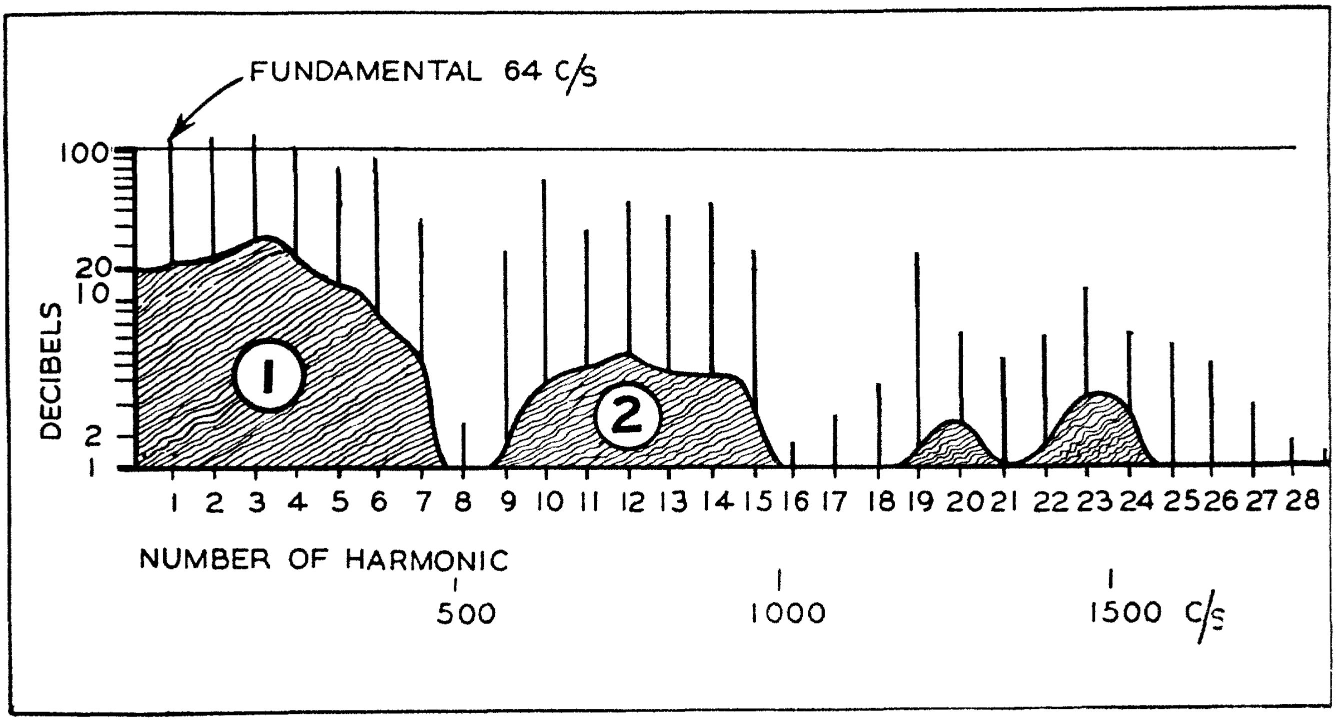


Fig. 18. Band and line spectra of pianoforte note (64~) two octaves below middle C.

Consider the curve in Fig. 19; it represents the acoustical pressure due to some form of impulse. By mathematical analysis this isolated sound pressure disturbance can be transformed into a frequency spectrum. It can be considered to consist of a band of frequencies, extending from zero to infinity, in which the amplitude of each component depends upon the shape of the impulse. For example, in the case of the glass marbles, the most powerful components will be in the neighbourhood of the natural vibrations, which happen to be in the inaudible part of the spectrum. When the marbles are chinked, there is an impulsive sound whose frequency spectrum extends from zero to infinity. The same reasoning applies to the book and to the stroke of the piano hammer. The ear picks out the audible portion of the spectrum, and owing to the heterogeneous mixture of frequencies, the sounds are sensed in the well-known manner. As will be seen from Fig. 18 the intensity level of the band spectrum is low compared with that of the line spectrum, which represents the natural vibrations of the string. The above argument can be applied to all percussion instruments, e.g. drums, cymbals, castanets, and also to stringed instruments played *pizzicato*. It applies in lesser degree to all musical instruments, since the 'beginning' of a note is in the nature of a blow, although in the organ the effect is of short duration following depression of a key at the console. Consequently, certain musical instruments depend upon a small amount of noise for their characteristic qualities. The 'noise' components are usually at the upper end of the audible range [110]. It appears, therefore, that even in musical instruments there is no escape from that ubiquitous accessory 'noise'.

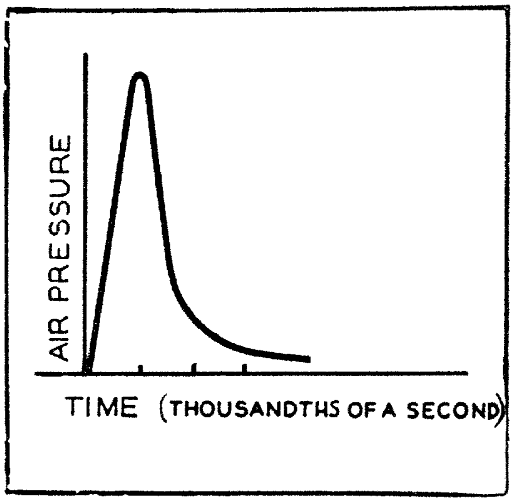


FIG. 19. Illustrating an impulse.

2. *Examples of noise spectra.*

We can now turn our attention to 'neat' noise, that is sounds which are undiluted by pleasing tones and harmonies. As a first example we choose the noise of a metal hammer on a metal plate, this symbolizing the vocation of the village blacksmith. Any one who is his own private mechanic, and many have to be in this era of automobiles and radio receivers, knows what a deafening din can be created by the above implements. Measurement with a noise audiometer shows that indoors, 2 ft. from the resounding metal plate, the noise level can reach 120 db. This is within 10 db. or so of the threshold of feeling. As in the case of the piano, the blow must be taken into consideration, together with the natural frequencies of the plate arising therefrom. The analysis in this instance takes the form portrayed in Fig. 20, and consists of a line spectrum and a band spectrum [84]. The latter commences at zero frequency and covers a wide range, thereby accounting for part of the familiar noise. The fundamental vibrational frequency of the plate appears to be about 3,500 ∼, but the overtones are not integral multiples of this as they are in the case of a piano string. It will be observed that many of the overtones are more intense than the fundamental. These two circumstances combined tend to create an unfavourable aural sensation, which we regard as a harsh penetrating noise. In interpreting Fig. 20 we must keep the curves of Fig. 3 in mind, and make due allowance for the variation in sensitivity of the ear throughout the frequency range covered. Obviously, the band spectrum below 300 ∼ will be of little account, whilst that above this frequency is partly masked by the upper tones, i.e. the line spectrum. Despite the wide frequency spectrum

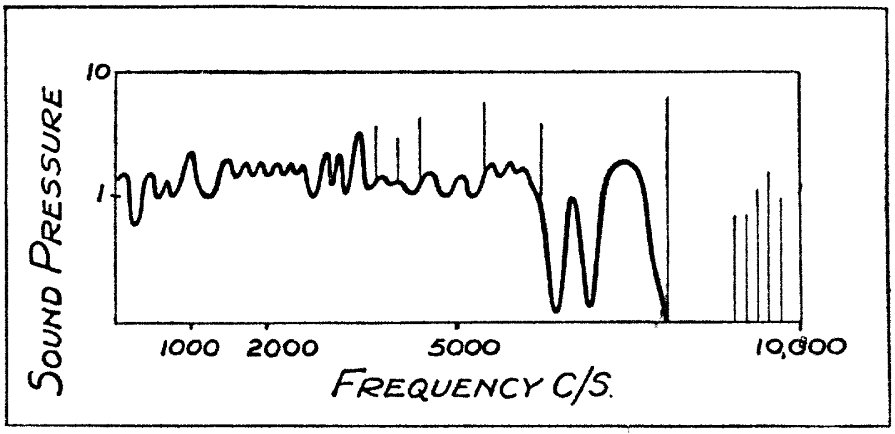


FIG. 20. Noise spectra of metal hammer on metal plate.

it is possible by referring to the aural characteristics of Fig. 3 to explain why the sounds from a blacksmith's shop are high pitched. As a contrast, we can study a gentler form of hammering, namely, when a wooden board is hit by a wooden mallet [84]. The frequency range covered by the sound (Fig. 21) is much more restricted than that shown in Fig. 20. Owing to the high damping in the case of wood, the line spectrum is not clearly defined, although it is indicated by the peaks. On the whole the diagram is more a band spectrum type than that of Fig. 20. The absence of high frequencies from the spectrum means that the sound is much less annoying than that from the steel plate, which goes to prove that a carpenter would be a pleasanter next door neighbour than a blacksmith. The spectra of a bass drum are shown in Fig. 22, the funda-

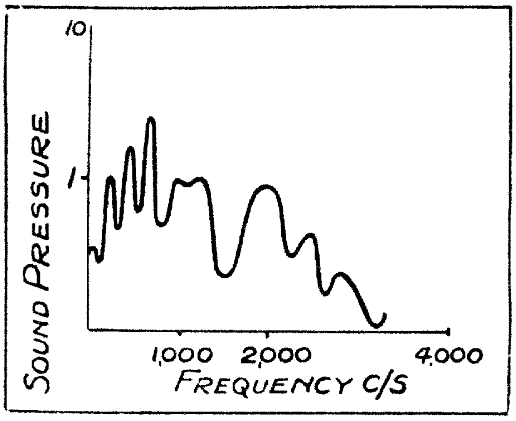
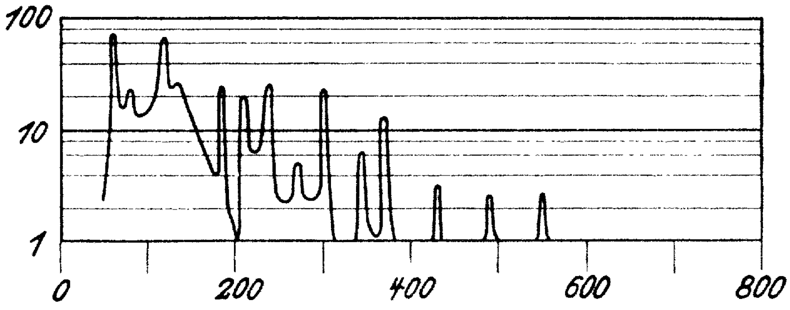


Fig. 21. Noise spectra of wooden hammer on wooden board.



Frequency ~.

Fig. 22. Spectra of bass drum.

mental frequency being 60 ∼. The peaks correspond to the overtones; they are not integral multiples of 60 ∼. The higher overtones are relatively weak so that they do not distress the ear to any appreciable extent, which is in great contrast to the effect of the metal plate vibrations. The band spectrum for the drum is wide and relatively powerful over the range 60 to 180 ∼, which tends to mask the overtones. At this juncture we might draw attention to the fact that we have now explained precisely why the sound from a drum comes within the scope of the antiquated definition of noise given on p. 3.

3. *Scratch noise in gramophone reproduction.*

When reproducing gramophone records, the so-called needle scratch annoys some people more than others. In general, persons who have acute hearing above 4,000 ∼ are particularly sensitive to needle scratch. Before discussing the spectrum of scratch noise, it is well to describe briefly how it arises. Suppose we have the ordinary disk record and a perfect pick-up devoid of resonances, and one whose needle does not wear away. The scratch noise is then due to the minute particles of the record material causing a slightly uneven motion as the surface passes the needle. These particles are not small enough to obviate the tiny irregularities on the surface. Nevertheless, the intensity-level of the noise would be well below that ordinarily experienced. The greater level in practice is due to the upper resonance frequency of the pick-up needle, which usually lies between 4,000 and 6,000 ∼. The tiny particles of the disk material keep impulsing the needle incessantly, so it vibrates continuously at its natural frequency. Despite the rubber damper, the amplitude, and therefore the noise-level, exceeds that which would occur with a perfect pick-up, or with one whose resonance frequency is highly damped and lies beyond 6,000 ∼. The average pick-up has a second major resonance usually below 100 ∼. Moreover, the intensity-level of the noise spectrum will be greatest in the neighbourhoods of these resonances. Since the pick-up needle is impulsed, i.e. a percussion effect, the spectrum extends over a wide frequency range, as depicted in Fig. 23 [84]. This curve is the spectrum at the outer part of the record where the needle point is not worn. As the record proceeds the needle wears, the surface velocity decreases due to the smaller radius of the groove, so the amplitudes of the high frequency components are reduced. This point is illustrated in the curve of Fig. 24 [84]. Owing to the greater surface velocity at the outer and middle parts of the record,

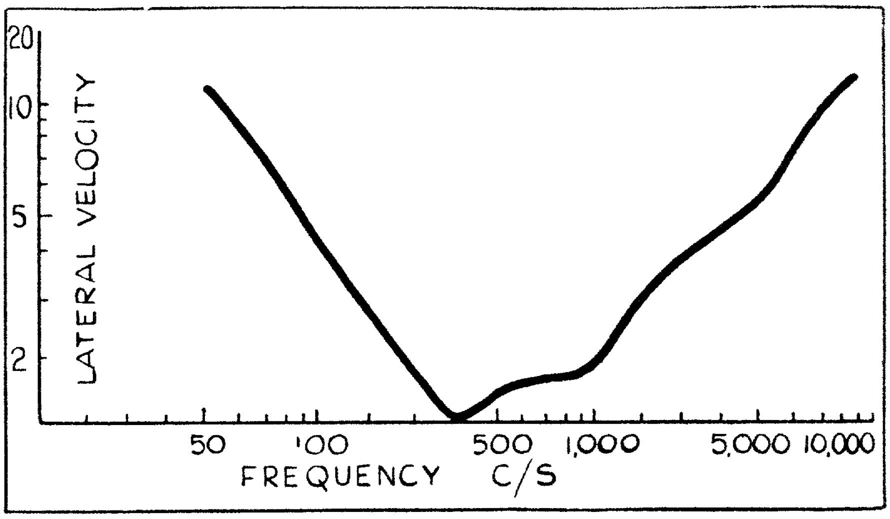


Fig. 23. Analysis of gramophone needle scratch at beginning of record expressed is terms of equivalent needle velocity.

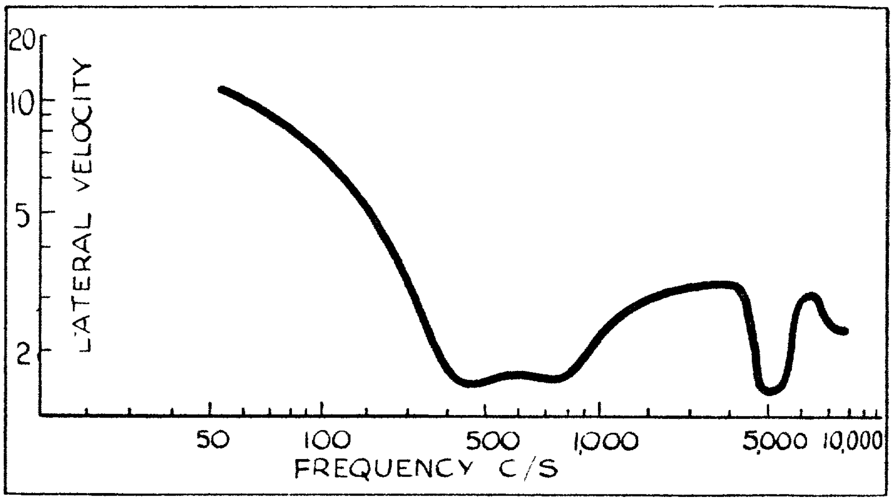


Fig. 24. Analysis of gramophone needle scratch at end of record.

the intensity level of the noise exceeds that which occurs near the end of the record. In certain cases the rise towards the low-frequency end of the spectrum may be due in part to unbalance of the driving motor. To interpret these curves we must again refer to Fig. 3. The low-frequency end of the spectrum will be inaudible owing to the insensitivity of the ear, but the upper end accounts for the irritating sound with which we are so well acquainted.

4. *Miscellaneous noises.*

There are many other noises of considerable interest, particularly those not due to vibrating structures or resonant air columns. Noises caused by bursting a paper bag or an inflated balloon are impulsive, and are largely of the band-spectrum type. In the same category we have footfalls, horses' hooftreads, hand-clapping, whipcracks, and the roll of the sea on the shore. Paper rustling, coin jingling, withdrawal of a cork from a bottle, an engine puffing, and gun-fire, although impulsive, have both band and line spectra. The engine puffing consists of two components: (*a*) due to vibration of the gases in the smoke-stack which acts like an organ pipe; (*b*) that due to the outrush of steam discharged from the cylinders at each end of the piston stroke. Unless one is near the engine, (*a*) is usually masked by (*b*). This brings us to seek the reason why a jet of steam discharged from a safety valve is accompanied by a hissing sound. The issuing steam causes vortices (a swirling action) at the edge of the jet, and these pulsate or move first one way and then another, thereby creating sound-waves. Vortices also occur when a stretched wire is held in a steady, unidirectional current of air. Provided the air velocity exceeds a certain critical value, the air swirls first to one side of the wire then to the other, thereby alternating. When the velocity is high enough the alternation is sufficiently rapid to cause audible sound. If the natural frequency or that of an overtone of the wire is identical with the vortex or swirl frequency, the sound is reinforced. This is the basis of the æolian harp, which consists of a series of wires of different diameters mounted on a sounding board. All wires are tuned to the same low frequency. The vortex frequency varies according to the diameter of the wire and is not the same for each. Thus different overtones in various wires will be excited if the wind blows over the harp. The singing of overhead telegraph wires in the wind is due to vortex action, i.e. æolian tone effect, as also is the sighing of wind in a clump of trees, or its whistling effect amongst the bulrushes (the Moses effect!).

The noise which accompanies gun-fire is highly impulsive, although it consists of line as well as band spectra. There are sub-sonic (inaudible) waves, of frequency about 1 ~, accompanied by a train of waves due to reflections of the pulse from various obstacles. In addition there is the low-frequency oscillation of the gun itself and vibration of the gas in the tube, as in the case of an organ pipe. When a projectile whose velocity exceeds that of sound passes an observer, it creates the same aural effect as that of an explosion. ‘Screaming’ may be due to vortex motion in the wake of the shell, or to rotation as it travels through the air with screw motion like an aeroplane propeller, or to both of these. Owing to viscosity, air may be dragged round by the shell and set into motion.

When impulsive sounds are reproduced by a radio receiver, they are in general seriously distorted. The timbre of the sound emitted when the announcer turns over his news sheets is quite unrecognizable as paper rustling. This can be explained by the fact that paper rustling is accompanied by sounds whose spectrum extends two or more octaves above the frequency range of the average receiver. All impulsive sounds contain very high frequencies, and when these have been removed, the residue gives but a travestied version of the original. Crispness and naturalness disappear, so the otic perception is unsuggestive of the original and is, therefore, unsatisfying.

5. *Acoustical spectra and wave forms of motor-horns.*

There are several kinds of motor-horn, (*a*) operated by a small series-wound electric motor, (*b*) vibrator type, which includes double diaphragms, (*c*) high-frequency type. This is not the place to enter into constructional details of horns, so the reader is referred to [120]. In the motor-operated horn the diaphragm is actuated by an electric motor which drives a wheel having studs on its periphery. During rotation the studs strike a boss attached to the centre of the diaphragm. The number of revolutions of the wheel per second is arranged so that the studded wheel strikes the boss, say, 300 times per second. In the double diaphragm type, one diaphragm having a frequency of 450 ∼ is mounted coaxically behind another diaphragm whose frequency is 900 ∼. A steel armature is attached to the first and, by aid of a battery and magnet system, the armature is caused to vibrate. A projection on the first diaphragm comes into contact with a screw at the centre of the second diaphragm once every cycle of the former, and therefore every two cycles of the latter. Thus the outer diaphragm, which is associated with a resonating chamber, is kept in continuous vibration at 900 ∼. There is a strong harmonic at 2,700 ∼ present in the sound output [120].

In measuring the reftone level of the sound due to a horn, it is actuated by an accumulator, and the steady sound picked up by apparatus of the type mentioned in Chapter II. The microphone is placed at a suitable distance from the horn, e.g. 23 ft. There should be no walls nearby to introduce reflected waves other than those due to the ground, since reflection therefrom is the condition which obtains in practice. A number of horns were tested, in this manner in connexion with the noise survey in New York City. The readings of the microphone amplifier attenuator apparatus are given in decibels above zero level of 200 microdynes per sq. cm. The loudest horn had a reftone level of 108 db., and the weakest 78 db. Only five horns were lower than 94 db. The levels at distances exceeding 23 ft. can be obtained approximately by subtracting 6 db. every time the distance from the horn is doubled. Thus, at 92 ft. the distance has been doubled twice, i.e. 46 ft. and 92 ft., so the above levels would become 96 db. and 66 db. respectively. Neglecting the initial starting and final stopping periods, the spectra are entirely of the line type. By aid of the apparatus described on p. 34, or one somewhat similar to that on p. 27, in which the correction network is replaced by two tuned circuits, the spectra of the horns can be found. The tests are conducted in an acoustically 'dead' room to avoid reflection from the walls. By so doing the level of each constituent of the sound can be measured. An oscillogram of the sound output from a double diaphragm horn is reproduced in Fig. 25 [120], whilst the spectrum of a vibrator type of horn is illustrated in Fig. 26 [90]. As mentioned above, there are three main frequencies due to the former type of horn, namely, 450 ∼, 900 ∼, and 2,700 ∼. The pitch, as judged by ear, corresponds to the lowest frequency. The line spectrum of the vibrator horn in Fig. 26 extends beyond 5,000 ∼, but measurements were not made above

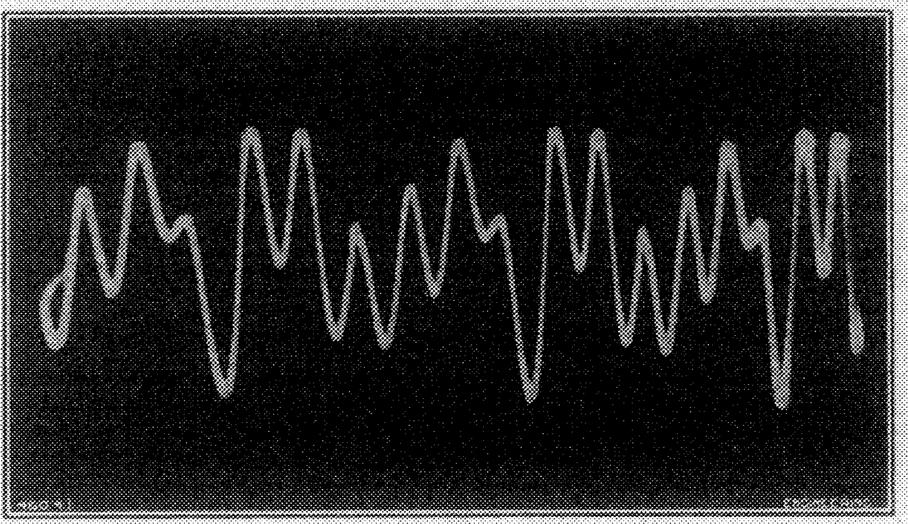


FIG. 25. Acoustical output of double diaphragm horn (Lucas & Co.).

this frequency. The fundamental is about 250 ~, and it is seen that the levels of some of the overtones exceed that of the fundamental.

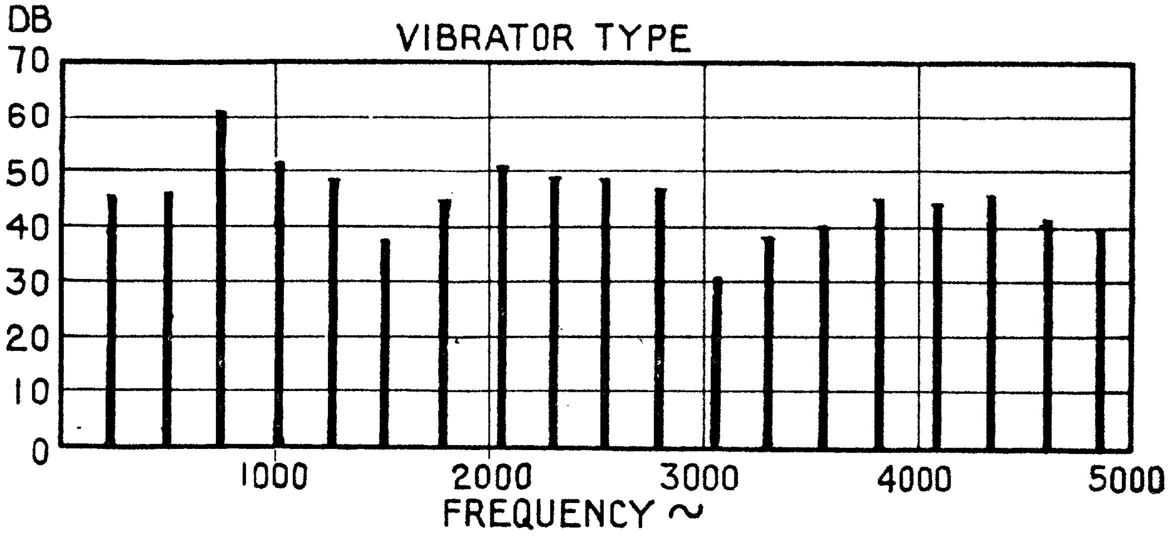


FIG. 26. Line spectra of vibrator type motor-horn (American).

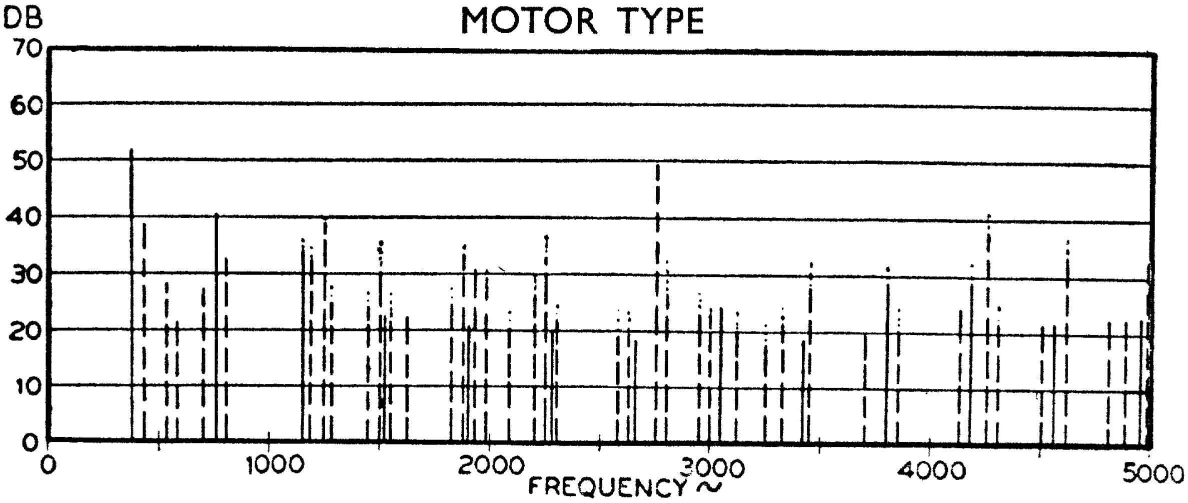


FIG. 27. Line spectra of motor-driven horn (American).

To interpret these results we must go back to Fig. 3, which shows the variation in sensitivity of the ear, and we deduce that the reftone level of the upper frequency components will predominate. This is, of course, an every-day experience. The frequencies of the overtones shown in Figs. 25, 26, are all integral multiples of their respective fundamentals.

The spectrum of a motor-operated horn is shown in Fig. 27 [90], whilst an oscillogram of the sound output from a similar type of horn is reproduced in Fig. 28 [120]. The full lines in Fig. 27 represent harmonic tones whose frequencies are integral multiples of the fundamental, the latter being below 400 ∼. The dotted lines represent inharmonic tones, these not being integral but fractional multiples of the fundamental. The kinematograph oscillogram in Fig. 28 represents the output wave form of a motor-operated horn taken from the time the switch closed [120]. The sound increases gradually in intensity and alters in wave form during the acceleration period of the motor, which may be from 0·1 to 0·5 second. This lack of immediate response is a practical drawback, as also is the deceleration period, which may exceed 0·5 second. Thus, in sounding a staccato note, the maximum intensity is never attained, and in general the motor-operated horn cannot be used to give a short, sharp warning [120]. A kinematograph oscillogram of a 'high-frequency' horn is shown in Fig. 29, from which it is seen that the delay in maximum response after closing the switch is relatively

FIG. 28. Kinematograph oscillogram of motor-driven horn (Lucas & Co.).

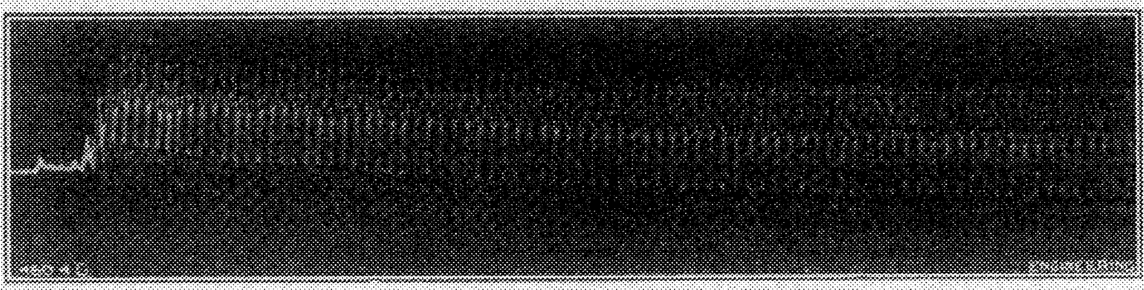


FIG. 29. Kinematograph oscillogram of high-frequency horn. (Lucas & Co.).

small. A horn of this type can be used, therefore, for staccato warnings.

Having obtained the spectra of a number of horns and knowing the reftone level of each at a certain distance, aural tests were conducted to select the most suitable horn for warning purposes [90]. To this end all horns were numbered and ranged along one side of a large, highly damped sound-proof room in which a 'jury' sat at a distance of 20 ft. or so from the horns. Each horn was sounded in turn, a light shining on the corresponding number meanwhile. The numbers were noted and the jurors recorded their impressions as to the frightening or startling effect of each horn. In general it was found that the horns with inharmonic overtones (Fig. 27) were much more objectionable than those with harmonic overtones (Fig. 26). Thus the vibrator horn is preferable to the motor-operated horn of equal reftone level. The sounds from either type of horn were more pleasing when a filter was used to eliminate all frequencies above 4,000 ~. This test was conducted by sounding the horns in one room, picking up the sound by microphone, then amplifying and reproducing it in another room by means of a loud speaker. An electrical low-pass filter was interposed in the amplifier, and by means of a key the filter could be put in and out of circuit. Thus the sound from any horn could be heard (1) as it would be in practice, (2) with the frequencies above 4,000 ~ removed. Several factors appeared to influence the jury's vote on the unpleasantness of different horns, one being the reftone level. Horns giving high levels were objectionable, irrespective of the character of the sound, and all the reftone levels high enough to be of practical value as a warning were voted against. Overtones above 2,000 ~, of relatively high level, cause the sound to have a sharp disagreeable character, whilst those below 2,000 ~ make the sound seem more musical. The presence of inharmonic overtones introduces a raucous, strident tone, which is no better as a warning than a sound of equal reftone level with harmonic overtones [90]. The inharmonic tones cause subjective tones which combine together and make the aural sensation very unpleasant. The reftone level of the motor-horn of Fig. 27 at 23 ft. was 101 db., and that of the vibrator horn of Fig. 26, 99 db. Forty votes were recorded against the former, but only eight against the latter, which indicates clearly which type of horn is desirable. Tests show that a reftone level of 95 db. is ample to give warning in traffic whose average reftone level is 83 db. [90]. The 'deafening' effect of the traffic is 68 db. (see p. 26), so that there is a margin of 95–68 = 27 db. above the masking threshold.

To sum up, it appears that a horn having a fundamental tone lying between 300 and 450 ∼, whose overtones are harmonic, and which at a distance of 20 ft. gives a reftone level of 20 to 25 db. above normal traffic level, should be suitable for most purposes. In order that the horn shall be tolerably musical, the harmonics above 2,000 ∼ must not be too powerful. Also, the note should reach a steady level without appreciable delay after closing the operating switch. In using a horn for warning purposes, little is gained by long blasts. These seem to have a paralysing effect on the fugitive pedestrian, whereas a series of staccato notes gives due warning of impending danger without inculcating the sense of fear or at times of great rage! In this respect the reader will be able to interpret the following quotation from *The Mikado* appropriately:

To sit in solemn *silence*
In a dull dark dock,[1]
Awaiting the sensation
Of a short sharp *shock*.

Some remarks regarding the distance at which horns are audible in free air may be of interest. The horn used by Alexander the Great to summon his armies is *said* to have been audible at a distance of 10 miles or so. A drawing of this historic piece of acoustical apparatus is reproduced

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[1] A place frequently visited by motorists!

in Fig. 30. We have no means of knowing the mathematical law governing the expansion of the horn from the mouthpiece to the final opening. But there is no doubt that the necessity for flaring at the opening was recognized as an essential feature of the design. The motor-horns discussed herein would be audible at a greater distance than Alexander's horn, when used under identical conditions. Under normal quiet conditions in the country at the present time, the range of audibility to an observer on the road (not to another motorist bathed in his own decibels!) would not exceed half a mile. But in Alexander's day we presume that silence reigned supreme, except during the hours of daylight when he pursued his famous hobby of waging war. On the whole we are inclined to the view that *if* the horn was audible at 10 miles, the conditions for transmission must have been especially favourable—as in the free air on mountain tops—and the noise-level at the reception point must have been negligible.

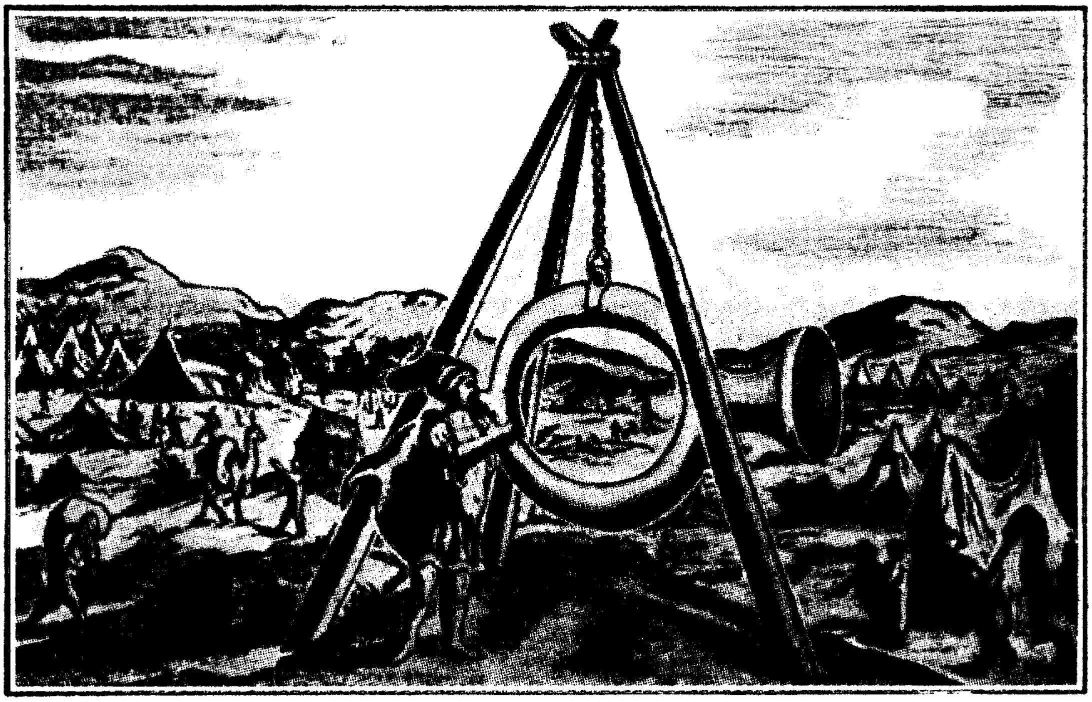

FIG. 30. The horn used by Alexander the Great to summon his armies.

In transmission over long distances the absorption loss due to the ground, trees, and the like, also that in the atmosphere, cannot be neglected. Thus the range of audibility depends upon the nature of the physical elements between the two terminal points. Sirens used on lighthouses may be audible from 5 to 10 miles, but the power output is colossal compared with that of Alexander's horn. In the latter case, however, the power is concentrated in the form of a beam, whereas the siren radiates equally in all directions, and since it is only used in foggy weather the range is reduced compared with that under ideal conditions. Furthermore, on a ship the reftone level of the siren's note must be sufficient to be audible *above* the level of the ship noise. If the noise-level at the observer were as low as 20 db., the range of the siren would be greater than that normally experienced.

Data relating to a motor-horn and to the hypothetical audibility range, calculated by aid of the rule stated earlier on in this chapter, are given below. At 20 ft. the reftone level on the axis of a certain motor-horn was found to be 102 db. The rule states that 6 db. must be deducted each time the distance from the horn is doubled,[1] so that at 10 miles the level *in front of the horn and on its axis* would be 36 db. above the datum level of 200 microdynes per sq. cm. This reftone level of 36 db. would give comfortable audibility in a quiet spot. In practice, owing to absorption and other effects, the level at 10 miles would be too low to be audible. This is a very comforting fact, for in the absence of an adequate amount of absorption, we should live in a babel of decibel demons.

6. *Some effects of intense audible sounds* [49].

Although the subject-matter of this section does not fall within the scope of the word noise, the results are of

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[1] In this case the listener would always have to be in front of and on the axis of the horn, since it does not radiate power equally in all directions. The 6 db. rule is applicable over short distances and in locations away from buildings, &c., provided the measurements are always made in the same direction relative to the horn axis. Twenty feet *behind* the above horn the reftone level would be less than 102 db.

sufficient interest for inclusion here. The frequency of the sound used in the experimental work was 8,900 ~, which is a little more than an octave above the top note on the pianoforte. The loudness was sufficient to cause pain to the naked ear, but this was avoided by using cotton-wool plugs. Evidently the reftone level was of the order 130 db. The radiation was produced by longitudinal vibration of a nickel tube of circular section, to one of whose ends an inner disk of nickel was welded. The length of the tube was 26·4 cm. and the radius 0·95 cm. During vibration the distribution of sound from the flat end was uniform. When a tube of nickel is placed coaxially in a coil through which is passed a direct current with a.c. superposed the nickel elongates and contracts at the frequency of the current.[1] This is due to magnetostriction, since nickel is one of the materials in which the effect of a magnetic field causes a change in the length of the tube. Now if the frequency of the current is adjusted to make the rod resonate longitudinally, the oscillations are very powerful indeed. The amplitude of the end disk was 0·03 mm. when the tube was in air, but 0·01 mm. with the upper half in water, the latter amplitude corresponding to a sound output of approximately 12 watts.

When the tube is submerged with its axis vertical and its closed end 1 cm. below the surface of a small tank of water, there is a miniature fountain 5 cm. high. With the end 6·5 cm. below the surface a mound is formed thereon. Since the end of the tube reciprocates with a sine wave motion, there must be a unidirectional pressure component to cause the mound. This can be explained as follows: The acceleration of the end of the tube is some 32 times

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[1] If there is sinusoidal alternating current only, the tube contracts during each half alternation, so the frequency of vibration is twice that of the current, d.c. magnetization causes contraction, whilst a.c. magnetization, whose amplitude is less than the d.c. value, merely varies the contraction on each side of the steady value. Hence the tube elongates and contracts, although it is always shorter than its unmagnetized length.

that of gravity, and when the rod moves downwards it does so with a velocity 32 times that of the water, which is therefore left behind.[1] The falling column of water is caught by the tube on its return stroke, but in the meantime there is a partial vacuum, so the water round the rod flows in radially. This gives rise to an upward pressure which creates the mound on the surface. The recession of the tube from the water causes cavitation, and the impact of the two on the return stroke gives rise to a 'water hammer' effect which is revealed by a clattering noise (like motor-cycle valve tappets). Owing to cavitation, the upper surface of the tube is eroded and a star pattern forms thereon after 10 hours or so. The same action occurs in ships' propellers when the metal leaves the water behind, and enormous impulsive pressures ensue [99]. This, however, is explained in Chapter 7, p. 99, to which reference can be made.

If a glass flask is filled with liquid and held near the end of the vibrator, the flask is ultimately fractured. Larvae of the mayfly, when put in a test tube containing water and held 2 mm. from the endplate of the oscillator, are killed in a few seconds. Bacteria in solution, in a flask, also share the same fate in due course. By exposure to intense sound it is thus possible to kill the bacteria in milk, i.e. to sterilize it. In so doing the whole of the bacteria are not annihilated at the same time, i.e. the process is a gradual one. Frogs, tadpoles, and fishes are quickly killed when subjected to the intense radiation. These effects also occur when the radiation is supersonic (above audibility at, say, 50,000 ∼). Bubbles formed in the muscle and haemolysis of the blood-corpuscles are probable causes of death. If a cork is tightly wedged in one end of a nickel tube, vibration culminates in an explosion caused by expansion of the gases within the cork with rise in temperature, and the interior of the cork is burnt, due to viscous internal loss.

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[1] The acceleration varies sinusoidally, but the initial value is 32 times that due to gravity.

IV

NOISE IN BUILDINGS

1. THE noise-level in a street usually exceeds that within the buildings which line it, except in the case of factories where internal noise is sometimes very loud, e.g. a boiler-maker's shop or a weaving-shed. In view of the great expansion of industrial work and the introduction of labour-saving devices, the number of persons who spend the greater part of their lives indoors is very large indeed. They are exposed to the influence of noise during working hours, and it is desirable to know the noise-level experienced by them under various conditions. Data pertaining to indoor noise-levels are given in Table 2*a*, from which we see that even in a peaceful home the reftone level is 26 db. above the datum, or 400 times the power necessary for audibility at 1,000 ∼ in a 'dead' room.

TABLE 2*a*. *Reftone levels of noise in buildings* [90]

Type of Building	*Reftone level*	
	db.	
Boiler-maker's shop	100	Measurements mainly in New York
Loud radio in home	85	
Typists' office	75	
Noisy general office	63	
Average office	52	
Noisy residence	50	
Quiet office	42	
Average residence	36	
Country residence	26–30	

In a typists' office where *ordinary* machines are used, the noise reaches the relatively high level of 75 db., or about that of moderate radio in the home. The level would be lowered appreciably by using 'silent' typewriters. In residential quarters the noise may be due to indoor or outdoor sounds, but on the whole that due to the former seems to be the chief source. Day-time measurements in non-residential locations, e.g. offices, factories, workshops, stores, &c., show an average level of 55 db. The lowest noise-level is likely to occur in some secluded telephone box, where it may be about 35 db. In machine-shops the average value is 75 db., but in certain cases it is much greater. On the whole, the noise-level in city offices is likely to be from 20 to 30 db. higher than that in the home. Some comparative results are shown in Fig. 16 [90, 64].

We now consider faulty designs and methods of reducing noise in buildings. For convenience many hospitals and educational institutions are situated in central and therefore very noisy areas. The use of double windows and artificial ventilation is of considerable assistance in noise mitigation, but although walls and ceilings lined with sound-absorbent material are efficacious acoustically, care must be taken that they do not harbour germs. Consequently, special hygienic sound-material must be used. This restriction is inapplicable where offices and class-rooms are concerned. Many lecturers labour under exposure to a noise-level of from 50 to 60 db., which entails greater mental concentration. The attention of both lecturers and students is distracted by the noise. There are some choice examples in London, particularly those buildings near tramway crossing-points or tram depots. In cases where movable partitions are used, the lecturers on the two sides interfere with each other and cause temporary confusion of thought. Apropos of these points, the curve of Fig. 31 is of interest and shows that hearing conditions are unsatisfactory when the level of the background noise exceeds 40 db. A survey of the classrooms throughout large towns in this country would doubtless reveal that in many cases this figure is exceeded appreciably due to extraneous noises. There seems little doubt that if economy were not the main deterrent to education under congenial conditions, our colleges, polytechnics, and schools would be suitably located and have classrooms which were properly designed acoustically and hygienically. It would then be possible for teachers to impart more information with less effort than is needed at present. The ratepayers and educational councils might, however, regard this as too much of a sinecure!

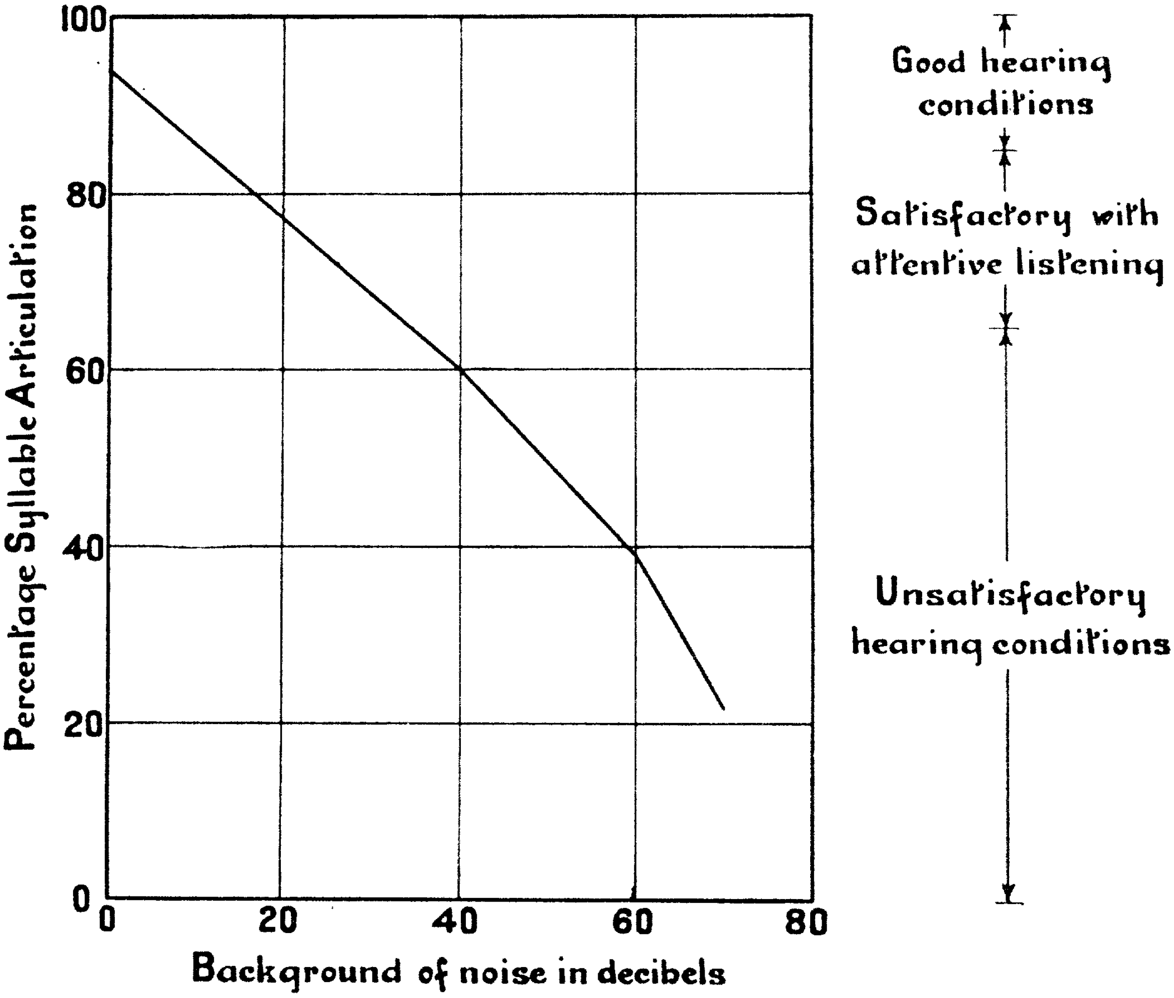

FIG. 31. Effect of extraneous noise on intelligibility of speech.

In the home, numerous defects abound which are instrumental in augmenting the general noise-level, for example, the use of hard wall-plasters which reflect rather than absorb sound. Small, sparsely furnished rooms with polished floors and meagre curtains introduce reverberant conditions, so that sound is amplified rather than absorbed. Numerous pipes for hot and cold water supply and for radiators, ducts for electric wiring and the like, introduce acoustical conduction from room to room. If the hall radiator is banged, the noise is conducted via the floor and the hot water pipes to the remainder of the house. The use of resilient material between pipe-flanges and bolts of a heating system prevents transmission of sound by conduction. All holes in walls and ceilings through which pipes are led should be caulked with resilient material to prevent ingress of sound from room to room. Although the areas of the holes may be small, it will be realized on perusal of the section hereafter relating to reinforcement of sound in rooms, that they permit sound to percolate through, and this builds up in intensity. Radiators can be securely fixed and insulated from the floor. If fixed to an inner partition wall, the use of insulating material between the radiator and the wall is of greater importance than when a rigid outer wall is used.

Lifts should be enshrouded with brick walls, and special care is required to ensure that the electric driving motor is situated where vibration transmitted to the building is negligible. The vibration can be minimized by mounting the motor on cork matting or on a spring suspender, as described in Chapter VIII. Ventilating apparatus is liable to be troublesome, due to vibration transmitted down the sheet-metal ducts, particularly that from the fan motor. This can be avoided by using a well-designed machine resting on resilient supports, the liberal use of resilient material at the duct joints, and the avoidance of direct contact with other structural parts through which vibration can be transmitted by wave motion. Preferably the ducts should be lined with or constructed with sound absorbent material. It is advisable that baffles should be used at the grill where air enters a room, to exclude air-borne noise coming down the duct, e.g. the windage sound from the fan. This is of vital importance in sound-film studios. The velocity of the air should not exceed 8 ft. per second, and for this purpose large fans revolving relatively slowly are preferable to small fans making many revolutions per second.

Owing to the flimsiness of modern ceilings, partitions, and walls, noise originating in one room experiences but little absorption in passing to other rooms. Insulation against noise can be effected by the use of either double partitions, where the interspace is filled with absorbent material, or by massive construction so that the vibration is small. This is treated in detail later, in the section on the transmission of sound through partitions. Double partition design must be conducted on scientific lines to obtain good results. The law should stipulate a *minimum* sound insulation by party walls equivalent to a thickness of 9 in. of brick which ensures a reduction in reftone level of about 50 db. It is essential that floors should be sound-proof, especially in blocks of flats. Continuous floors of ferro-concrete, on which partition walls are built, enable the vibration occurring at one part of the structure to be transmitted to the remainder. Under this condition, the floor, walls, and ceilings act like diaphragms and cause the air in the rooms to vibrate. Owing to reverberation the sound is magnified. A certain amount of relief can be obtained by using rubber matting on the floors. In general 'floating floor' construction, in which the floor is insulated from the walls, is preferable. Two typical examples illustrating this type of floor are shown in Fig. 32 [64]. At the same time the ceiling beneath the floor should be independent, so that vibration due to footsteps or other impacts are not transmitted directly from the floor above. If the mass of the floor is increased by using concrete slabs beneath the floor boards, the amplitude of vibration due to mechanical shocks is reduced proportionately, so the effective sound insulation is increased. These forms of construction usually fulfil a double purpose, (1) prevention of sound due to music, conversation, and the like from penetrating the ceiling; (2) avoidance of sounds due to structural vibration. Where a piano is concerned, the vibration of its sound-board is transmitted directly to the floor. It frequently happens that the piano castors rest on the bare boards, so the loudness is augmented due to the additional area in vibration. This is a source of considerable annoyance in flats, especially to the party immediately beneath, since with ordinary floor construction the sound from the vibrating ceiling is quite appreciable. In a certain case the notes in the two lowest octaves of a piano played downstairs caused resonance of the ceiling and floorboards immediately above, the amplitude being sufficient to make one's feet tingle. The bass register of the piano was reinforced, which pleased the performer, but bewildered the occupant aloft who felt the music in his toes!

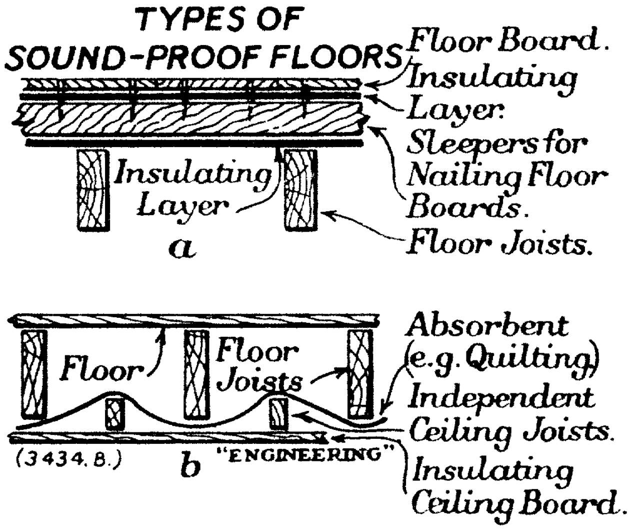

FIG. 32. Showing methods of insulating floors and ceiling.

2. *Reinforcement of sound in rooms.*

It is an everyday experience that sound is reinforced in an enclosure, which means that the source of sound appears to be much weaker in the open air than it does indoors. Suppose we have a loud speaker set in one wall of a room. The speaker is supplied with current from an oscillator whose frequency can be varied at will, and the value of the current is regulated so that the acoustical output is constant at any particular frequency. We can assume this to be 256 ~, which corresponds to the pitch of middle C on the piano. If there is a calibrated microphone at some suitable location in the room, the sound pressure can be measured and, by connecting the output from the microphone amplifier to an oscillograph, the wave form can be delineated. When the loud speaker is switched on, the sound pressure at the microphone grows from zero to a steady value as shown in Fig. 33. This represents the start transient, the sound pressure growing in accordance with an exponential law as the current does in an inductive electrical circuit. A similar effect occurs when the speaker is disconnected, the 'stop' transient then being obtained. During the interval marked 'start transient', the sound in the room builds up to a final steady value. If there were no loss, the building-up process would continue indefinitely, but to realize this condition more and more power would have to be supplied to the loud speaker. Consequently in practice, even if the zero absorption state could be obtained, the value of the sound pressure in the room would be limited by the power available from the speaker. The time duration represented by 'start transient' in Fig. 33 is dependent upon the absorption of the room at the frequency of test. In a room built of concrete 1 ft. thick, whose inner surfaces were lined

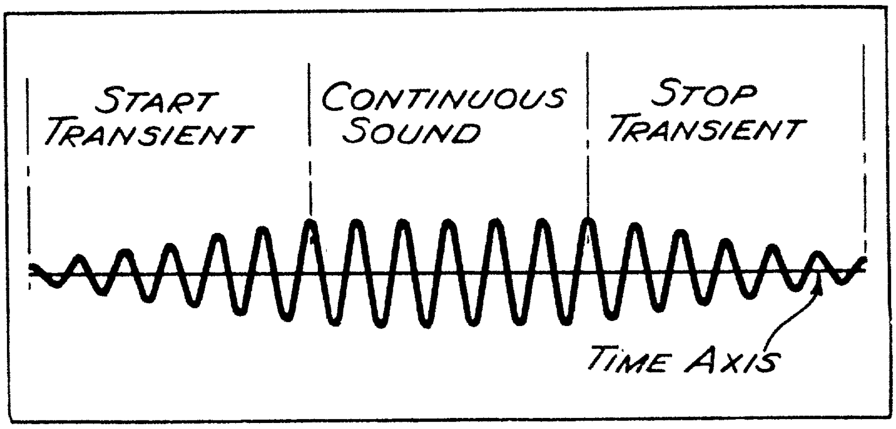

FIG. 33. Simplified diagram showing wave form of pure tone started and stopped in an enclosure. Owing to interference, &c., the actual wave form is complicated.

with hard glossy tiles, the time of growth at 50 ~ might be 15 seconds or more. In practice we are only concerned with that portion of the transient during which the sound is audible. Measurements are usually made of the decay transient. This process consists in breaking the electrical circuit of the speaker, and determining the time taken for the intensity level to fall 60 db., i.e. a power ratio of one million to one. This is known as the reverberation time, and it usually varies with the frequency of the note emitted by the loud speaker. In specially designed rooms, e.g. broadcasting studios, the reverberation time decreases to an extent with rise in frequency. Reverberation is recognized to be essential in the production of pleasant speech and music, but it must not be overdone. The optimum reverberation time depends upon the size of a room and the purpose for which it is used. For instance the reverberation time of a large broadcasting studio for a military band would be much greater than that of a 'talks' studio.[1] To ensure high intelligibility the reverberation time for speech should exceed that for music. Although speech is improved by increasing the reverberation time at the higher frequencies, to avoid harshness it must not be made excessive. Harshness often accompanies the reproduction from conical paper diaphragms used for loud speakers. This is due to the conspicuous resonances between 2,000 and 5,000 ~ which accentuate the sibilants.

The mean sound pressure throughout a room can be calculated approximately when a known amount of power is delivered thereto. To perform the calculation a formula is needed, whilst it is necessary to know the values of the various physical factors in the formula. The derivation of a formula is outside the scope of the text, so we give it without proof. The average sound pressure in dynes per sq. cm. in a room is $p = 41{,}000\sqrt{\dfrac{P}{A_s}}$ approximately, where

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[1] A studio for talks is usually made acoustically 'dead', so that the speaker appears to be in the listener's room.

P is the output from the loud speaker or source in watts, and A_s is the total absorption due to the surfaces in the room. That is to say, A_s is the sum of the product of all the superficial areas and their corresponding coefficients of absorption. The latter is the ratio of the sound power absorbed to that impinging on the surface in question. The remainder is reflected and returns to the room. If A_1, A_2, A_3, &c., are areas and a_{s1}, a_{s2}, a_{s3}, &c., the corresponding absorption coefficients, the value of A_s is $A_1 a_{s1} + A_2 a_{s2} + A_3 a_{s3} + \ldots$ To illustrate reverberation time and the effect of an enclosure in enhancing the reftone level, we can take a simple numerical example. Suppose we have a cubical room whose edges are 20 ft. long, and that each face is covered with material whose coefficient of absorption is 0·1 at 256 ~. The total superficial area is six times that of one face, so $A = 6 \times 20 \times 20 = 2{,}400$ sq. ft. or $2{,}400 \times 900 = 2{\cdot}16 \times 10^6$ sq. cm. The total absorption of the room is accordingly,

$$A_s = 2{\cdot}16 \times 10^6 \times 0{\cdot}1 = 2{\cdot}16 \times 10^5.$$

When the absorption is not too large, the reverberation time is given approximately by the formula $t \doteqdot \dfrac{V}{600\,A_s}$ sec., where V is the volume of the room in cubic centimetres, and A_s is the total absorption, the area being in square centimetres. For our cubical room

$$V = (20 \times 30)^3 = 2{\cdot}16 \times 10^8 \text{ c. cm.},$$

so $t = \dfrac{2{\cdot}16 \times 10^8}{600 \times 2{\cdot}16 \times 10^5} = \dfrac{10}{6} = 1{\cdot}67$ sec., this being quite a normal figure.

If a loud-speaker diaphragm were set in a hole in the floor of the above room, and the driving coil fed with current at 256 ~, let the power radiated continuously be 0·01 watt. After the steady state has been attained, the surfaces of the room absorb the power at the same rate as it is supplied by the speaker. Substituting the values of P and A_s in the foregoing formula, we obtain the average sound pressure $p = 41{,}000\sqrt{\dfrac{0\cdot01}{2\cdot16\times10^5}} = \dfrac{41{,}000}{1{,}470} = 8\cdot83$ dynes per sq. cm. From p. 10 we find that the intensity-level is

$$74+20\log_{10}p = 74+20\log_{10}8\cdot83 = 74+18\cdot9 = 92\cdot9 \text{ db.}$$

Turning to Fig. 3 it is seen that this represents a reftone level of substantially 92·9 db.

Now imagine the four walls and the ceiling of the room to be removed so that the loud speaker radiates into free space. At a distance of 14 ft. from the speaker, this being at one corner of the floor, we desire to know the sound pressure. To make the necessary calculation we observe that the speaker radiates into semi-infinite space. If we conceive a hemi-spherical surface 14 ft. = 420 cm. radius, the power from the speaker passes across it and is uniformly distributed over it. The superficial area of the hemisphere is $2\pi r^2 = 2\pi\times420^2 = 1\cdot108\times10^6$ sq. cm., and since the power is 0·01 watt or 10^5 ergs per second, that passing through each square centimetre is

$$10^5/1\cdot108\times10^6 \doteqdot 0\cdot09 \text{ ergs per sec.}$$

The formula for the power per square centimetre is $p^2/42$, so we have $p^2 = 42\times0\cdot09 = 3\cdot68$, giving

$$p = \sqrt{3\cdot68} = 1\cdot92 \text{ dynes per sq. cm.}$$

The corresponding intensity level is

$$74+20\log_{10}1\cdot92 = 74+5\cdot67 \text{ or nearly } 80 \text{ db.,}$$

which is about 13 db. below that of the intensity level in the room. Thus the power level in the latter case is some twenty times greater than it is in the open air 14 ft. from the speaker. In other words, for equal reftone level, the power radiated by the speaker into the open must be twenty times that into the room.

We can now juggle with our formulae to make some simple *approximate* calculations relating to noise. Suppose the room discussed above is fitted with a window whose width is 4 ft. If the intensity level of a 256 ~ note due to a ship's siren is 88 db. outside the window, what is the intensity level in the room if the window opening is 1 in.?

First of all consider the formula $p = 41{,}000\sqrt{(P/A_s)}$. We know A_s, but we have to find the power entering the room through the window before the sound pressure p can be calculated. Since $74 + 20\log_{10}p = 88$, we have

$$20\log_{10}p = 14,$$

giving $\log_{10}p = 0{\cdot}7$; so $p = 5$ dynes per sq. cm. The area of the source (window) is $\frac{4}{12}\times 900 = 300$ sq. cm. Since the sound power passing through unit area is $p^2/42$, that entering the room is

$$\frac{300p^2}{42} = \frac{300\times 25}{42} \doteqdot 180 \text{ ergs per sec.}$$

or 18×10^{-6} watt. Thus the average sound pressure in the room is

$$p = 41{,}000\sqrt{\left(\frac{18\times 10^{-6}}{2{\cdot}16\times 10^{5}}\right)} = 0{\cdot}38 \text{ dyne per sq. cm.}$$

The corresponding intensity level is

$$74+20\log_{10}0{\cdot}38 = 74-8 = 66 \text{ db.}$$

We see, therefore, that a window opening whose area is 1/7,200th that of the internal surface of the room will let in sufficient noise to raise the intensity level from zero to 66 db. This calculation is merely an approximate one, and it is advisable to mention that the noise level in the room does not increase to any appreciable extent after the opening of the window exceeds a certain amount. The experimental data plotted in Fig. 34 illustrate this point, and it will be seen that the noise level increases but slowly after the first inch of window opening, a fact we know very well from experience [98]. From measurements in a modern large office building, adjacent to two main thoroughfares in the West End of London, a reftone level of 44 db. was found with the windows closed, 54 db. with one window fully open, 58 db. with two windows open, and 74 db. outside the window. There was a certain degree of sound absorption within the office due to carpet, curtains, &c. Additional data obtained in a third floor office in Fleet Street, London, is given in Table 3 [124].

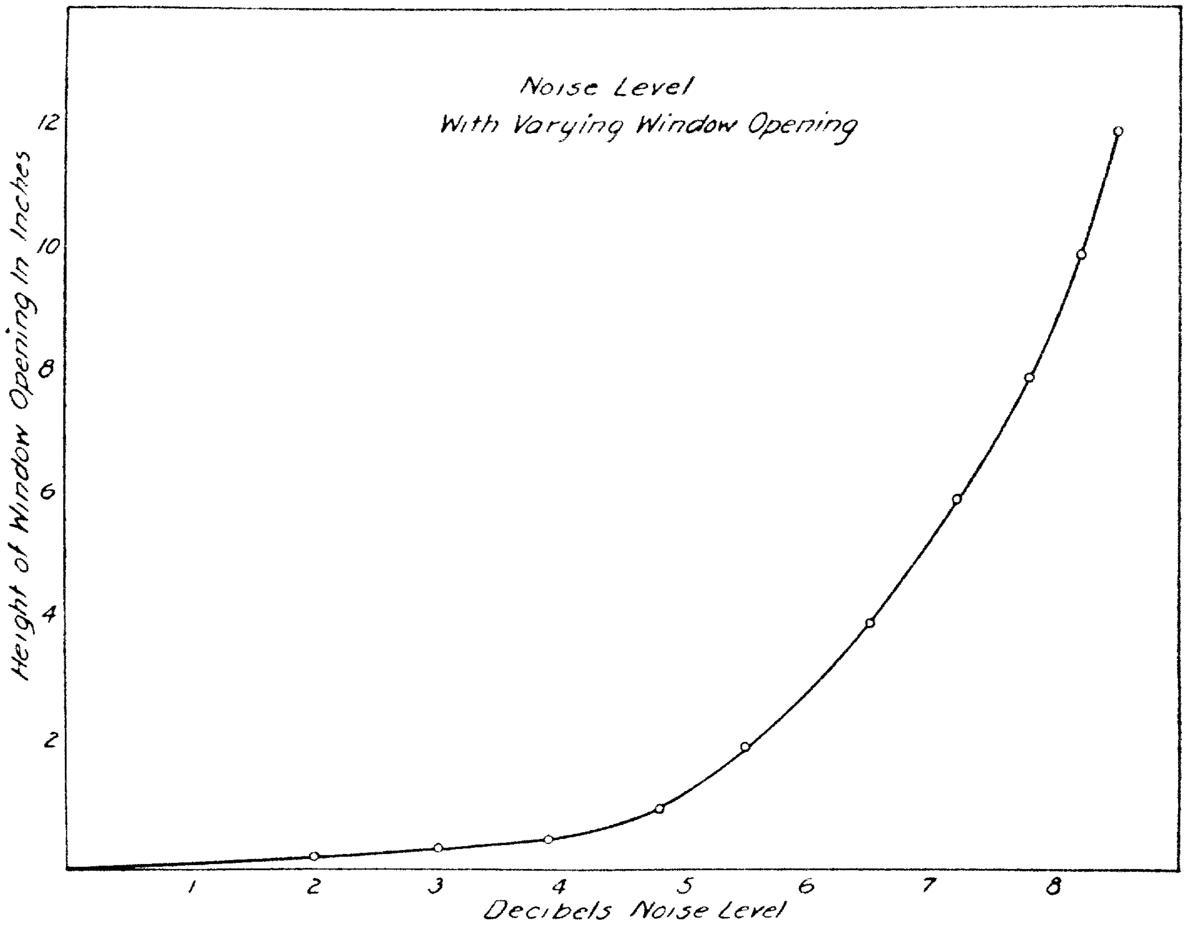

FIG. 34.

It follows that ventilation and freedom from noise are mutually exclusive unless a special type of ventilator is used. In discussing aeroplane noise (Chapter VII), we stipulate the maximum permissible area of cracks, &c., to be 1/10,000th the internal area of the cabin, and the above computation is apposite in this respect.

If the coefficient of absorption in the cubical room were raised from 0·1 to 0·3, A_s would be trebled, and the intensity level reduced $10 \log_{10} 3 = 4{\cdot}8$ db., which is inconsiderable compared with the increased cost due to the extra absorbent material required.

TABLE 3. *Reftone levels of noise in third floor office in Fleet Street, London* [124]

Source of Sound	*Condition*			
	Windows shut	*3 ventilators and 1 window open*	*All ventilators and five windows open*	*Microphone outside window*
	db.	db.	db.	db.
Medium traffic	60	64	69	75
Heavy traffic	65	73	76	80
Buses starting	69	..	..	..
Motor-horns	70	..	..	82

There are two ways of rendering an enclosure soundproof: by (*a*) using massive walls, floor, and ceiling so that the transmissibility is correspondingly low (e.g. the type of wall found in ancient prisons!); (*b*) using an abundance of absorbent material to kill the sound, so to speak, before it reaches the room. The noise levels within two rooms of the above types depend upon the absorption coefficients of the inner surfaces as presented to an internal source. Thus, if the first room has hard bare walls, whilst the second room has walls of absorbent material, the noise level due to an internal source of given strength will in the former case exceed that in the latter. If one absorption coefficient is 0·05 and the other 0·5, the difference in noise level will be $10 \log_{10} \frac{0{\cdot}5}{0{\cdot}05} = 10$ db. These data emphasize the necessity for preventing noise entering the cabin of an aeroplane or a building where silence is desired, for once it gets there it is enhanced due to reverberation.

3. *Transmission of sound through partitions.*

Apart from the direct passage of sound through ventilators, windows, &c., it is transmitted through partitions in two ways. The first is by direct longitudinal wave motion through the partition, which might be a brick wall. The wall is compressed and rarefied in the same way as air when it is traversed by sound waves, but the amplitude of vibration of the particles in a brick wall is insignificant compared with that in air, owing to the much greater density and stiffness of the brick. In the second mode of transmission, the partition is set into vibration by air waves in the same way as our ear drums. The partition acts like a very large diaphragm, and if the frequency of the sound is equal or nearly equal to the natural frequency of the partition, a large amount of sound is transmitted due to diaphragm action. Obviously, in some cases transmission will occur in both ways. The greater part of the sound incident on the external surface of a heavy partition is reflected away from it. The remainder is transmitted, but during transmission a certain degree of absorption occurs which helps to reduce the intensity level on the inside of the wall. When sound waves pass from one medium to another, reflection occurs unless the mechanical resistances of the two media are identical. If ρ_0 is the density and c the velocity of sound in a medium, the mechanical resistance of the medium per unit area is $\rho_0 c$. For air at 18° Centigrade this is nearly 42, whereas for steel it is 4×10^6, or one hundred thousand times as great. Thus, when air waves impinge upon the steel plates of a ship's hull they are almost totally reflected. The sound which is transmitted reaches the inner surface of the metal, and here again, owing to the enormous difference in the values of $\rho_0 c$ for steel and air, reflection occurs once more. A similar action takes place with a brick wall, but here the value of $\rho_0 c$ is less than it is for steel. A somewhat similar condition would arise in a long loaded submarine cable if a very large inductance were connected between the far end and the receiving apparatus. The sudden change in electrical characteristics at the inductance would cause serious reflection, so the signals would be mutilated and reduced in strength. Although the greater part of the incident sound is reflected from a thin partition, diaphragm action may cause an intensity level on the inside which is comparable with that in the absence of the partition. So far as outer walls are concerned, they have to present adequate resistance to the egress of heat from within during winter and its ingress from without during summer. But here one is apt to be stymied by large window space, unless very thick glass or double windows are used. Double windows would be advantageous in several ways, but an unfortunate economy militates against their general use. Data pertaining to single windows are set out in columns 2 and 5, Table 3, p. 70.

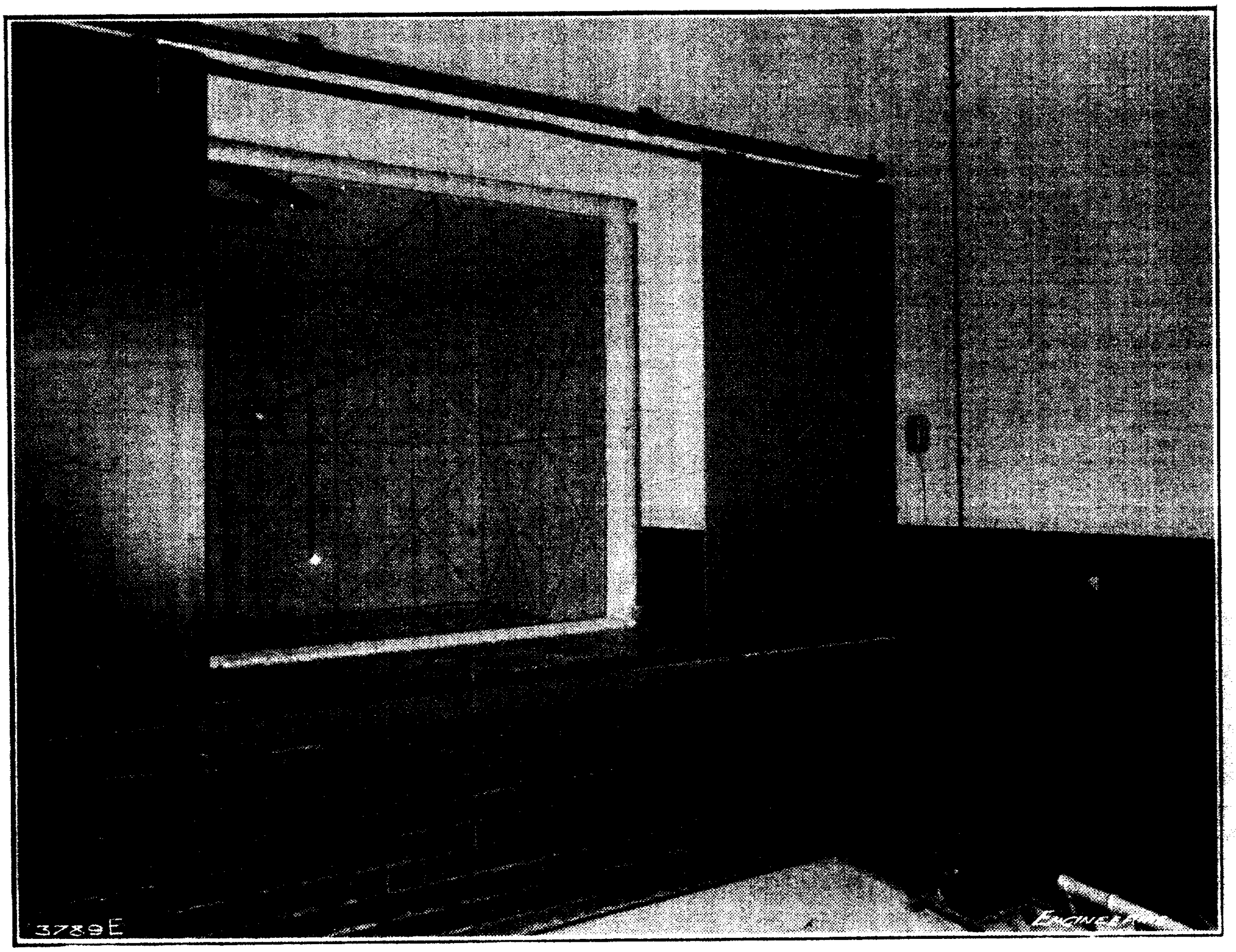

FIG. 35. Room for sound transmission measurements. (Metropolitan Vickers.)

It is not our purpose to give detailed descriptions of the methods of testing the transmissibility of partitions; rather are we concerned with results in the form of numerical data. The essence of a test is to find the difference in intensity level with and without the partition between a sound source and a microphone. Fig. 35 shows a photograph of a room used for such tests. The partition to be tested is clamped in the aperture left by the sliding doors. A loud speaker is actuated in the small room, and transmission through the partition is deduced from sound pressure measurements made on each side by calibrated microphones. Experiment shows that the sound insulation of homogeneous partitions is proportional to the logarithm of the mass per unit area, the latter usually being taken as 1 sq. ft. [63]. A graph for solid brick walls of different

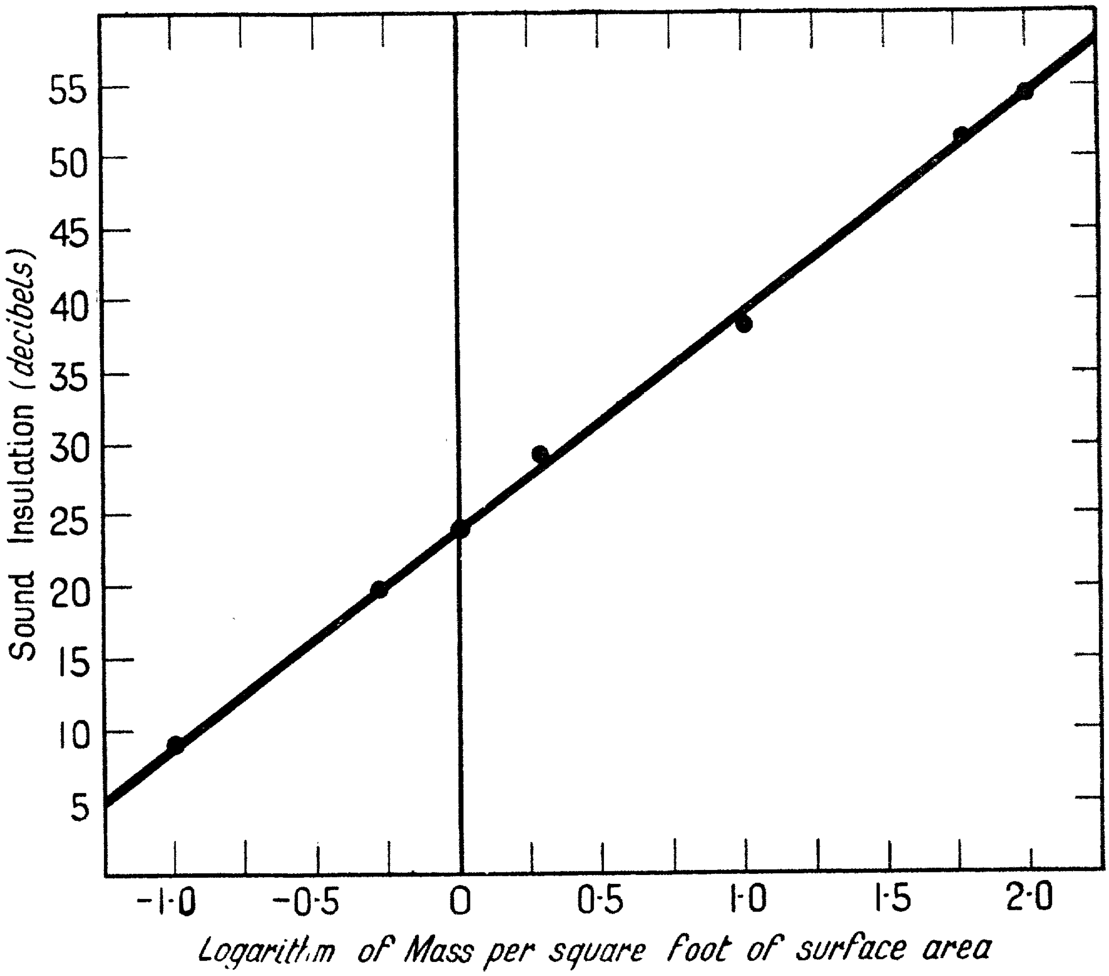

FIG. 36. Showing the linear relationship between sound insulation in decibels and the logarithm of the mass per square foot of brick walls of different thicknesses.

thicknesses is given in Fig. 36, in which the logarithm of the mass per square foot of wall area is plotted against the reduction of intensity level in decibels. The relationship is a linear one, the equation of the line being

$$\text{db.} = 15 \log_{10} m + 24.$$

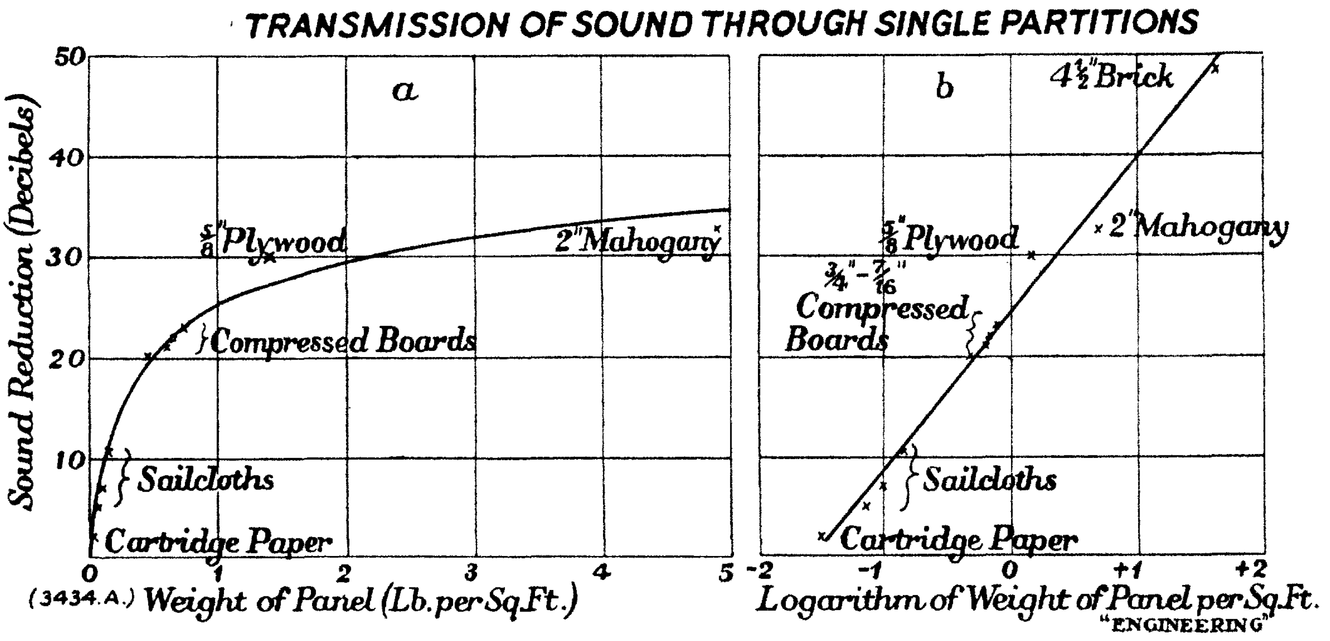

FIG. 37.

Now the mass of a brick 4½ in. thick is 40 lb. per sq. ft., so the sound insulation is

$$15 \log_{10} 40 + 24 = 48 \text{ db.}$$

The dimensions of a standard brick are $3 \times 4\frac{1}{2} \times 9$ in., so that if the bricks were turned round and twice as many used, the mass per square foot would be doubled. The sound insulation would then be $15 \log_{10} 80 + 24 = 52{\cdot}6$, so that a wall costing about double gives an additional insulation of only 4·6 db. If, however, the second lot of bricks is used to build another wall at a suitable distance from the first, the effect of the air space and this extra wall is to add another 40 db., making 88 db. in all. In practice this procedure is approximated in 'cavity' walls. Care must be taken to avoid what may be regarded as a vibrational 'short-circuiting effect' at the junctions of the walls.

A large number of tests have been carried out on the transmission of sound through various materials and some

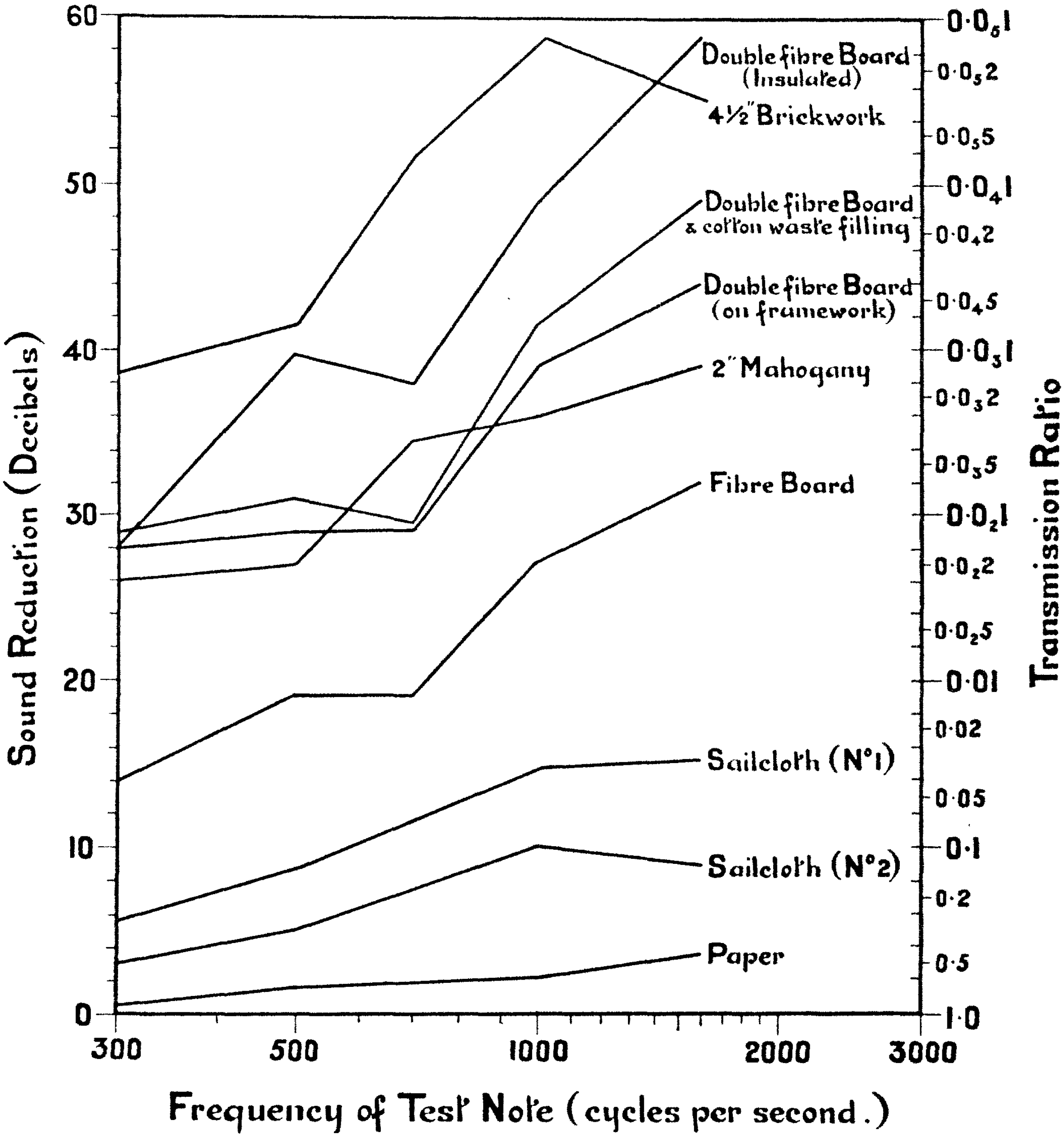

FIG. 38. Sound insulation of various materials at different frequencies.

representative data are exhibited in Fig. 37 [64]. The sound insulation varies with frequency, and, as might be expected, it increases with rise therein due to the enhanced frictional loss concomitant with motion of the particles of the material during wave transmission. Additional graphs relating to sound insulation are plotted in Fig. 38 [63].

V

TRAFFIC NOISE

In the noise survey taken in New York City, the majority of complaints were aimed at motor vehicles, particularly those of the lorry class [90], which constitute the main sources of noise in the heart of a large city like London. But there are also tram-cars, pneumatic drills and riveters for building construction which contribute their quota of noise. There is no doubt that trams, particularly where they rattle across points, cause a higher noise level than motor-cars. Next to the automobile in the list of New York's offensive sounds was that due to radio. This can be accentuated in many cases by flimsy partitions in modern houses, or by the proud owners airing their noise machines in the back garden. At the same time, owing to a psychological kink, some persons seem to be unable to live amidst quiet surroundings. This appears to be due to some peculiar complex of the 'can't be left alone in the house' variety.

In treating traffic noise, there are two principal levels to be considered, (*a*) the maximum or peak, (*b*) the average. The discrepancy between these two depends upon the location. This point is illustrated in Table 4 where the two noise levels are shown for a number of different locations in London.

Inspection of Table 4 shows that on the whole there is not a great difference between the peak and average reftone levels, except in Oxford St. during a traffic blockage and in Regent St. The variations in level are 14 db. and 15 db., respectively, which is a considerable amount. The reftone levels in the table are quite high, and a reduction of 10 db. all round would be very welcome.

We shall now examine noise data obtained in New York City and exhibited graphically in Figs. 39, 40 [90]. In addition to the peak and average reftone levels, the minimum level is also given, which is of great importance in residential quarters, particularly during the night. Radio Row in New York was known some years ago as an extremely noisy street, and this is confirmed by Fig. 39 from which it is seen that an almost constant level of 80 db. was maintained due to loud speakers being used out of doors.

TABLE 4. *Showing peak and average noise levels in London streets* [124]

Location	*Average reftone level*	*Peak reftone level*
	db.	db.
Fleet St. near Ludgate Circus	78	82
Ludgate Circus	78	84
Threadneedle St. (Bank of England)	77	80
Cannon St.	76	82
Oxford St. (traffic moving)	76	82
Oxford St. (traffic blockage)	70	..
Strand	76	84
Regent St.	69	84

Since the survey was made, loud speakers are used indoors, so the level is now much lower. The level at Forty-second Street on Fifth Avenue is some 70 db., whilst that of a residential street is 50 db. The presence of a heavy chain-driven lorry in a quiet residential street is apt to cause a rise in level of 20 db. or more, and this is rather disturbing to the residents. Although the peak value of the noise may be below that of the average level in the city, it is the increase in level above normal which is important, e.g. witness the greater distraction due to intermittent noises.

The level varies according to the time of day, and this point is illustrated in Fig. 40 which refers to New York City. A curve drawn through the largest dots shows that from 9 p.m. to 3 a.m. the mean level is about 10 db. below that during the day time. It is of interest to see that at 5.30 p.m., namely, the rush hour, when the office population seeks its own fireside, the average level is approxi-

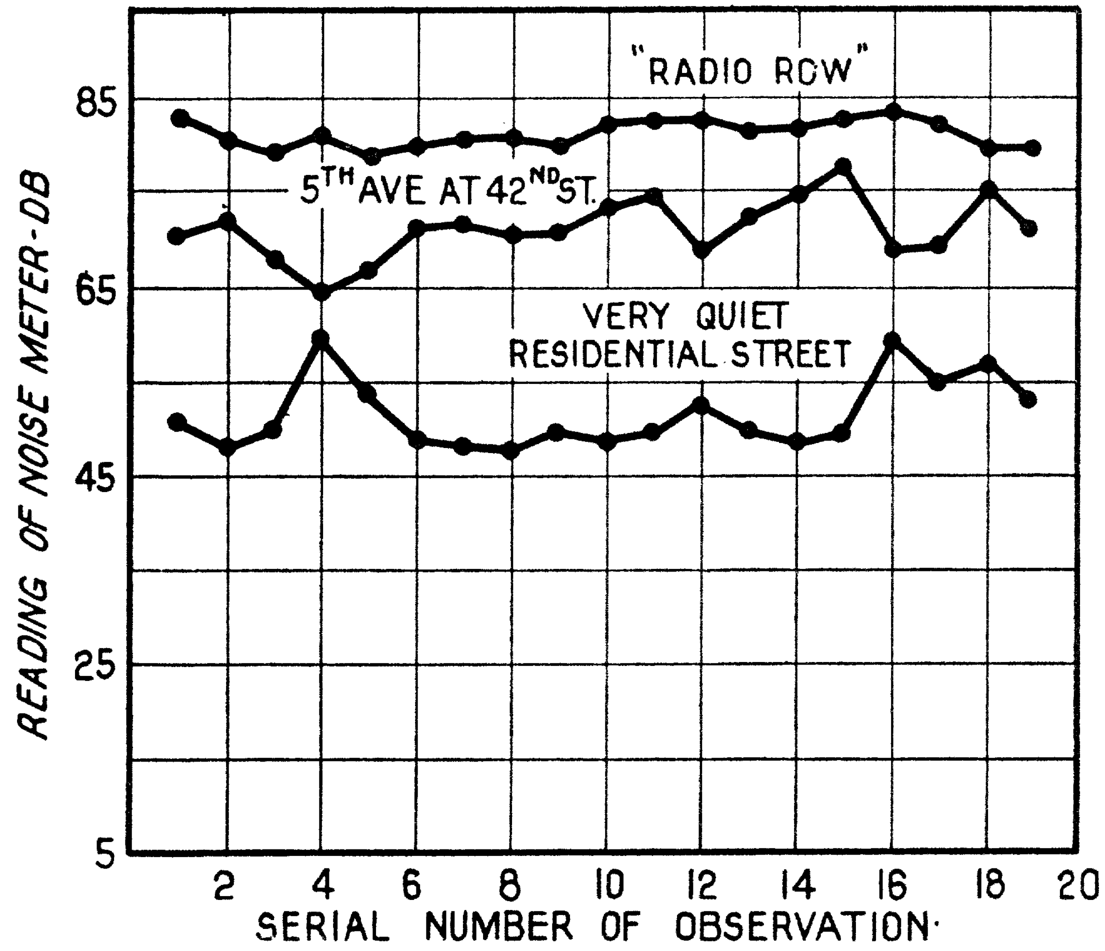

FIG. 39. Showing instant to instant variation in noise level in daytime in New York.

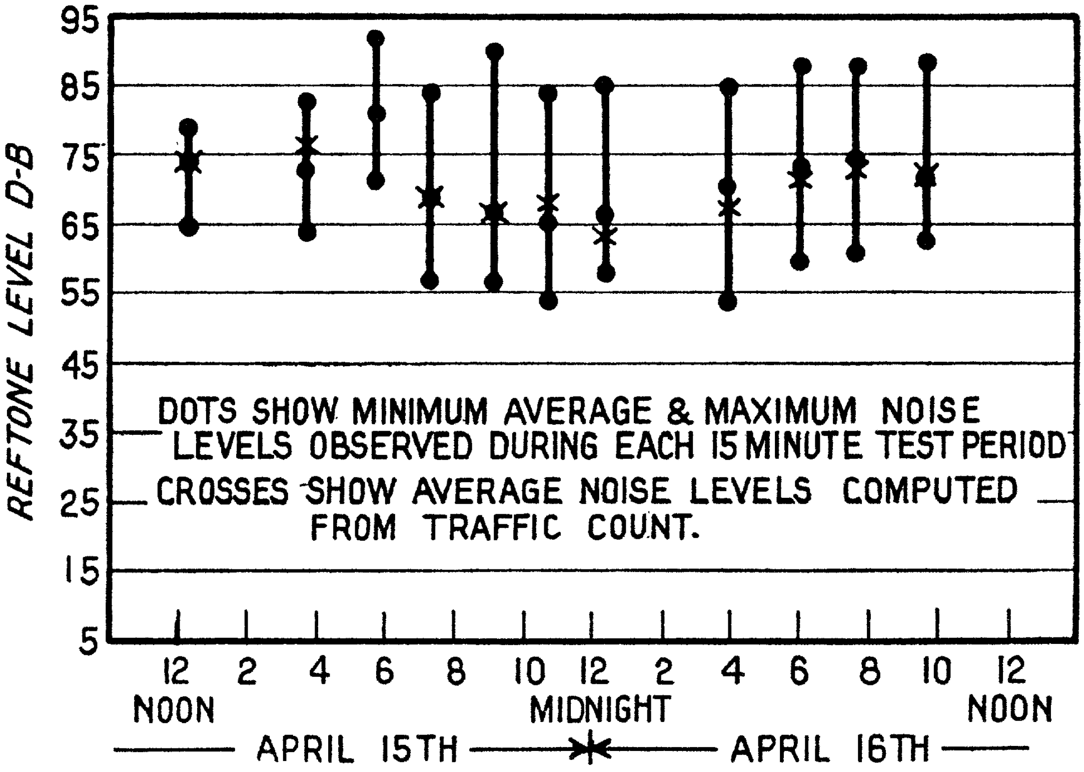

FIG. 40. Noise levels measured during 24-hour test at Canal St. and Broadway, New York City.

mately equal to the maximum level during the quieter periods.

It is natural to expect that two identical motor-cars make more noise than one. If each made the same amount of noise on the open road we should expect the noise level to rise $10 \log_{10} 2 = 3$ db., and this is approximately true. Owing to reflection of sound from buildings, the conditions in a thoroughfare are more complicated than in the open. This effect is likely to be much more serious in New York, with its skyscrapers, than in London where the buildings are relatively low and sound can escape upwards more readily. Measurements in New York show that there is an approximate relationship between the number of vehicles and the noise level. It is necessary, however, in order to get a proper basis of comparison that the traffic should be homogeneous, e.g. chiefly private motor-cars and not a mixture of cars, lorries, and trams. Eleven locations were tested in which there were no trams, and passenger traffic constituted 90 per cent. of the total. Taking our cue from the result deduced above in connexion with the two motor-cars, we might argue that n vehicles would raise the noise level $10 \log_{10} n$ decibels above that due to one vehicle only. This is approximately true up to a certain value of n, above which the rise in level is less rapid than before. Apart from differences in the component frequencies and their magnitudes for different vehicles, the preceding result can be explained in the following way. Suppose one is in a captive balloon equidistant from n identical motor-cars spaced uniformly on a circle on the ground. If all engines run in synchronism, the noise level will be $10 \log_{10} n$ db. above that of one car. Whilst making measurements in traffic, the observer has perforce to stand near the pavement. Moreover, as the traffic gets denser, he is farther away and partially screened from that on the opposite side of the street, whilst there is an appreciable variation in the sounds caused by different vehicles. The relationship between average noise and the number of vehicles passing per minute is shown in Fig. 41 [90]. It is linear up to 60 vehicles per minute, beyond which value the level increases less rapidly.

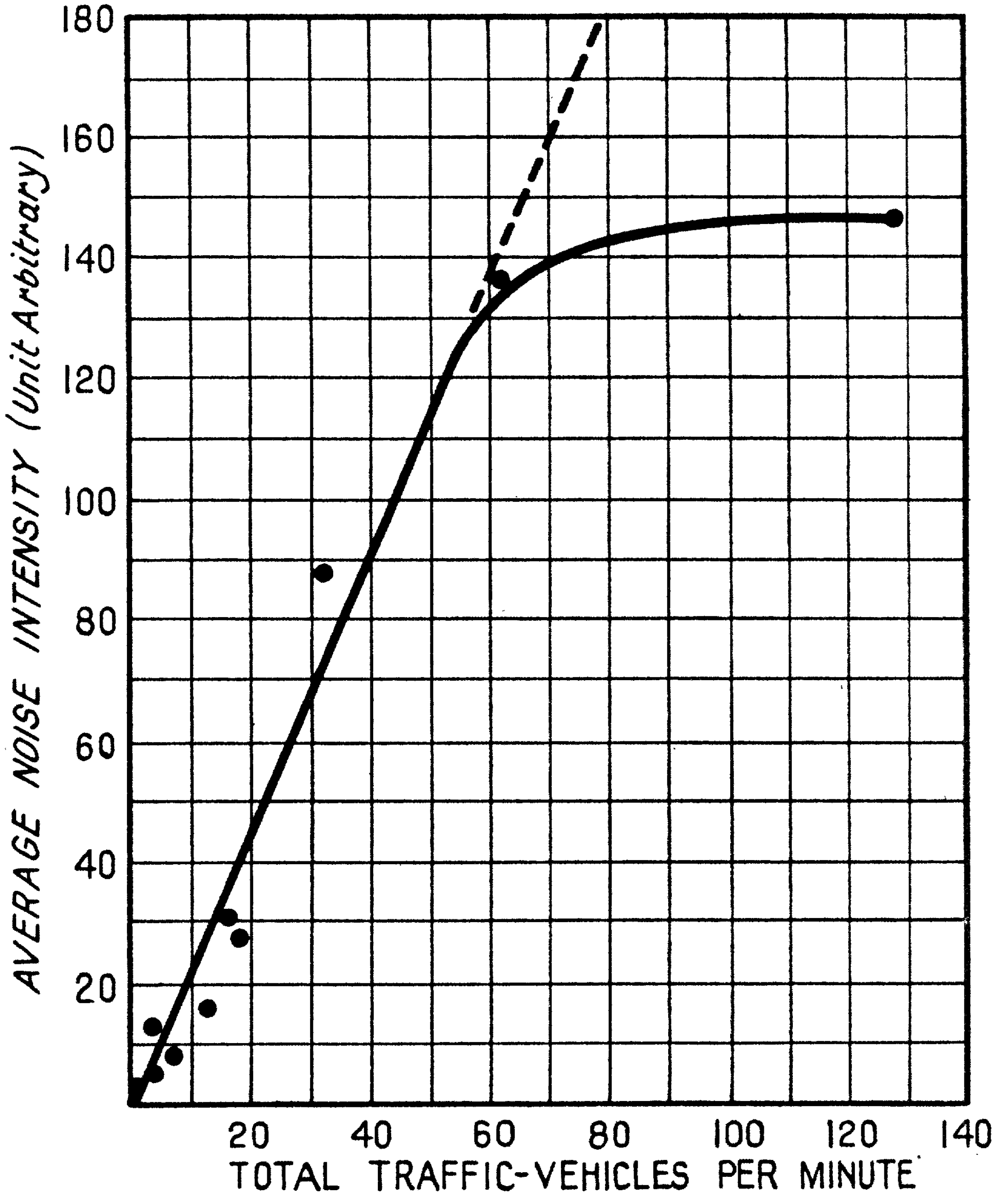

FIG. 41. Noise levels.

The noise level depends upon the character of the traffic. Commercial vehicles and buses are usually noisier than private cars and coaches. Tests made on this point show that if the number of vehicles passing per minute is constant, the level increases in proportion to the increase in the percentage of commercial vehicles. This is borne out by the graph in Fig. 42 [90]. Without commercial vehicles the level corresponding to 30 passenger cars is 67 db. As the percentage of commercial vehicles rises, so also does the noise level. With a percentage of 50 the level is augmented 9 db., an amount which cannot be overlooked.

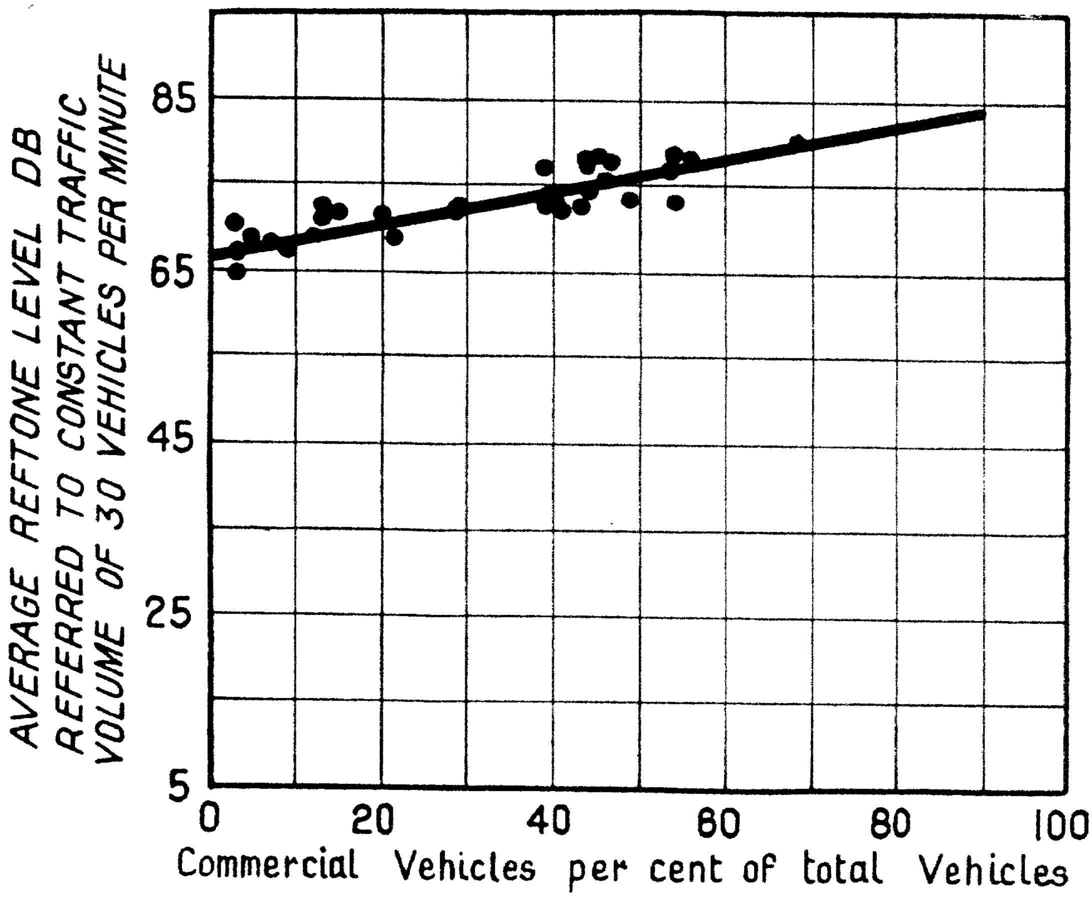

FIG. 42. Noise levels.

By aid of data of the type given in Figs. 41, 42 it is possible to predict the change in noise level which accompanies a known change in the type or the density of the traffic in any location of a similar nature. Thus the information obtained from an averaged series of noise measurements for several locations can be used to predict the level elsewhere, provided the type and density of the traffic are known. Examples of estimates of the mean level made from such data are indicated by the crosses in Fig. 40. The actual values are those shown by the large black dots, so the errors in computation are negligible.

Measurements of traffic and other noises provide data which tell us the levels of the various sources. These enable engineers, architects, and others whose business it is to reduce noises, to know how much the level ought to fall in order that it may be within the limits of toleration. The results of tests made in London and in New York are given in Tables 10–17, pp. 137, 138, and cover a comprehensive range. It may be remarked that the low level in Temple Gardens (Table 15)—the lawyers' stronghold—should be conducive to uninterrupted thought in solving the wrangles of the populace. The noise level of trams entering Kingsway tunnel under Waterloo Bridge (see Table 16, p. 138) is eclipsed by the pointsman's whistle by 10 db. The noises which emanate from this particular location, where traffic is stopped every few minutes, are very distracting to those who attempt to think deeply in the library of the Institution of Electrical Engineers. The reftone level therein exceeds the permissible value quoted in Table 18, p. 138, item 5, whether the windows are open or closed.

From Table 17 we see that the reftone level of the roar emanating from the 'king of beasts' is of the same order as that due to an underground train or a very noisy street. In dense traffic the lion's roar would not strike terror into the populace, for it would pass unnoticed! The noise level within a room, whose windows face a thoroughfare, depends upon the window opening, also upon the size and absorbent properties of the room. The results set out in Table 5 were obtained in a fifth-floor room of a modern

TABLE 5. *Reftone level of noise in London office* [124]

Condition	*Average reftone level*	*Peak reftone level*
	db.	db.
Both windows closed	44	49
One window open	54	60
Both windows open	58	64
Both windows open, curtains drawn .	54	59
Outside the window	74	79

office building in London, having a carpet, hangings, and upholstered chairs.

A steamship siren is a very powerful source of sound. At 115 ft. from a siren an average loudness level of 98 db. has been obtained, whilst in a tenth-story room in New York 1,450 ft. distant and facing the ship, the level was 75 db., the windows of the room being open [90].

VI

TRAIN NOISE

THE noise level in a tube train is relatively high, being of the order 75 to 100 db., which experience shows is adequate to drown conversation at normal reftone level. The problem of noise reduction falls under four heads: (1) reducing the amount of noise created at the source to a minimum, (2) absorbing this noise in the space outside the train, (3) preventing as much of the noise as possible from entering the cars, (4) absorbing the sound which enters the cars, so that the noise level is curbed. The noise is due primarily to impulsing of the wheels at the rail-joints, and also to the mode of travel of the wheels over the track. It is found by experiment that the wheels are not in continuous contact with the track, but proceed by a series of jumps. The track itself is resilient, as can be confirmed by watching an express train travel over a railway line. That section of the track covered by the train is depressed visibly. The carriage wheels are connected to the framework by a spring suspension, and the oscillating system is a complex one. Provision is made for damping out the oscillations which occur. We saw in Chapter III that the noise of a hammer on a steel plate had a wide range of line and band spectra, and this is equally true of the noise due to the wheels passing over the rail-joints. The vibrations of the rails and the wheels not only generate sound waves, but such vibrations are transmitted directly through the springs to the coachwork, which acts like a huge sounding board, as in a piano. There is, therefore, a large radiating surface, but since the oscillation frequency of the coaches on the springs is very low, the high-frequency vibrations are not readily transmitted to the coachwork, which merely reinforces the rumble. Any one who has spoken, whistled, or made a noise in a long tunnel, e.g. the covered footway between

South Kensington station and the Science Museum, knows that sounds are reinforced and persist for a longer time than they do in the home. The same thing occurs, but in a different degree, in a railway tunnel. The noise has no chance of exit (except at the ends of the tunnel) and goes on building up in strength, until the rate at which it is generated equals that at which it is absorbed by the train and the tunnel.

To reduce track noise when wheels pass over the joints, various constructions have been tried [35*a*]. The only method which gave a perceptible reduction in noise level was that where certain kinds of ballast were laid across the track surface up to within 1¼ in. of the top of the rail. The ballast for this purpose consisted of ¼ in. granite chips placed over ¾ in. crushed pit ballast. This method could not be adopted generally owing to the impossibility of inspecting the rail track properly. If a suitable ballast material can be found which is mechanically strong and adequately sound absorbing, it might replace the upper layers of the present type. The wheels themselves emit high-pitched sounds, in fact the character of the sound is used as a criterion by wheel testers who go about tapping wheels with long-shafted hammers to detect cracked tyres. By suitable design the 'ring' of the wheels might be reduced, provided the fault-testing possibilities were not eliminated. Obviously the shorter the rail lengths between joints, the more the impulses received per minute and the greater the general noise and clatter. The older tubes had rail lengths of 36 to 42 ft., but on the new extension routes the lengths are 90 feet, which has caused a reduction in general noise level.

In the open air away from walls and buildings there is no reflection of sound, except that from the ground, which is inevitable, although it raises the level some 6 db. above that in free space. To simulate the latter condition it would be necessary to line the tunnel walls very heavily with sound-absorbent material. The noise level would be relatively low provided the above-mentioned schemes regarding ballast and long rail lengths were in force. Needless to say this approach to Utopian conditions is beyond the bounds of possibility, but the application of a reasonable amount of absorbent material on the walls, from a little above the rail level to about the height of the top of the car windows does cause an appreciable reduction in noise level. The cast-iron tunnel provides a convenient arrangement for applying absorbent material, as it can be fixed between the flanges connecting consecutive tunnel rings [35*a*]. In one set of tests the absorbent was sea grass 4 in. thick, this being kept in place by small-mesh wire-netting. Bands 6 ft. deep were placed on a length of tunnel as shown in Fig. 43, and a considerable reduction in noise ensued. Although an excellent absorbent, this material is unfortunately unsuitable from the mechanical and fire-

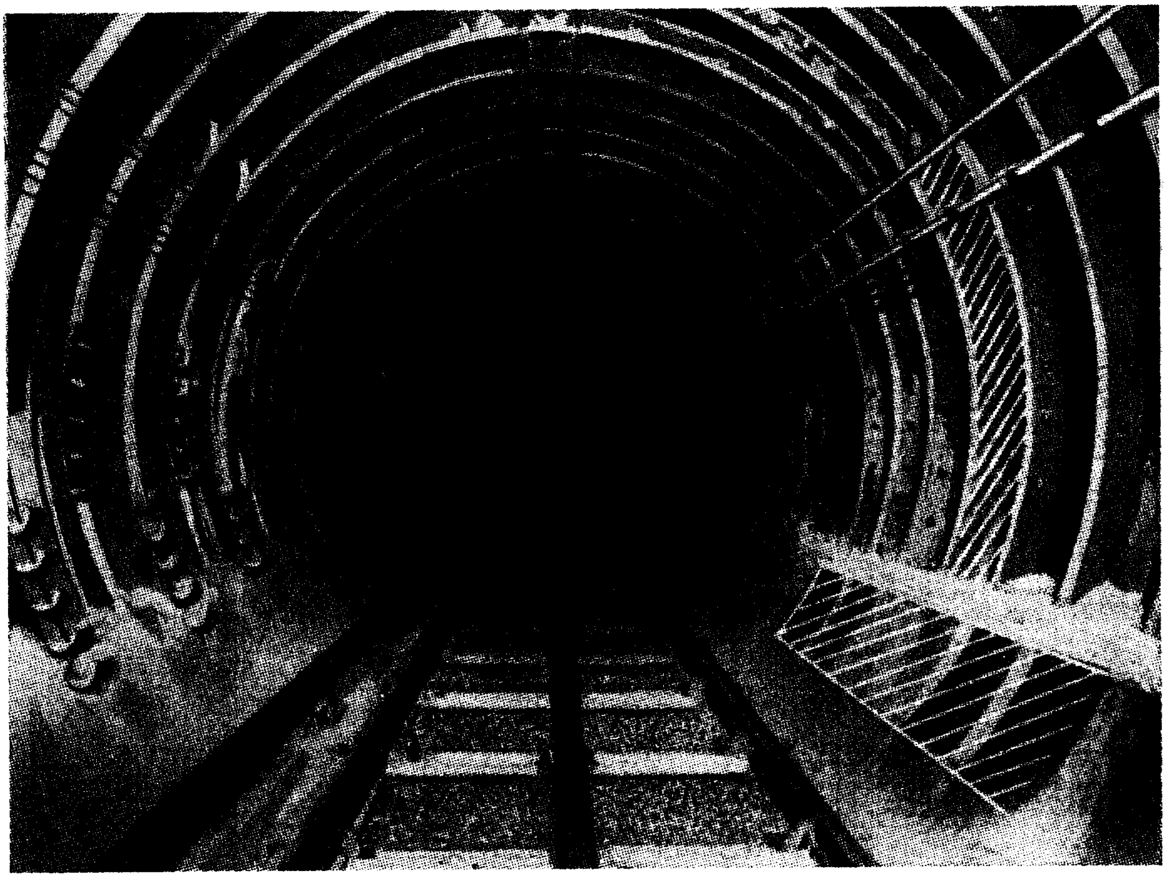

FIG. 43. Interior of tube railway showing position of noise-absorbing material.

proof points of view. A number of materials were tested in the above manner, but those suitable acoustically were unsatisfactory otherwise. They were not absolutely fireproof, were liable to disintegrate in the powerful draughts in the tube tunnels, and held dirt and dust.

One type of mattress constructed of loose-textured asbestos felt about an inch thick, faced with woven asbestos fabric for protection, had good absorption properties. However, a more practical form of applying the absorbent and improvement in various details is necessary before the above method can be adopted. Asbestos has been sprayed to a thickness of half an inch on the interior walls of the tunnels over a length of 400 yards, a special binding material being employed to prevent disintegration. A surface finish easy to clean was obtained, but the absorption was markedly less than that with the sea grass mattresses.

Experiments were also conducted with a view to noise reduction, by insulating the track from the concrete foundations and tunnel structure. One method was to insert special rubber pads between the sleepers and the concrete road bed. Two types of pad were used, one being solid and the other having oblique slots at intervals in order to facilitate movement of the rubber during the passing of a train. A lead wrapping was used with the object of damping the vibrations more rapidly and giving the rubber mechanical protection. The effect of pads of various materials between the rail-chairs and the sleepers was also tried. None of the above devices gave the desired result, which indicated that the noise was directly air-borne and was not transmitted from the rails via the road bed and tunnel lining. That is to say, the bed and the tunnel did not exhibit diaphragm action, although the noise from the wheels was enhanced by reflection from the tunnel surface nevertheless. Reflectors have been used to divert the noise downwards and prevent its entry into the windows and ventilators of the cars, but the method did not meet with success. A modified arrangement was installed in which the clearance between the train and the side of the tunnel at the footboard level was reduced to a minimum, but as might be expected from the data in Chapter IV, p. 67, the noise level was practically unaltered.

Extensive experiments have been made in silencing the rolling stock, but improvements have been partially offset by increased train speed. The interior of the car was covered with cotton wool and by removing this in turn from the floor, side panels, windows, roof, and ends, the effect of exposing each could be determined. It was found that the windows and ventilator openings were the main entries for the noise. A shroud was fitted round the bogies close to the wheels and the rail with the object of screening the noise. Although effective to an extent, it introduced difficulties in inspecting, greasing, and repairing the cars. The improvements resulting from the investigation consist of sound insulation on the floor, in the side panels and roof, thicker glass windows, moquette in place of cane seating, also reduction in electric motor, gear wheel, and braking noises [35*a*]. Indirect ventilation of the cars by noise-baffling passages reduces the sound power entering the cars to a considerable extent. Difficulty arises in its adoption, for although effective ventilation can be provided, the public wish to see open windows to admit air, and herein lies the major cause of the trouble, since noise enters out of all proportion to the benefits conferred by the influx of air. However, like other innovations, the forced draught system will doubtless gradually come about as the public gets educated to the scheme.

Some data respecting noise level in London tubes is given in Table 6 [124].

From Table 6 it is seen that the District Railway is the least noisy in the tunnels, and this is well known from everyday experience. In the open, however, there is not a marked difference between the District and Piccadilly Railways. At points and crossings the noise level rises from 6 to 8 db. above the normal running level. The effect of absorbent material in the tunnels is to reduce the noise level 8 db. or so.

TABLE 6. *Noise levels in London tubes*

Measured with objective noise-meter of Fig. 12. All results are at 30 miles per hour approximately, and were obtained inside the trains during normal running hours. Most of the ventilators were open.

	Average reftone level in open air		*Average reftone level in tube*		
Line	*Trailer*	*Motor Coach*	*Trailer*	*Motor Coach*	*Peaks*
	db.	db.	db.	db.	db.
Hampstead and Highgate	80	82	91	94	98
Piccadilly	75	79	84	91	95
District	76	77	79	84	95
Central London	..	..	90	97	101
Bakerloo	..	..	84	..	92

In a railway train the increase in noise with speed is very noticeable. At 60 to 80 miles per hour the noise level in a carriage with the window open is 74 db. which can be reduced to 69 db. in a third class compartment and 64 db. in a first, by closing the window [63]. Certain sections of rail track are much noisier than others. The noise increases at level crossings, passing over bridges and water troughs. The train noise can be divided broadly into two parts: (*a*) rumble due to the wheels rolling over the line and proceeding in a series of jumps as described above, (*b*) the joint noise. The latter is the chief source of disturbance and like the noise of the hammer on the steel plate treated in Chapter III, it contains high-frequency sounds of short duration. In fact the joint noise is a series of impulses and gives rise to peaks in the level. The continuous wheel rumble in a tunnel is reinforced more than the intermittent joint noise and masks it to an extent. The effect of reverberation is to make the joint noise seem to be continuous. If joint noise in the open could be reduced by 10 db., thereby eliminating the peak values in the sound level, train noise would be less distracting and travelling more pleasant.

VII

NOISE DUE TO AEROPLANES, SHIPS' PROPELLERS, AND MOTOR VEHICLES

1. We do not need to be told that aeroplanes create a considerable noise, for it is sometimes rather loud in our homes. The aeroplane, but a mere dot in the distance, is not at present a silent spectacle of progress in aviation. Fortunately, the audible portion of the noise is of relatively low pitch when heard some hundreds of yards away, and does not cause the same degree of annoyance as the high-frequency tearing sounds which are audible at close quarters. Throughout this book the reftone level has been stated in decibels above a certain datum, but it may be of interest to treat the question of the power behind the noise. In problems associated with heat, there are two things to be considered; (*a*) the temperature, (*b*) the power or energy supplied per second as heat to maintain the temperature. These two correspond to the acoustical quantities intensity level and the power to maintain a certain level. A relatively small fire serves to keep the temperature of a small thick-walled room at, say, 65° F., but a very large fire would be required to keep a person warm in the open, on a cold night, 15 ft. from the fire. In the first case the volume of the enclosure is small so the heat is conserved, whereas, in the second, the space is very large, so the heat escapes and is lost. This approximate analogy can be applied to the acoustical problem which we are considering. An ordinary radio receiver reproducing the tuning-in note at full strength in a concrete room 10 ft. cube would cause a very loud and extremely annoying sound, although the acoustical power output might be only 0·05 watt. Owing to small absorption by the concrete walls, the sound builds up to a large intensity, so a small output can cause a high reftone level. This is fully explained in Chapter

IV, § 2. In the open, sound can escape and passes away into space like the heat. We see, therefore, that the temperature or the level due to a given source of power, depends upon the external conditions. To obtain a high reftone level in the open necessitates a very powerful source. The aeroplane constitutes such a source. Reftone measurements disclose that when steps are not taken to reduce the noise, the aeroplane holds the record for machinery. About 10 ft. away from the airscrew, the reftone level is well nigh on the threshold of feeling. The level in an open cockpit is 110 to 125 db. and conversation is quite impossible [38, 39]. Enterprising airway companies used in the early days to provide cotton wool plugs to seal the aural apertures, but, as we have seen already, sound is conducted through the bones of the head, so one travels with a plethora of noise. Many persons have been deterred from air travel owing to the 'acoustical atmosphere', which may induce a feeling of insecurity.

There are four main sources of noise associated with an aeroplane: (1) the airscrew, (2) the exhaust, (3) the engine clatter caused by tappets, &c., (4) the shedding of eddies from the wing and body surfaces. Experiment shows that frequently it is the airscrew noise which predominates, and for a given screw the higher the speed of rotation the greater the reftone level of the noise. The speed of the blade tips seems to be the controlling factor, and the reftone level increases about 10 db. per 100 ft. per sec. increase in tip speed. Some airscrews have a tip speed of from 800 to 900 ft. per sec., so a reduction to 500 or 600 ft. per sec. would be accompanied by a fall in reftone level of 30 db., which is a considerable amount, representing a ratio of 1,000/1 in acoustical power output [22, 38]. To take some test data obtained from a 400 h.p. air-cooled engine at zero forward speed (i.e. the aeroplane strapped to the ground) the level of the airscrew noise in the plane of the screw 8 ft. from the centre was 134 db. at a tip speed of 850 ft. per sec. and 114 db. at 650 ft. per sec., i.e. a fall of 10 db. per 100 ft. per sec. The exhaust noise 10 ft. away was 114 db. and the engine clatter about the same [39]. We see, therefore, that at high tip speeds the airscrew is the predominating source of noise. When, however, the tip speed is reduced to 650 ft. per sec. the reftone levels of each of the three sources are substantially the same. If the screw were silenced, the noise level would fall only 1·76 db., and if the exhaust were also silenced, the level would be reduced another 3 db. The total fall in level is 4·76 db., this being negligible. Consequently to reduce the noise appreciably, it is imperative to tame all three of the sources. We have seen that the airscrew noise can be curbed by lowering the tip speed, although this affects the performance adversely to an extent. It is necessary, however, to make some sacrifice in speed to attain a reasonable degree of otic comfort.

We now come to the problem of reducing exhaust noise. According to the above data, at a tip speed of 650 ft. per sec. the three sources are almost equally loud, so that nothing would be gained by reducing one or even two of them. In an aeroplane, however, we must consider the position of the airscrew, engine, and exhaust in relation to the cabin. The two former may be well away from the cabin, thereby effecting a reduction in reftone level to 85 db. in an ordinary canvas-sided cabin, but if the exhaust is near the cabin, it may appear to be louder than the screw noise. Under this condition exhaust silencing will be beneficial. The maximum reduction in reftone level obtained with silencers of the simple long perforated tube variety is about 10 db., which is totally inadequate [22]. The degree of exhaust silencing depends upon the permissible allowance for extra weight and head resistance due to the silencers. Also the back pressure imposed at the engine manifolds must not be sufficient to affect performance adversely. It is possible to design silencers weighing 75 lb. which will reduce the exhaust noise of a 500 h.p. engine by 25 db., the back pressure at full throttle not exceeding about 2·5 lb. per sq. in. This is probably as far as it would be worth while to go in most cases, for with the exhaust silenced to this degree, the airscrew noise would predominate [102].

An important point in connexion with exhaust silencers for aircraft is the danger from fire, due either to the silencer becoming filled with explosive mixture while the engine is being started up, or in the event of a crash, through petrol coming into contact with the hot metal of the silencer. The danger could be minimized from both points of view by fitting special valves in the engine exhaust system, so that the silencer could be 'cut out' when desired [102].

Having shown how the noise due to the above-mentioned trio can be reduced appreciably, we now attend to the cabin. If the cabin walls were constructed of thick metal sheet much sound would be excluded. This will be clear from Chapter IV, § 3, since it is shown that the sound obstructing propensity of a solid non-vibrating partition depends upon the mass per square foot. Obviously thick metal or any equivalent substance must be ruled out by virtue of its great weight. Moreover, we must invoke the aid of science in order to find an alternative to the sheer brute force method. If we use a single layer of fabric weighing one ounce per square foot, the noise level is reduced 5 db., which is insufficient. Plywood $\frac{1}{8}$th in. thick, weighing 8 ounces per square foot, gives a reduction of 20 db. A better scheme is to employ inner and outer panels, the intervening space being filled with an absorbent material such as Kapok blanket [39]. Using an outer skin of aluminium sheet 0·025 in. thick, an inner skin of Micarta imitation leather, and a 2 in. interspace filled with Kapok, the reftone level can be reduced 27 db. This means that the reftone level in the cabin lies between 74 and 84 db. which is of the same order as that observed in an express train, the compartment window being open. The weight of the double filled panel per square foot is 12 ounces, and this may be just on the heavy side. If it is deemed necessary to modify the construction and use less material, the reduction in reftone level should not fall below 16 db.

Having taken all reasonable precautions to prevent ingress of sound, there are several side issues which require careful attention. The panels must be free from drumming, that is to say their natural frequencies must differ from the main frequencies in the noise. If a panel resonates, it must be braced, reduced in size, or treated in some way to alter its frequency. There must not be any large cracks or crevices through which the noise can enter. In this respect great care must be taken to avoid the type of ventilator which admits too high a proportion of noise. Ventilators should be situated where the noise level is relatively low. There is room for improvement not only in the ventilation of aeroplane cabins, but in any form of covered vehicle or stationary enclosure where mankind is wont to congregate. Despite glowing accounts in the press, of wonderful ventilation systems in new public buildings, the atmosphere in many cases is distinctly depressing from a physiological point of view. We know from experience that when a door or a window is open an inch or so noise trickles in, and there is little difference in reftone level if the opening is doubled. This is explained in Chapter IV, § 2. Due to the sound building up in intensity after it gains entry to a room, the reftone level can be relatively high when the area of entry is quite small. Moreover, since the difference in noise level between the two sides of a sound-proofed aeroplane cabin is so large, it is very important that cracks and crevices should be reduced to a negligible amount. An approximate calculation (see Chapter IV, § 2) shows that the area of all sound inlets should not exceed one ten-thousandth part of the total superficial area of the interior of the cabin. The absorption within the cabin will be enhanced by its occupants, by curtains and the like, but the reduction will not exceed 10 db.

2. *The airscrew as a source of sound.*

If a stick is whisked through the air a swishing sound is heard, but it cannot be associated with any particular frequency. The air at any position momentarily occupied by the stick, during its motion, is displaced and returns when the stick has passed. If the stick makes 50 revolutions per second, the air at any point in the orbit is displaced and returns to its original position 50 times per second. Thus the main frequency is 50 and the noise is audible. The sound generated in this way is not due to the vibration of a structure, but to its rotation. There are several effects to be considered, but for the present we shall deal with the main source of noise due to an aeroplane propeller having two blades. This noise arises in the same manner as in the case of the whirling stick. If the speed of rotation is 800 revolutions per minute, i.e. 13·33 per second, the fundamental frequency of the main noise is $13{\cdot}33 \times$ number of blades $= 26{\cdot}66 \sim$. The sound contains harmonics whose frequencies are $2 \times 26{\cdot}66 = 53{\cdot}32 \sim$, $3 \times 26{\cdot}66 = 79{\cdot}98 \sim$ and so on. The *intensity* level (see Chapter I) due to the fundamental is greater than that of any harmonic, but the reftone level and the quality or timbre of the sound depend upon the distance of a listener from the plane. In practice exhaust noise is superimposed upon that of the screw. At a distance of 600 yards or so the sound is usually low pitched, but nearer the aeroplane there are also high-pitched tearing sounds of an unpleasant character. These are due to eddies being shed from the tips of the propeller blades and from various parts of the structure, this disturbance being known as 'drag' noise. When an aeroplane has two or more engines, the screws run at approximately the same speed. A slight difference in speed causes beats, so the sound waxes and wanes in the well-known manner. The same effect occurs when two single-engined planes are flying side by side.

Measurements of the sound due to an airscrew 14·8 ft.

diameter at zero forward speed, the aeroplane fuselage being strapped to the ground, show that the power is not uniformly distributed round the screw [65]. This is exemplified in Fig. 44, where the distribution of the fundamental (27·8 ~), the third harmonic (83·4 ~), and the sixth harmonic (167 ~) are depicted. The curve for each frequency is reminiscent of the butterfly diagrams obtained with loud speaker diaphragms. The maximum intensity for the first and third harmonics occurs at an angle of from 15° to 30° behind the plane of rotation of the propeller. Owing to the variation in sensitivity of the ear with frequency, it does not follow that the reftone level of the noise (which includes all harmonics) will be a maximum in the

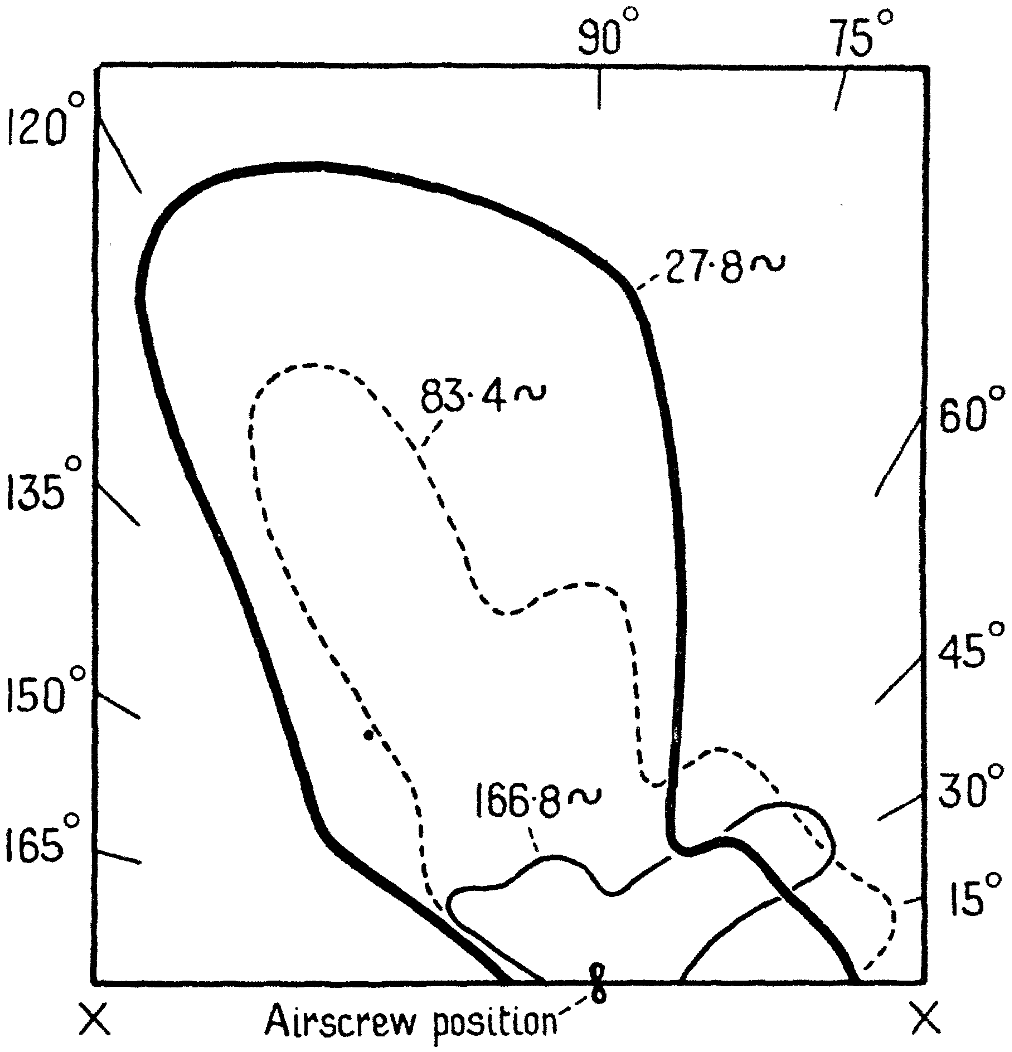

FIG. 44. Showing distribution of sound from airscrew, the plane of the screw being vertical and at 90° to xx.

above angle range, and this is confirmed by experiment. The power emitted by the screw due to the harmonic constituents of the noise is given in Table 7 [65]. The total power is only 36 watts, which is a tiny fraction of that developed by the airscrew during flight—about one part in ten thousand. When we compare this with the 1/100th watt obtained from a domestic radio set, it is very large indeed. By good fortune the harmonic constituents are low pitched, and therefore cause less annoyance than would be the case if the frequency band were several octaves higher.

TABLE 7. *Power in harmonics of airscrew noise*

Harmonic	*Frequency*	*Power*
	~	watts
1	27·8	17·8
2	55·6	7·4
3	83·4	6·8
4	111·2	2·4
5	139	0·6
6	166·8	1·2
	Total	36·2

The acoustical power cited above was assessed from measurements on a propeller 14·8 ft. diameter making 800 revolutions per minute, which gives a tip speed of about 600 ft. per second. This is the right order of tip speed to obtain a relatively low noise level. In many cases the tip speed exceeds 600 ft. per second, the noise is more intense and the power radiated as sound varies from 50 to 100 watts. Experimental evidence shows that in cruising flight at a distance of 15 ft. from a two-bladed screw, the noise level is approximately $20+0{\cdot}1v$ db., where v is the tip speed in feet per second [22]. Thus if v is 600 ft. per sec. the level is 80 db., whereas with a tip speed of 850 ft. per sec., it is 105 db., which is more the order one experiences in some commercial machines.

We have already considered the main source of airscrew noise, and now pass on to two other sources. These are the eddies shed from the neighbourhood of the tips of the propeller blades and aerofoils, also flexural vibration of the blades themselves [43]. The former is akin to the vortex action explained in Chapter III, § 4, being due to eddies swirling from side to side of the edge of the blade or the aerofoils at high frequencies. The band of frequencies covered extends up to about 1,000 ~ [40]. The propeller blades being cantilevers, fixed at the propeller boss, are in a perpetual state of flexural vibration. In general, the sound created in this way is masked by the other sounds which are more powerful.

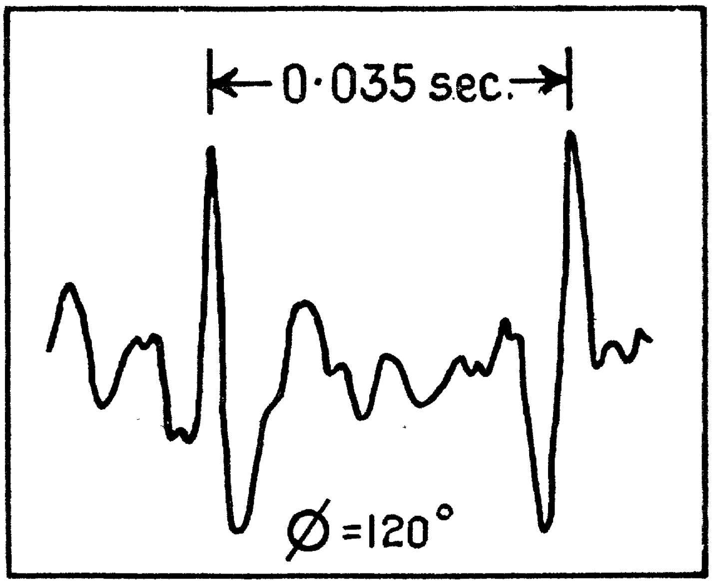

Fig. 45. Oscillogram of airscrew noise.

The rotational noise, discussed at first, tends to be of an impulsive rather than a continuous nature. A typical oscillogram which includes all types of noise is reproduced in Fig. 45, this being taken at zero forward speed with a microphone situated 30° behind the plane of the screw [65]. The principal frequency is that of the fundamental note of the screw, calculated as shown above from the product of the number of blades and the revolutions per second. Harmonics are present and also a certain amount of interference due to an imperfectly silenced exhaust. The wave form when the aeroplane is in flight will doubtless be modified.

2 a. *Subaqueous noise from ships' propellers.* During the war much ingenuity was expended in devising means for detecting sounds due to ships' propellers. To do so it is necessary to use an instrument called a hydrophone. There are various patterns, but a simple type of hydrophone consists of a short length of rubber tubing $\frac{5}{8}$ in. thick, 3 in. outside diameter, closed at each end by circular disks of rubber of like thickness. A carbon button microphone is fixed to the inner face of one disk and connected by a cable to a battery, transformer, and telephone ear-pieces. The hydrophone is lowered into the water, using a lead sinker if necessary. Sounds from ships' propellers set the rubber disk in vibration, so that the microphone is actuated and corresponding sounds can be heard in the telephones. As the propeller revolves, the water pressure at the rear of the blades is reduced. This causes a partial vacuum and vortex cavities are formed [99]. These cavities are unstable, and when they collapse the result is to cause an impulsive disturbance which is transmitted through the water as sound. The noise is characterized by 'beats' in the case of vessels driven by reciprocating engines, and by a 'rushing' in the case of turbine steamers. The vortices are formed only when the speed of the propeller exceeds a certain value. Below this critical speed, i.e. in the silent zone, the noise emitted by the screw is negligible and difficult to detect. The subaqueous sound due to ships steaming at normal speed is audible at sea under normal conditions for some miles [131].

3. *Exhaust noise of motor vehicles.*

Where locomotion by internal combustion engines is concerned, much noise from the exhaust is usually taken to signify correspondingly high power and efficiency. Any one who has removed the silencer from a touring car—sometimes they fall off or disintegrate, which is convenient for experimental purposes!—knows that it makes little difference to the performance. It does, however, add considerably to the otic discomfort of the occupants, attracts the attention of and evokes comments from passing motorists. If the driver is unlucky he may find himself in the arms of the law! In this mechanized age, when applied science is used mainly for the amusement of the populace rather than for the amelioration of more vital matters, the design of a silencer which will render the exhausts of automobiles well-nigh dumb, without impairment of performance, ought to be possible. In racing cars and motor cycles, the exhaust noise is as loud as the rules of the track or the latitude of the law permits. There is too much latitude where motor cycles are concerned, and in nine cases out of ten these vehicles are examples of noise creation at its worst, especially in the early hours of the morning. The objection raised to effective silencing is that it affects performance adversely, owing to increased back pressure on the piston during the exhaust stroke. Recent experiments show, however, that the more probable explanation is that the increased back pressure prevents a full charge being drawn into the cylinder during the suction stroke owing to the increased amount of exhaust gas remaining in the cylinder. The pressure in the exhaust pipe when the valve closes is the prime factor, and the mean exhaust pressure is no sure indication of the gain or loss of power [26]. In fact a high *mean* back pressure may be associated with relatively large power. Research shows that it is possible with automobiles, where the power is small compared with that of an aeroplane engine, to design silencers which reduce the exhaust noise to a high degree without detrimental effects on performance. When this step has been taken in practice, the remaining noises due to gears, chains, tappets, carburettors, and tyres will all call for serious consideration. As our knowledge of noise and its measurement steadily grows, it will be incumbent on those who manufacture noise-generating machinery to see that the reftone level under specified conditions does not exceed a certain value. To allow for deterioration and the effects of wear in increasing the noise level, the permissible value for a new machine should err on the low side.

Although every one can distinguish the exhaust noise of a motor cycle or a car from other sounds, this does not yield any information of scientific value. We feel that there is considerable power at low frequencies and a knowledge of the mechanical side of the business confirms this. There is a series of pulses, which in the case of a motor cycle may occur as frequently as 200 times per second. At low speeds there may be only 10 per second. Although a pure tone of this frequency is inaudible, it will be realized from the remarks in Chapter III, §§ 1, 2, that we are now dealing with impulses whose frequency spectrum covers the entire range of audibility. The power will be centred mainly round the frequency of the exhaust discharge. But we must not overlook the vortex action at the exhaust valve and within the silencer, together with the impulsing effect of the explosions on the exhaust system. This is excited and executes various modes of vibration of which we may mention the radial type. At the moment when the exhaust valve opens, the pressure in the exhaust system suddenly rises, for that in the cylinder is in the neighbourhood of 50 to 60 lb. per sq. in. The rise in pressure causes the pipe and the outer casing of the silencer to expand radially. Expansion is not maintained owing to the elastic properties of the material, so the exhaust system contracts in an attempt to regain its normal size. When the static equilibrium position is reached, the system sweeps through it owing to the energy of motion and contracts still more. Thus mechanical vibrations occur at the natural frequencies of the component parts of the exhaust system, and the external surface radiates sound. Owing to its large area compared with that of the final aperture in the exhaust pipe, the sound power may be appreciable. The salient frequencies of exhaust sounds are divided into two groups. One of these is below 600 ~, whilst the other is above 2,000 ~ [26]. Remembering that the ear is comparatively insensitive to low frequencies, although the sound power may be considerable relative to that at high frequencies, the effect of the latter on our hearing may be large enough to cause discomfort. To obtain information regarding the relative effects of high and low frequencies we can consider the oscillograms reproduced in Fig. 46 [118]. Both curves were obtained with a condenser microphone situated near the open end of an unsilenced motor-car exhaust. The microphone was connected simultaneously to two valve amplifiers having different response curves, each amplifier being joined to a separate pair of oscillograph strips. A third pair of strips went to an oscillator to obtain the timing wave. The first amplifier was uniformly sensitive throughout the frequency range and gave curve *a*, whilst the second had an 'ear-like' response, i.e. one of the curves of Fig. 3 inverted, so that the middle and upper frequencies were favoured more than the lower. In this way objective and 'subjective' results were obtained. In the objective curve *a*, low frequencies corresponding to the exhaust pulsations are noticeable, but relatively weak higher frequency components are superimposed thereon. The subjective curve is quite different, and we see that the ear perceives bursts of high frequency sounds which occur at each exhaust discharge. The envelopes at the crests and troughs of the oscillations are akin to those obtained in reverberation tests of rooms (Chapter IV, § 2). The amplitude builds up to a maximum and then decays. Fig. 47 illustrates

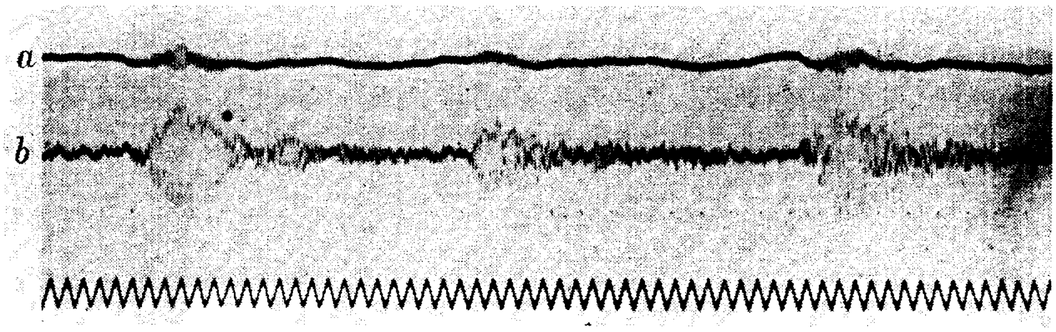

FIG. 46. Sound wave form of motor exhaust without silencer.

the effect of fitting a silencer, *a* being the objective and *b* the subjective record [118]. In the former case the low-frequency components predominate, those of higher frequency being relatively inconspicuous. Nevertheless they are quite distinct in the subjective record *b*. Compared with the unsilenced exhaust, the higher frequencies are now innocuous.

The nature or quality of the exhaust noise does not depend to any great extent upon the engine speed. When the exhaust valve opens the gas stream issues through a comparatively small but gradually increasing valve area, and this results in the creation of eddies and turbulence. These, in addition to the vortices in the silencer, and shock excitation of the exhaust system mentioned previously, may be the main source of the high-frequency sounds. Having regard to the oscillogram Fig. 47*b*, this explanation seems to be feasible. So far as the sounds of lower pitch are concerned, the cylinder and the exhaust system form a coupled acoustical resonator. The volume of the cylinder varies during the exhaust stroke, as also does the area of the valve opening which connects the two resonating systems. The gas in the complete system is set into oscillation as soon as the exhaust valve lifts, this being accompanied by a sudden discharge. Owing to the varying volume of the cylinder and the coupling to the exhaust system, the pitch of the note may alter progressively. The arrangement is somewhat on the lines of an open organ

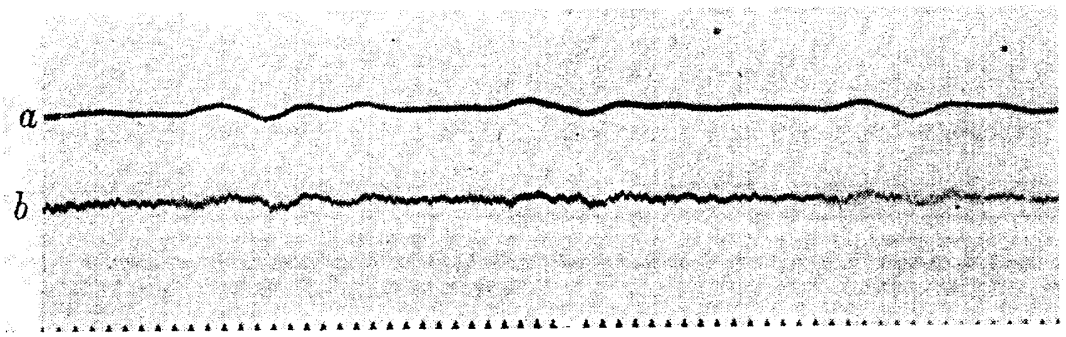

FIG. 47. Sound wave form of motor exhaust with silencer.

pipe (the exhaust system) being fed from a resonator of changing volume through a passage of varying area. It can be shown mathematically that the acoustical wave form contains an infinite number of component frequencies. Thus we account for the two principal frequency bands as follows: the lower band is due to the lower frequency components in the spectrum of the exhaust impulses, and to the ensuing natural oscillations of the gas in the cylinder and exhaust system. The upper band is due to the impulse spectrum, to vortex or eddy-current action at the valve and in the silencer, and to free vibrations of the metal parts of the exhaust system caused by impulsing.

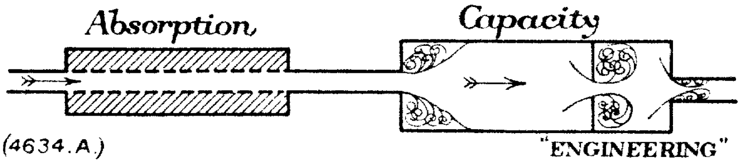

FIG. 48. Schematic diagram of exhaust silencer.

Coming to methods of reducing exhaust noise, in designing a silencer we have to cope with two frequency bands 50 to 600 ~ and 2,000 to 10,000 ~, which can conveniently be designated lower and upper. Referring to Fig. 48, imagine the portion marked 'absorption' to be replaced by the normal exhaust pipe [26]. This means that the engine is connected to an expansion chamber fitted with a baffle having one or more holes. When the gas reaches this, sudden expansion occurs and eddy currents or vortices are created as indicated. The gas passes through the baffle holes, expands again and then makes its exit via the narrow tail part of the exhaust pipe. This form of silencer, usually known as the capacity type, is said to be effective in reducing the acoustical power of low-pitched sounds [26]. We now take the complete arrangement illustrated in Fig. 48, the result being a reduction in the high-frequency portion of the noise. The reduction is due to glass silk which acts as an absorbent. By using separate silencers to reduce the sound power in the upper and lower frequency zones, it is found that the former is more objectionable than the latter. When both zones are adequately silenced, the upper does not appear so objectionable, owing to the masking effect of the lower, provided of course, that the latter zone is loud enough. It appears, therefore, that the main purpose of silencer design should be to curb the upper frequency zone as much as possible. At the same time, the general noise level must be reduced to a minimum, for an exhaust which is not troublesome on the open road might cause considerable annoyance in a suburb or in a back lane, owing to reinforcement of the sound due to reflection from walls and palings. This is particularly pernicious at about 7 a.m.

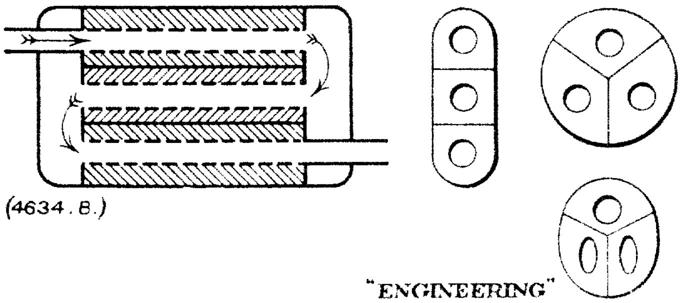

FIG. 48*a*. Schematic diagram of exhaust silencer.

A type of silencer in which the capacity and absorption principles are incorporated is illustrated in Fig. 48*a*. The exhaust gas coming from the cylinder passes through a perforated tube surrounded by glass silk, which absorbs part of the sound power in the high-frequency zone. This is followed by a capacity chamber from which the gas flows through another absorption tube. After this there are two similar stages prior to the gas being discharged into the atmosphere. The noise level of an unsilenced exhaust from a four-stroke motor cycle was found to be 110 db. whereas with the above type of silencer it dropped to 91 db. For a two-stroke engine the levels were respectively 104 and 79 db. [89]. This silencer did not impair the performance of the machine, a point which is confirmed by brake horse-power tests [26].

VIII

VIBRATION DUE TO MACHINERY

If the front of a motor-car is jacked up, the wheels sometimes oscillate slowly before coming to rest. This means that the lowest part of the wheel is heavier than it ought to be, so the wheel is out of balance. In a bad case the tyre may be out of balance by as much as $\frac{3}{4}$ lb., and on a front wheel, at 60 miles per hour, this would cause bumping and difficult steering. At 60 m.p.h. when the unbalanced part of the wheel is at the top, there is a force exceeding 1 cwt. tending to raise the front end of the car. Little wonder, then, that the car rocks about. At 84 m.p.h. the lifting force is twice as great, since it increases as the square of the speed. If a lead weight of $\frac{3}{4}$ lb is securely fixed to the inside of the rim opposite to the heavy point, the car will travel smoothly.

In rotating machinery of various kinds, e.g. electric lift motors, tramway motors, ventilating fan motors, alternating and direct current generators, turbines and the like, there is always a certain want of balance. Since this class of machinery invariably runs at high speed, the out-of-balance forces give rise to vibration. To prevent this being transmitted to nearby structures, the machine is clamped to a heavy concrete foundation. The concrete base is not readily moved owing to its great mass, but elastic waves are transmitted through the foundations and the ground, as in the case of earthquake tremors. If the vibrational frequency due to unbalance is identical with that of some nearby structure, the ensuing rattle is usually annoying.

There are two main problems associated with the reduction of vibration due to machinery: (1) balancing of the rotating parts in turbines and electrical machinery, also of rotating and reciprocating parts in pumps, gas engines, &c.; (2) attenuation of the vibration transmitted from a machine to its supports, by aid of mechanical filters, or, what is the same thing, vibrational insulation of the machine from its supports. The first problem is beyond the scope of the text and is the prerogative of designers of machinery. There are various mechanical constructions which can be used to solve the second problem. The basic principle involved is common to all, and will now be described.

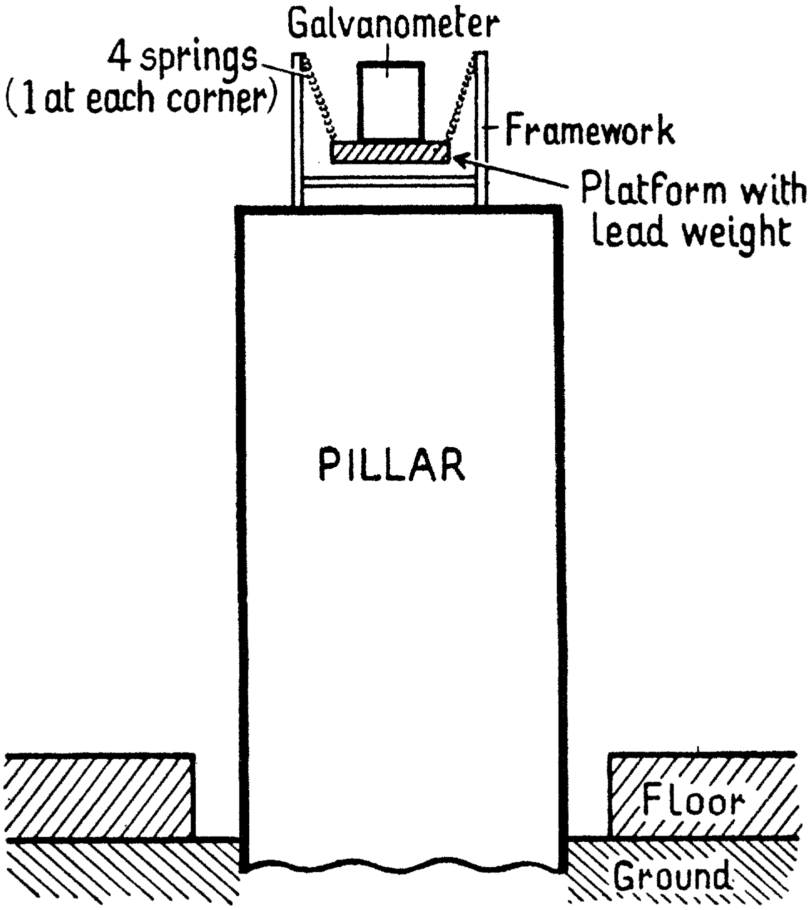

FIG. 49. Illustrating anti-vibration system or mechanical filter.

Delicate galvanometers have been used with success for many years in factories where vibration is rampant. These instruments are isolated from the foundations by a form of suspension. The arrangement usually adopted is illustrated diagrammatically in Fig. 49. A concrete pillar from 4 to 6 sq. ft. in cross-section is let into the ground beneath the floor to a depth of several feet, and an air space of 1 in.

or so is left all round. Although the tremors on the surface of the floor are avoided and the great mass of the pillar guards against excessive motion, the fact remains that the problem of insulating the galvanometer from vibration is only half solved. If the instrument is placed on a lead-loaded platform suspended from an outer framework as shown schematically in Fig. 49, the pillar itself can be hit with a wooden mallet without causing any visible effect on the galvanometer, *provided the natural frequency of the suspended mass does not exceed* 3 $\sim$. This principle was introduced in connexion with valve amplifier design over ten years ago. Owing to air-borne and mechanically transmitted shock excitation, the electrodes of the input valve were in a state of continual vibration at audible frequencies. The mechanically transmitted vibrations were eliminated by suspending the valve either by sorbo rubber or by delicate springs, so that its vibrational frequency was well below audibility. The air-borne vibrations, due to the loud speaker, still remained, and the resultant feed back effect caused a continuous howl. This 'microphony' effect was cured by enclosing the valve in a box having an absorbent lining. Spring-suspended valve holders for reducing mechanical vibration have been in existence for some years. Microphony has disappeared largely owing to improved mechanical construction of the valve electrodes, and in many cases the spring suspension is not required.

The problem of insulating the foundations of a machine from vibration is the reverse of the example given above. Referring to Fig. 50 the machine is represented by a mass m resting upon a spring of stiffness s, which is fixed to the foundation. There is usually a certain amount of mechanical resistance due to the frictional loss in the spring, and this is represented by the dash-pot at the side. The effect of unbalance in the machine, which might be an electric fan motor, is to cause an alternating force to act on m. The unbalanced action may occur in any direction, e.g. it might rock the mass sideways, but for simplicity we shall assume that it acts in a vertical direction.[1] We have to determine the conditions under which the force transmitted to the foundation through the spring will be only a small fraction of that due to unbalance. Although the mathematical analysis is quite simple, it is beyond the scope of the text, so we shall merely quote the result. The ratio $\epsilon = \frac{\text{force on foundation}}{\text{unbalanced force}}$ is defined to be the 'transmissibility' [59]. The smaller the value of ϵ the less the transmissibility and, therefore, the less the vibration transmitted to the foundations. The relationship between ϵ and the frequency of vibration due to the unbalanced part is shown in Fig. 51. Curve 1 refers to a moderate amount of resistance due to the spring, and is a fair guide to what may be expected in practice. When the unbalance frequency is below that of the machine on its spring support, the transmissibility exceeds unity and the amplitude of vibration of the foundation is greater than it would be without the spring. As the unbalance frequency is in-

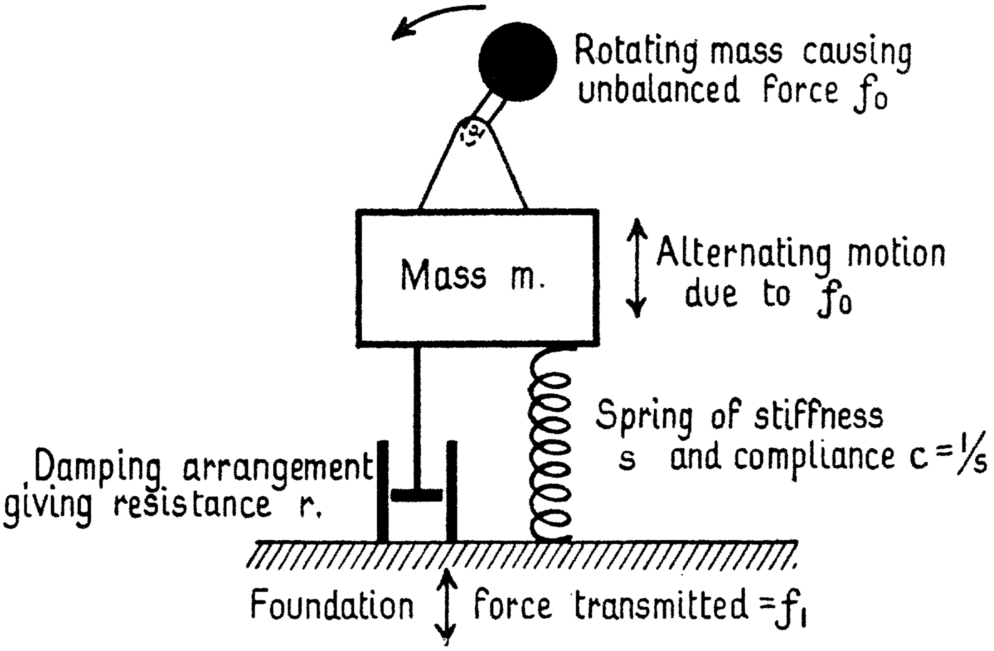

FIG. 50. Schematic diagram of anti-vibration system.

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[1] That is to say only the vertical component of the unbalanced force due to the rotating mass is considered.

creased from *P*, the vibration of the foundation increases also, and attains a maximum value when the two frequencies are equal at *Q*. As the unbalance frequency increases beyond *Q*, the amplitude of the foundation gradually subsides until it becomes quite small. To reduce the value of

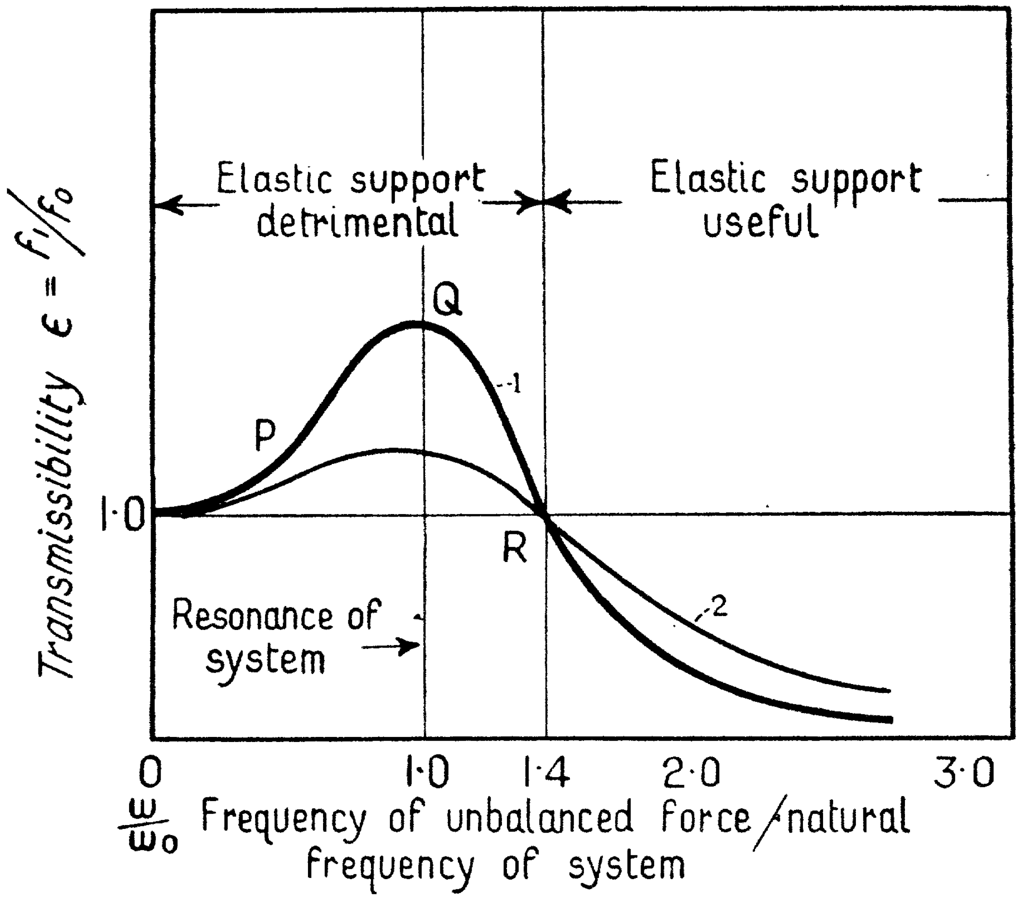

FIG. 51. Showing transmissibility of anti-vibration system at various frequencies of the unbalanced force.

ϵ and, therefore, the vibration, the resonance frequency of the machine on the spring should be less than one-fifth the unbalance frequency. Actually, the smaller the frequency ratio the better. From analogy with an electrical filter, of which Fig. 52 represents one stage of a 'low-pass' type, the above mode of reducing vibration can be regarded as a *mechanical* filter; since the forces due to all frequencies above the point *R* in Fig. 51 are attenuated. Thus, if the frequency of a machine on its suspension is 5 ~, the forces due to all unbalance frequencies exceeding about 7 ~ are attenuated. For an unbalance force of 50 ~, the vibration amplitude would be reduced to a small fraction of its value when the machine was bolted direct to the foundation.

In practice, the question arises as to the best construction for achieving the desired result. A pliable material like cork board is frequently adopted. To obtain the necessary compliance using cork 1 in. thick, the area must be only a fraction of that of the machine base to be insulated. Consequently, the cork is subjected to high compressive stress. The best practice is to load the cork to a safe maximum within its elastic limit. When the compliance and resistance of cork have been found experimentally for specimens 1 in. thick and 1 sq. in. in cross-section, design is facilitated by means of a table giving the natural frequency under various loads (per sq. in.). For example, a machine mounted on cork 1 in. thick has a natural frequency of 74 ~ when the load is 1 lb. per sq. in., but only 18 ~ when it is 100 lb. per sq. in. Rubber enables a lower frequency to be obtained but, on the whole, it is not so satisfactory as cork.

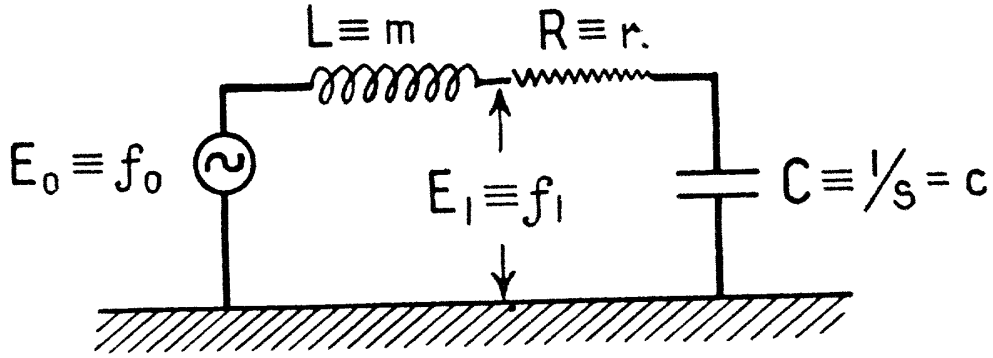

FIG. 52. Electrical analogue of Fig. 50.

One method of applying cork insulation is depicted in Fig. 53. The machine is bolted to a heavy concrete block to increase the mass and reduce the resonance frequency. The block, which is let into the floor, is surrounded by an air space and rests upon a layer of cork. Instead of cork it is feasible to use spring insulators. These have the advantage that the compliance is independent of the load, whereas with materials like cork and felt this does not hold. Also it is necessary to renew pliable materials periodically, since they age, thereby causing ϵ to increase. A representative type of spring insulator is illustrated in Fig. 54. It consists of a base plate on which is mounted an outer conical shaped casing. Within the latter is situated an inverted hollow conical member to which the base of the machine is bolted. The bolt is attached at its lower end to a thick plate pressing on four double helical springs.

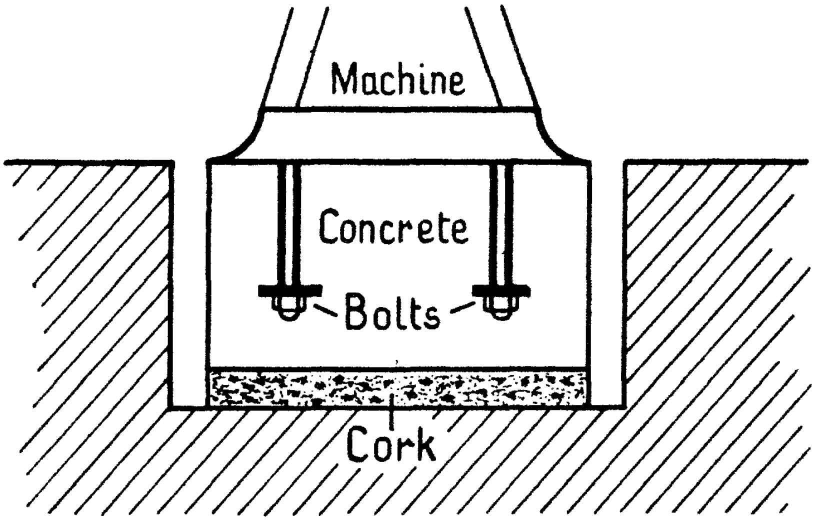

FIG. 53. Illustrating method of insulating machine from its foundation.

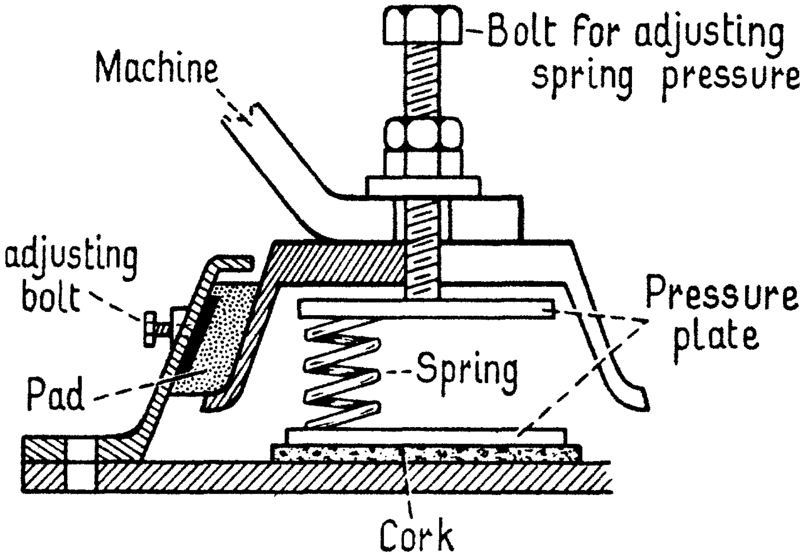

FIG. 54. Illustrating method of insulating machine from its foundation.

Beneath the latter is another plate insulated from the base plate by cork or like material. This precaution is essential since the spring transmits vibration through its coils by wave motion as in the case of a curved bar. The space between the inner and outer conical portions is filled with insulating material, so that these parts cannot come into contact due to a rocking motion. The bolt is screwed into the top of the inner casing, and by rotating it the compression of the spring and, therefore, the natural frequency of the system can be varied. This is useful in practice, since there is often a tendency for the rotating part to rock end for end (pitching as in a ship), owing to the balance not being perfect in all vertical planes from one end of the machine to the other. Under this condition it may be necessary to counteract the rocking effect by varying the compression of the springs at the different points of support beneath the machine. This cannot be done with materials like cork. Pedestal springs can be designed to carry from 50 to 10,000 lb. per spring. A girder type of spring, however, can be adapted to carry much heavier loads than the pedestal type. Springs are useful for machines which operate with sudden loads, e.g. linotypes, lifts, also for printing presses and small reciprocating plant.

If we consider the centre of gravity of the machine, three mutually perpendicular axes can be drawn through it. One of these is vertical and the other two horizontal. Take one of the horizontal axes, say that along the centre of a rotating shaft. The machine can twist around this axis, whilst it can also vibrate parallel to it from side to side. Obviously, these two modes of vibration are common to all three axes, so that there are six possible main modes of vibration. In designing a vibration insulating system, the possibility of the five modes in addition to the vibration vertically must not be overlooked.

IX

NOISE DUE TO ELECTRICAL MACHINES

1. THE noise due to electrical machinery arises mainly from the following causes: structural vibration caused by the varying magnetic force between the rotor and the stator, or between contiguous laminations, air pulsations due to cooling fans or the passage of slots and armature lugs past the stator, and brushes on slip-rings or commutator. Noise due to the latter is caused by (1) brushes riding on the commutator bars, this being a scraping sound; (2) commutator slots passing under the brushes. High or low mica insulation between the bars causes a chattering noise which is unpleasant. Brushes on slip-rings emit a rasping noise, whilst windage (air pulsations as mentioned above) contributes a high-pitched whistle. Transformers give a note of double the supply frequency, owing to vibration of the laminations, since these are attracted to each other during each half-cycle. Thus, on a 50 ∼ supply the fundamental frequency will be 100 ∼, and this is accompanied by overtones of 200, 300 ∼, &c. In general, the noise from a properly designed transformer is not very loud except in the immediate vicinity. Care must be taken to ensure that the outer casing does not vibrate appreciably or the noise may be rather disturbing.

By putting a machine in an acoustically 'dead' room of the type illustrated in Figs. 55, 56 [30], it is possible to measure the sound intensity in dynes per sq. cm. at any relative position. Thus, some notion of the noise level and the sound distribution under this condition can be obtained. Experience gained from noise measurements in power stations and representative places where the machine is likely to be installed, will provide information regarding the probable order of noise level, provided that the sound output in the 'dead' room is known. By aid of 'dead' room tests it is possible to discover which elements in the machine contribute certain frequencies in the noise.

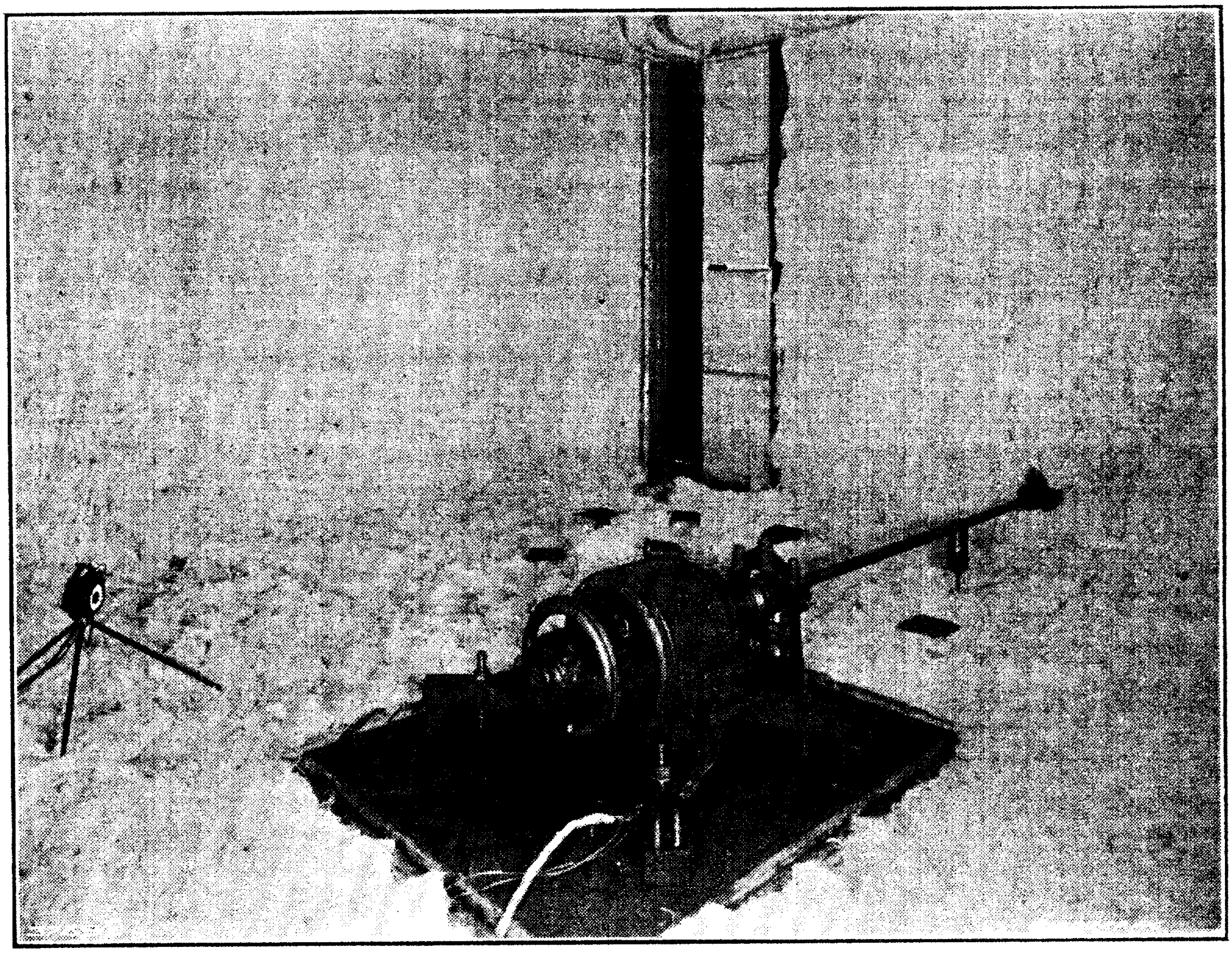

FIG 55. Interior of large acoustically 'dead' room with bolting down slab at centre. (Metropolitan Vickers.)

The reftone level of the noise does not depend upon sound pressure alone, owing to the variation in sensitivity of the ear, as explained in Chapter I. Measurement of overall noise level is conducted by means of apparatus of the type described in Chapter II, where the noise is balanced by a standard tone of 1,000 ∼.

Some examples may be useful in indicating the general trend of results obtained from tests in an acoustically dead room. First of all, take the case of a 10 h.p. induction motor running unloaded and connected to 3-phase, 50 ∼, 420 volt supply mains. The values of sound pressure at different frequencies, measured 100 cm. from the centre of the machine case, are set out in Table 8 [30].

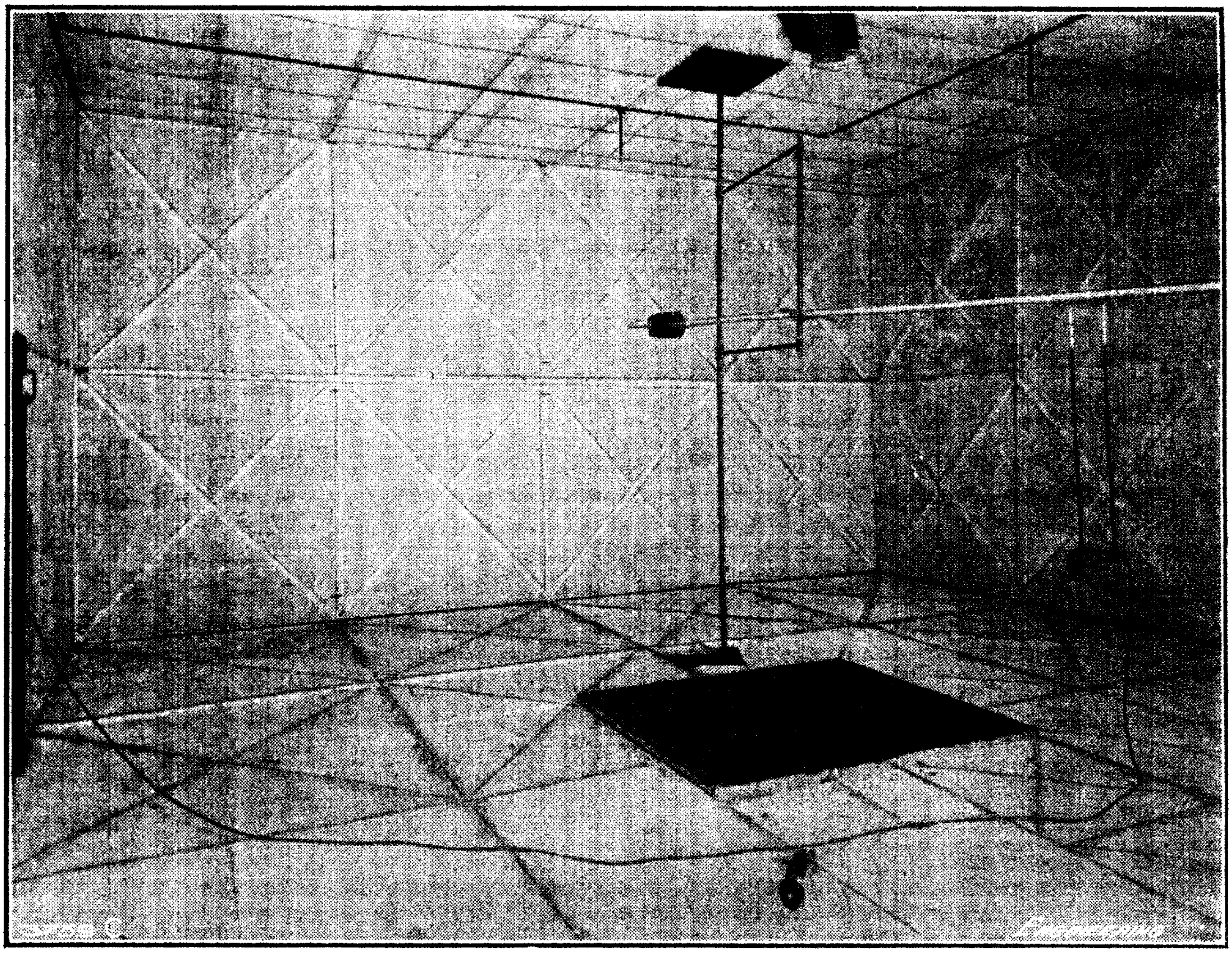

FIG. 56. Interior of small acoustically 'dead' room with motor under test. (Metropolitan Vickers.)

The 100 ~ tone is twice the supply frequency and is, therefore, due to the laminations vibrating as explained above. The sound pressure is small compared with that at 225 ~, and, owing to the low sensitivity of the ear at 100 ~, the noise level would not be high enough to attract attention. Since the other constituent frequencies are associated with the speed of the machine, clues to the sources are obtained on dividing the frequency of the tone by the number of revolutions per second, as shown in Table 9 [30].

TABLE 8. *Sound pressure due to* 10 *h.p. electric motor*

On axis of shaft		*At* 90° *to axis opposite centre of machine*	
Frequency ~	*Sound pressure*	*Frequency* ~	*Sound pressure*
	dynes per sq. cm.		dynes per sq. cm.
100	0·07	225	0·625
225	0·235	360	0·37
310	0·27	524	0·18
394	0·35	590	0·18
590	0·12	675	0·18
1,120	0·12	1,640	0·10
1,230	0·07		
1,640	0·06		

TABLE 9

Revolutions per second = 25.

Frequency of tone *n* [~]	*n/r.p.s.*	*Inference*
225	9	Fundamental tone due to nine-bladed fan
675	27	Third harmonic of fan
1,120	45	Sound due to rotor having 45 slots

After removal of the cooling fan the 225 ~ and 675 ~ components were absent. Some of the remaining components in Table 8 are probably due to the varying magnetic pull of the rotor on the stator, this constituting what is termed magnetic noise due to vibration of the machine, as explained in more detail below. Fig. 57 illustrates the sound wave form obtained from a motor generator set [29]. From the data in Table 8 it is clear that the quality and reftone level of the sound will vary as one walks round the machine. This is due to the manner in which the vibrations associated with the noise occur, and is reminiscent of the focusing effect obtained with loud speaker diaphragms at high frequencies.

In certain types of alternating current machine, e.g. synchronous motors, the rotor has poles which cover a number of stator slots. There are two cases: (1) where the number of slots covered per pole is an integer, (2) a fraction. In case 1 the system is symmetrical and fluctuations occur as the rotor passes the stator teeth. Thus the frequency of vibration is the product of the number of stator slots and the number of revolutions per second. The arrangement in case 2, however, is such that at any instant the pull between the rotor and the stator is greater in some places than it is in others. Thus, in the case of a machine having $6\frac{1}{5}$ stator slots per rotor pole, if the flux passing from one pole to the stator has its maximum value at a given instant, the next pole being 1/5th of the tooth pitch away from the same relative slot position will have slightly less flux, and so on, until a pole is reached where the flux and therefore the pull on the stator is a minimum. Thereafter the flux per pole will increase until maximum flux again occurs at a distance of 5 poles from the start. If the machine has 10 poles, there will be two diametrically opposite positions where the pull between rotor and stator is a maximum and two positions at 90° thereto where it will be a minimum. The stator is slightly deformed and takes an

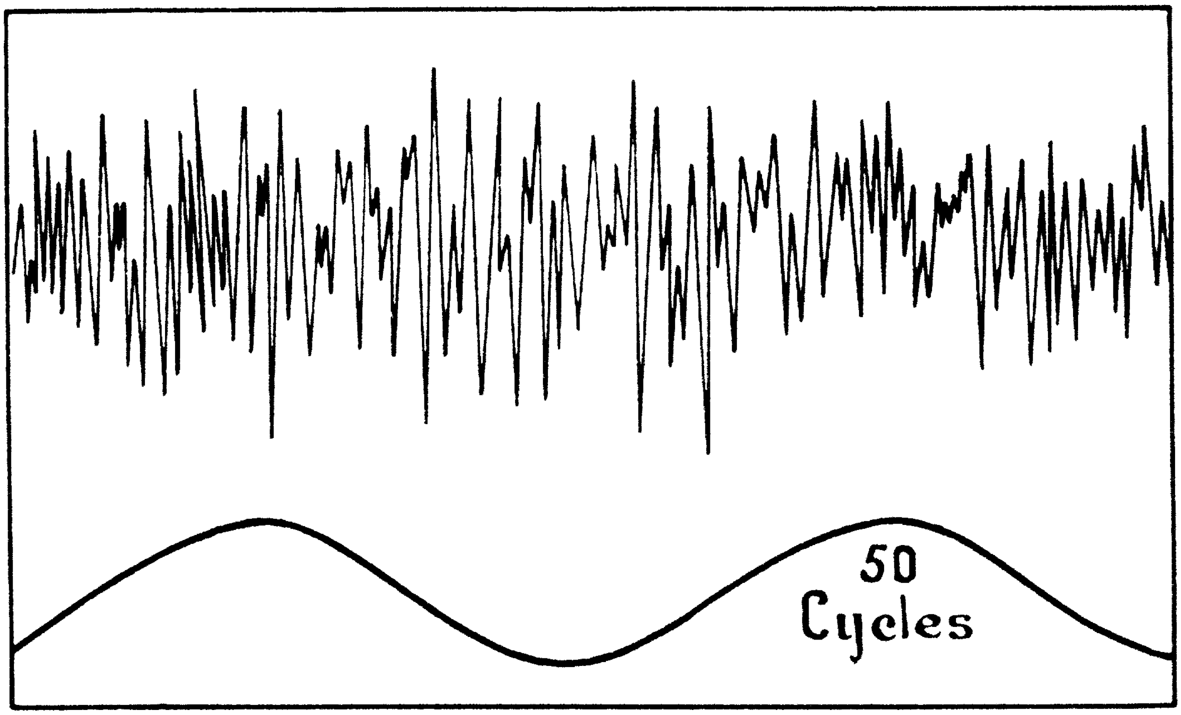

FIG. 57. Sound wave form due to motor generator.

oval form momentarily. But since the positions of the maximal and minimal forces are rotating with the rotor, it follows that any point on the stator is subjected to an alternating force. In fact, there is a rotating wave of stress which causes the stator structure to vibrate accordingly. Thus we have an effect of the same nature as in a *flexural* wave transmitted down a very long iron bar, except that the wave travels round and round the stator instead of progressing onwards. If the frequency of the alternating force coincides with a resonant mode of the stator, the amplitude is relatively very large, although it seldom exceeds 2/1,000ths of an inch. The machine must be designed to avoid this condition which may not only cause an unpleasantly loud noise, but also be responsible for ultimate damage to the carcase.

2. *Radio interference noise.*

The machine noise which we have discussed above is that directly audible due to sound waves. But other disturbances of an electrical character occur which, although inaudible to the naked ear, are transmuted into sound vibrations by a radio receiver. A direct current dynamo does not supply a perfectly steady current. Owing to the peculiarities in construction, ripples and transient oscillations are superimposed upon the steady current. In like manner an alternating current generator does not deliver a pure sine-wave of 50 ∼, for on this are superposed harmonics due to the machine itself, and other disturbances arising in the network to which it supplies power, e.g. mercury arc rectifiers which often introduce considerable disturbance. The ripples have to be smoothed out by chokes and condensers before the mains can be used for operating a radio set, and, as the reader is well aware, the amount of hum can be reduced to a very low level. But there are other sources of disturbance which enter the arena in the form of vacuum cleaners, bacon slicing machines, and, in fact, almost any type of small (or large) electric motor in the immediate neighbourhood. This creates a hum which is frequently accompanied by a considerable amount of spluttering due to sparking at the brushes. The sparking is concomitant with current fluctuations in the mains, but it also gives rise to serious impulsing effects. Short lengths of conductor in the machines themselves and neighbouring pieces of metal are set into electrical oscillation at very high frequencies. Consequently, electrical energy is radiated in all directions and picked up by neighbouring aerials. At the same time it is transmitted down the mains and enters the receiver via the high-tension supply and the aerial, unless means are taken to eliminate it. The customary cure is to connect two equal condensers in series across the mains and to earth the common junction point. Then a path of very low impedance to earth is formed, so that the high-frequency voltage passed on to the receiver is negligible. As a general rule, the disturbance which enters via the aerial is the most difficult to suppress. Sometimes a screened down lead is efficacious, whilst in others the aerial may be moved to a distance and connected to the receiver by screened twin flex. In the latter arrangement it is necessary to have radio frequency transformers between the aerial and receiver to obtain impedance matching, thereby preventing too large a reduction in signal strength. In general, however, the above simple expedient of putting two 2 mfd. condensers in series across the offending machine itself and earthing the mid-point effects a cure. There are many other sources of interference, the majority of which can be reduced to an electrically innocuous state by the use of condensers and inductances. With overhead trams the disturbance is radiated from the overhead lines and is, therefore, widespread, owing to the great extent of the 'aerial'. It can be suppressed by using a choke between the trolley and the controller. High-frequency medical apparatus is virtually a radio transmitter, and this form of interference is very difficult to suppress. Efficient screening of the whole apparatus is beneficial although costly. Magnetos and ignition coils cause considerable disturbance in short-wave sets, owing to the very high frequency oscillations due to impulsing of short lengths of cable connecting the apparatus to the sparking plugs. The interference can be adequately reduced by screening the leads, employing suppressors at the sparking plugs, using a direct screened return to the magneto in place of the cylinders and machine framework, from which energy can be radiated. In general, apart from ordinary mains hum, electrical disturbances ought to be suppressed at the source.

3. *Thermionic valve noise.*

Every listener-in is acquainted with the rushing noise which is audible between items in a broadcasting programme. The noise is due to several causes, some of which we shall treat briefly. We know that the current in a thermionic valve is due to a stream of electrons passing from the heated filament to the anode. This electron flow is not quite uniform, so the number of miniature 'shot' reaching the anode is fluctuating continually. The fluctuation in anode current, known as the 'small shot-effect', is caused by random emission of electrons from the filament. It is revealed by tiny variations in the voltage and current associated with the anode circuit of the valve. The effect of the intermittent current, which is superposed on the steady flow, is to set the circuit oscillating weakly at its natural frequency, in much the same way as the minute irregularities on the surface of a gramophone record impulse the pick-up and introduce the hiss or scratch noise (see Chapter III, § 3). In a multi-stage amplifier the shot-effect due to impulsing of the anode circuit of the first valve is magnified by succeeding stages, and when revealed by a telephone receiver, it assumes the nature of a hissing sound. This resembles what one hears when the hand is cupped over the ear, i.e. a kind of sea-shell effect.

Another noise, which usually masks the shot-effect, is due to the spontaneous motion of the electrons in a conductor. The input to a valve, i.e. the connecting link between the grid and cathode, is in the nature of a conductor. The influence of 'electron disquiet' is to cause a difference of potential at the terminals of the conductor, and it is of a fluctuating character. The higher the resistance between grid and filament of the input valve, the greater the potential difference due to the motion of electrons. The potential difference is independent of the size, shape, and material of the conductor, but depends upon the absolute temperature [62]. This latter arises from the dependence of heat in the conductor upon the collision of atoms, which upsets the electrical equilibrium of the conductor. Thus the electrons move about in an attempt to preserve a stable condition. If the overall voltage magnification of an amplifier exceeds one million, the noise due to thermal agitation of the electrons is usually quite loud enough to be comfortably audible with a loud speaker. This is especially so, if the input resistance between the grid and filament of the first valve is very high, e.g. 0·2 megohm. Such noise invariably sets an upper limit to the useful amplification which can be obtained with thermionic valves. To reduce the noise level as much as possible, the input resistance to the first valve should be low, and the frequency range of the amplifier should not exceed that necessary for the proper transmission of signals.

When a broadcast receiver is switched on and the carrier wave is absent, the noise level due to the receiver itself is usually very low. In many cases, however, it is overridden by mains hum and induction noises from nearby electrical machinery. When the unmodulated carrier wave is present, the noise level rises, and we hear the familiar rushing sound which increases when the microphone is switched in. Apart from the microphone, the rushing noise originates in the high-frequency circuits due to thermal agitation and shot-effects. The carrier wave combines with the minute circuital oscillations, and the heterogeneous beat tones after rectification by the detector are sensed as noise.

There are other sources of noise due to faulty valve design, which can cause a greater reftone level than either thermal agitation or shot-effects. In 1927 when screened-grid valves made their début in this country, some special audio frequency amplifiers were constructed for long-distance telephone work. Using the best valves then available, the pure valve noise, other than shot-effect, was rather loud, but with a cheaper class of valve it almost completely masked the signals. The output from a telephone receiver was characterized not only by a general fusillade, but by sudden bursts of sound resembling that from a battery of howitzers in action.

X

PHYSIOLOGICAL AND PSYCHOLOGICAL EFFECTS OF NOISE

1. *Preliminary remarks.*

THERE is no doubt that on the whole noise is disagreeable to many persons. At times when he or she causes the disturbance, no sense of annoyance is felt, except by other recipients of the acoustical medley. The proud owner of a sports car is immune from its halo of noise, as also is the radio fan from the distraction which accompanies the trumpetings of his loud speaker. The busy office, subjected to the din of city traffic and the clicking of typewriters, probably calls for greater energy expenditure than that required under quiet conditions. The journey home in noisy and crowded tube and railway trains is hardly a fitting finish to the day's toil.

To obtain some idea of the number of persons in a large city to whom noise was objectionable, the Noise Abatement Commission of New York [90] prepared a questionnaire which was printed in all the metropolitan newspapers. A total of over 11,000 complaints was received, this being but a small fraction of the population of several million. The meagre total indicates either that the majority of the citizens were not interested, or that noise did not affect them seriously. This, however, is no criterion of the ultimate effect of noise. From Fig. 58 we see that by far the greater number of complaints were directed against motor trucks and car horns. In London the Hore-Belisha curfew has set the seal of silence between the hours of 11.30 p.m. and 7 a.m. It is illegal for the driver of any vehicle to give audible warning during this period.

The effect of noise is not entirely dependent on its reftone level. In a quiet residential neighbourhood intermittent noises such as hammer blows, the scraping of a spade on

TABULATION OF NOISE COMPLAINTS—March 1, 19[illegible]

SOURCE	NUMBER	PERCENT
Trucks——Motor	1,125	10.16
Automobile Horns	1,087	9.81
Radios——Homes	774	7.00
Elevated Trains	731	6.62
Radios——Street & Stores	593	5.36
Automobile Brakes	583	5.27
Ash & Garbage Collections	572	5.17
Street Cars	570	5.16
Automobile Cut-Outs	504	4.55
Fire Department Sirens and Trucks	455	4.12
Noisy Parties and Entertainments	453	4.10
Milk and Ice Deliveries	451	4.07
Riveting	373	3.37
Subway Turnstiles	317	2.86
Buses	271	2.45
Trucks——Horse Drawn	268	2.41
Locomotive Whistles and Bells	238	2.15
Pneumatic Drills——Excavations	233	2.11
Tug and Steamship Whistles	223	2.01
Pneumatic Drills——Streets	213	1.93
Newsboys and Peddlers	212	1.91
Subway Trains	183	1.65
Dogs and Cats	140	1.26
Traffic Whistles	137	1.24
Factories	117	1.06
Airplanes	113	1.02
Motor Boats	66	0.59
Motorcycles	41	0.37
Restaurant Dishwashing	25	0.22
	11,068	100.00

CLASSIFICATION

SOURCE	NUMBER	PERCENT
TRAFFIC (Trucks, Automobile Horns, Cut-Outs, Brakes, Buses, Traffic Whistles, Motorcycles)	4,016	36.28
TRANSPORTATION (Elevated, Street Cars, Subway)	1,801	16.29
RADIOS (Homes, Streets & Stores)	1,367	12.34
COLLECTIONS & DELIVERIES (Ash, Garbage, Milk, Ice)	1,023	9.25
WHISTLES & BELLS (Fire Dept., Locomotives & Tugs & Steamships)	916	8.28
CONSTRUCTION (Riveting, Pneumatic Drills)	819	7.40
VOCAL, ETC. (Newsboys, Peddlers, Dogs, Cats, Noisy Parties)	805	7.27
OTHERS	321	2.89
	11,068	100.00

FIG 58.

the pavement or the unsilenced exhaust of a builder's mixing machine, are more distracting than the continuous roar of traffic in the city. The sudden slamming of a door, intermittent and noisy gear changes, &c., whilst one's attention is focused upon, shall we say, the penning of these lines, are definitely distracting and difficult to ignore. Although the average reftone level over a time interval of several minutes is much lower than that in the city, the sudden 'peaks' are inimical to continuity of thought and to mental concentration. At the same time, it may be remarked that for a given reftone level, the degree of distraction depends upon the type of acoustical disturbance. The radio announcer is more difficult to ignore than the Queen's Hall orchestra. This is due in part to the intermittent or impulsive nature of speech, but mainly to the fact that one's interest in what is being said is unconsciously aroused.

These preliminary remarks are merely qualitative and indicate the influence of noise in a general way. To provide accurate quantitative results is the business of the scientist, and, in what follows, various experiments conducted with a view to obtaining precise information regarding the influence of noise will be described.

2. *Physiological effects.*

(*a*) *Auditory acuity.* The intensity level of the noise experienced by the average person is seldom high enough to be harmful to the acuity of hearing. It is only in special occupations that there is evidence of noise being detrimental to aural sensitivity. For example, it is possible to be temporarily deaf after a flight, say from London to Australia. The reftone level under flying conditions is from 90 to 120 db. which approaches the threshold of feeling [38] (see Fig. 3). Tube train drivers sometimes experience temporary deafness owing to the high level of the noise. Boilermaker's deafness is quite common in that trade. During operations within the steel boiler shell the workman uses a pneumatic riveter. Now the noise of a riveter used outside the shell is of the order 95 to 105 db. so that within the shell it will be higher due to reinforcement as explained in Chapter IV. Thus the boilermaker works under the influence of a noise level which approaches the threshold of feeling more closely than in the case of the aeroplane. Also, as shown on p. 42, the constituents of the noise are mainly high frequencies. Continued exposure to noise of this character results in middle-ear inflammation and lesions which culminate in permanent deafness.

By using a tone of 1,000 ~ it is found that the intensity level must be of the order 105 db. to cause any marked effect upon the acuity of hearing. Even then the effect passes away quickly, since the threshold of hearing may be raised 20 db. for a few seconds only. To cause an effect of like magnitude at lower frequencies requires a higher intensity level, and at higher frequencies a lower level. This indicates that high-pitched intense noises are more injurious to the ear than those of low pitch, which seems to be exemplified in the case of the boilermaker.

(*b*) *Respiratory and cardiac functions* [71]. The breathing rate of frogs decreases under exposure to pure tones, but increases for an intermittent sound such as that of an alarm clock. The same result is obtained after removal of the brain. With cats, dogs, rabbits, and the like, noises increase the rate of respiration even after removal of the brain. The occurrence of a sudden noise, e.g. a thunderclap, causes a momentary check in the respiratory rate of an individual, after which breathing is more rapid, but deeper and irregular. The unexpected noise of a large squib on Guy Fawkes night raises the blood pressure, whilst music has an opposite effect. The sudden and intermittent noise of a telephone bell causes the pulse to accelerate, as also does listening to music.

(*c*) *Effect upon stomach contractions* [72]. It is a well-established fact that emotional reactions affect the visceral organs. Our emotions are influenced by an unexpected loud noise, as also are these organs. It has been suggested that noise induces visible fear reactions. To test this hypothesis, experiments have been conducted to determine the magnitude and nature of the stomach contractions under the influence of acoustical stimuli. The method chosen was for the subject under test to swallow a thin rubber balloon attached to a tube. The balloon was inflated to a pressure equal to 10 cm. of water, and the tube connected to pressure measuring apparatus. The subject reclined on a couch for 20 minutes to get accustomed to the experimental condition. A record of stomach movements was then taken for 20 minutes of silence. Contraction of the stomach caused an increase in pressure of the air in the balloon, this being registered automatically on a revolving smoked drum. A record made under these conditions is reproduced in Fig. 59, the distance between vertical strokes on the pressure datum line corresponding to one-minute intervals. There is continuous dilatation and contraction of the stomach, but large upheavals occur

FIG. 59. Record of stomach movements under quiet conditions. The marks on the horizontal line at the bottom of the diagram represent minutes.

at intervals of 2½ minutes. The same experiment performed with the subject exposed to noise at a level of 85 db. gave the curve of Fig. 60, showing a marked effect due to the noise. Since the curve is nearer the pressure datum than that in Fig. 59, a reduction in stomach volume due to the noise stimulus is inferred. There is a 37 per cent. decrease in the number of contractions per minute, and they are less violent than those without the noise. Thus the activity of the stomach is curbed by an acoustical stimulus, a result also observed in a cat when a dog enters the room. The next stage of the experiments was to stop the noise and again record the stomach movements. The result is illustrated in Fig. 61 and shows the occurrence of over-compensation in the rate of contraction. A noise level of 65 db. was also tried and found to have a smaller and slightly modified effect. These stomach movements are similar to those caused by what is generally termed fear, and it is thought that they are the result of a fear reaction.

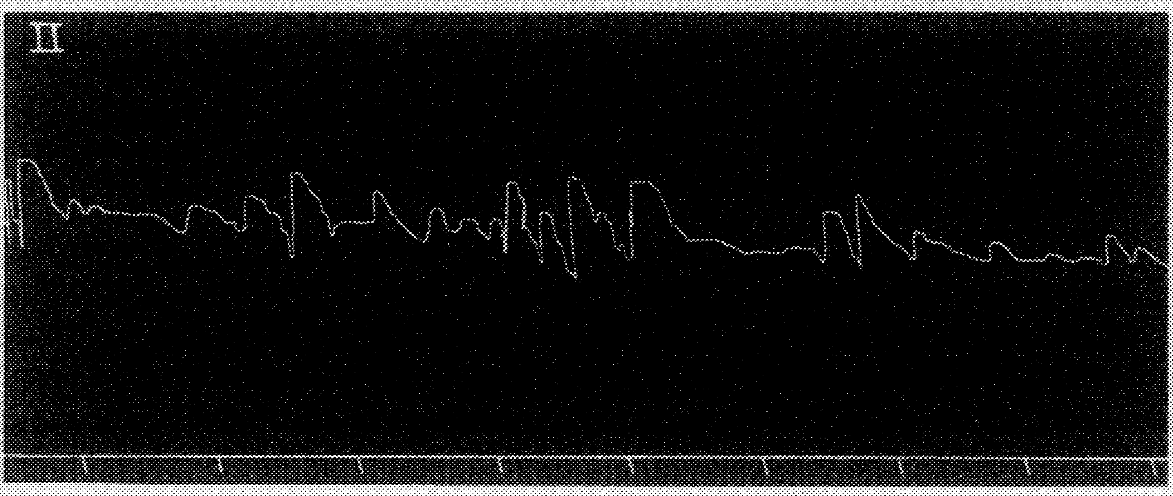

FIG. 60. Stomach movements with reftone level of noise 85 decibels. Note lessened rate and amplitude of contractions. The datum line is nearer the record than in FIG. 60, which indicates a smaller stomach volume, due probably to a slight tonic spasm of the stomach caused by the noise.

It is fair comment to point out that the various experiments described in the preceding paragraphs do not enable any conclusion to be reached respecting the ultimate effect of prolonged exposure to noise. Its influence may resemble *that of a drug which, although appreciable at first, gradually* wears off, so that to obtain the desired effect, the dosage must be increased. There is evidence in subsequent paragraphs supporting this contention, provided certain conditions obtain. Moreover, until additional evidence is forthcoming, the experiments should be regarded as providing information relating to the transient rather than to the prolonged influence of noise.

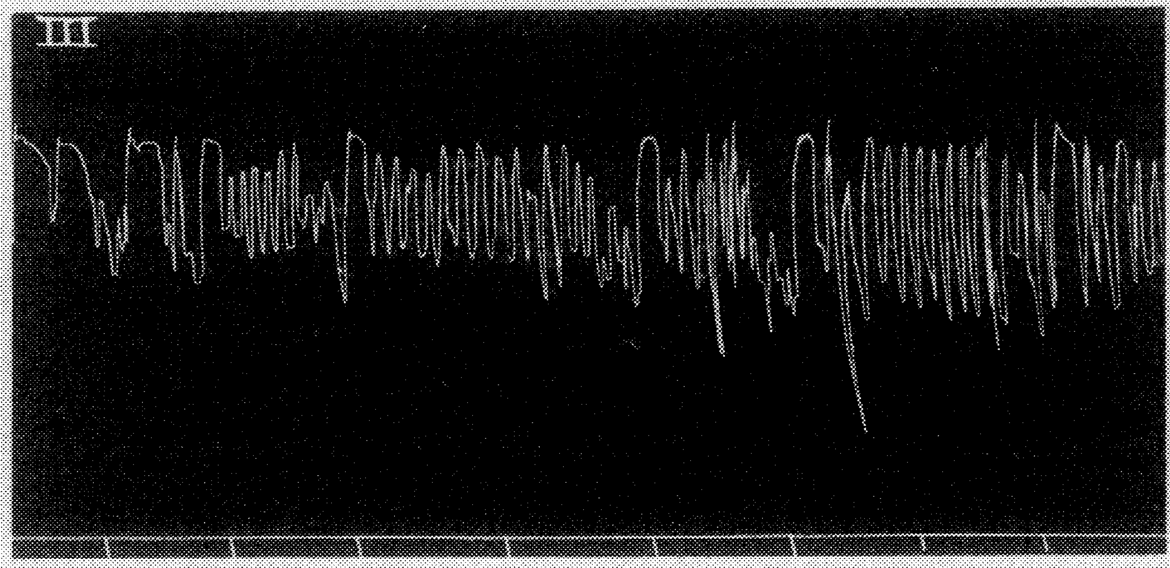

FIG. 61. Stomach movements in the quiet period following the noise. Note over-compensatory quickening and increased amplitude when compared with FIG. 60.

3. *Psychological Effects.*

(*a*) *Motor processes* [71]. The time taken to move a finger, after a signal had been made, was measured with and without the presence of noise from a metronome, a bell, and a tuning-fork, each being used separately. The distraction caused by the noise increased the reaction time, i.e. the time taken to respond to the signal. The bell with its intermittent sound was more distracting than the tuning-fork, so the reaction time was greater in the former case. Reaction time is found to be less during the sounding of minor musical chords than of major chords. If repeated often enough, however, it is probable that the stimuli would cease to produce the above effects.

When the legs are crossed, a tap just below the top of the knee of the free leg causes a sudden upward movement known as the 'knee-jerk'. This must not be confused with rhythmical motion of the leg due to heart pulsations which may alter due to noise. In the 'knee-jerk' the amplitude of the foot depends upon external stimuli. For instance, a swing of 7·4 cm. was obtained in a quiet room, whilst during the playing of Beethoven's 'Funeral March' from the Sonata in A flat, Opus 26, the amplitude increased to 10·5 cm., but with Chopin's 'Raindrop Prelude' in D flat, Opus 28, there was a reduction to 6·8 cm. These results show that the effect of the stimulus depends upon its character. In general, however, we may remark that the frequency of involuntary leg movements increases under exposure to noise. In connexion with these results the reader is referred to our comment in the last sentence of the preceding paragraph.

(*b*) *Mental processes* [100]. A number of undergraduates were set to perform certain tasks under the influence of noise. The tasks varied from simple manual operations to complex work requiring the solution of problems. In each case exposure to noise was accompanied by an initial drop in either the quality or the amount of work done in a given time, or in both of these. This did not happen with every subject tested, but it occurred in the majority of cases. The influence of the noise, which varied in reftone level from 45 to 95 db., was not always statistically significant. The louder the noise the greater its deleterious effect, but intermittent noise caused a greater reduction in performance than a constant noise of the same reftone level (maximum value). Also soft gramophone reproduction, when the subject-matter was of interest, caused more distraction than it did at higher levels owing to the lesser degree of concentration required in the latter case. Although at the commencement of the experiments the noise caused a good deal of annoyance, this phase disappeared quickly in some cases but slowly in others. It was then found that high performance was consistent with annoyance in many cases. Thus most of the subjects tended to accept the noise as part of the condition associated with the test.

(*c*) *Effects in industry* [127]. A series of tests lasting 26 weeks was made upon weavers under industrial conditions. The noise level in a weaving shed is very high indeed, being 100 db. By the use of ear defenders this was reduced to 91 db., which is still on the high side. The results of the tests showed that, on the whole, the output increased about 1 per cent. due to the above reduction in noise level. Even after years spent in a noisy factory, the ear does not completely adapt itself to its environment, but experiences the action of adaptation daily. Fatigue, which commences towards the end of the day, may counteract the effect of adaptation. Obviously a considerable part of this fatigue is not directly due to noise, for it would occur under quiet conditions.

It is only fair to add that the influence of noise on industrial work of a more intricate character and calling for greater mental effort, will undoubtedly be more marked than it was in the case of the weavers.

4. *Increase in energy expenditure due to noise.*

Tests have been made in which the increase in energy expenditure due to noise was measured [68*a*]. Four typists, two of each sex, were the subjects used. After breakfast each subject was taken to a test room and a face mask attached (see Fig. 62). The mask had separate inlet and outlet valves, so that air in the room was inhaled, whilst that exhaled passed through a tube to a container, the content of which was analysed. After resting for half an hour in front of a typewriter, the exhaled air was analysed, and from the analysis the energy expenditure during this period was computed. A special noise machine to simulate the din of a City office was then started, and the subject began typing letters. Electrical apparatus was used to determine the time taken to type a letter and to insert a fresh sheet in the machine. Every 15 minutes, during a two-hour working period, the exhaled air was collected and analysed. The energy expenditure in calories per minute was determined in this way. This routine was continued for a week, the test room being lined with sound absorbent material. The same procedure was observed during the next fortnight, excepting that the absorbent material was

FIG. 62. Testing energy expenditure

The effect of noise on energy expenditure is determined by analysis of the air exhaled under quiet and noisy conditions. The mask, with separate inlet and outlet valves, fits over the mouth and nose. The air of the room is inhaled, and the exhaled air, having passed through a short tube, can be collected and analysed. An operator quickly becomes accustomed to the mask; for nine months each of three subjects slept with a similar mask strapped to his face. Of special interest are—the wall of Acousti-celotex in the background; the calculograph for recording time; and the electrical connexions to the noiseless typewriter for measuring output. The typist maintained a speed of 150 words per minute removed. The following week, test conditions were identical with those during the first week.

The average increase in energy expenditure to perform the typing, over and above that during the rest period, was 52 per cent. with the sound absorbent in place, but 71 per cent. without it. That is to say, the noisier condition necessitated an additional energy expenditure of 19 per cent. Thus the extra expenditure to perform the typing alone is nearly 38 per cent. greater for noisy than for relatively quiet conditions. On the average the speed of typing was not affected much by the noise, but a super-typist was retarded 7·4 per cent.

5. *Summary.*

It appears from the experiments described in this chapter that the effect of noise on normal healthy persons is not quite so serious as we have been led to believe. In general, when a break-down in health occurs under exposure to noise, there are other influences at work. The noise seems to act as a catalytic agent or accessory factor, thereby inducing or accentuating a nervous state. Undoubtedly, in the absence of noise, the nation's nerves would be much improved. But the point to be emphasized is that if the other influences were removed, normal noise *per se* during working hours would not induce a highly nervous condition. In other words, given a nation of A 1 people free from the 'slings and arrows of outrageous fortune', the effect of noise in moderation during daily tasks would not produce a multitude of nervous and mental wrecks. It is essential that the slumbers of the nation shall be peaceful to maintain a healthy condition. In any country, however, one cannot cater for A 1 people only, so the effect of noise must be regarded seriously. Although on the whole it may reduce individual performance by a small percentage, in the aggregate, when all the losses throughout the population are considered, the sum total is not inconsiderable.

The physiological and psychological effects of noise can be epitomized as follows:

1. Hearing is apt to be permanently impaired in those who are constantly exposed to a noise level exceeding 95 to 100 db., particularly if the main constituents of the noise are high pitched. Below this level injurious effects are of a more transient nature.
2. Noise reduces the performance of the worker. It is distracting and makes concentration upon any task more difficult. The degree of distraction depends upon the nature of the task, e.g. mental work is affected much more than physical labour.
3. Acting in conjunction with other and more fundamental physiological influences, noise may induce and accentuate nervous disorders.
4. Noise interferes with proper sleep, even though in some cases the nervous system adjusts itself so that wakefulness does not occur. In this way excessive or intermittent noise is responsible for a large amount of unnecessary fatigue.

TABLES GIVING VARIOUS NOISE LEVELS

TABLE 10. *Very Loud Noises*

Source	*Observer's position*	*Reftone level*	
		db.	
Aeroplane . .	10 ft. from airscrew	120 to 130	[38]
,, . .	in cabin	90 to 110	[39]
Riveting machine .	35 ft. away	102	
Pneumatic drill . .	10 ,,	90 to 100	
Ship's siren . .	115 ,,	98	[90]
Niagara Falls . .	noisiest location	90	[90]

TABLE 11. *British Road Transport Noises* [63]

Source	*Observer's position*	*Reftone level*
		db.
Tram . . .	in street	see Table 16
Motor bus . .	inside	64 to 74
Quiet motor-car .	in street	64
Saloon car (average) 40 m.p.h.	inside	75
Motor horn . .	20 ft. away	94 to 102

TABLE 12. *American Road Transport Noises* [90]

Source	*Observer's position*	*Reftone level*
		db.
Street car, New York .	10 to 15 ft. away	75 to 80
,, ,,	inside car	75
Motor lorry, New York	15 to 50 ft. away	75
Motor-car (average) .	,, ,,	70
Horse vehicle on paved street . . .	,, ,,	80
Horse vehicle on asphalt	,, ,,	65
Motor horn . .	23 ft. away	95
Police whistle . .	15 ,,	85

TABLE 13. *British Train Noises* [63]

Source	*Observer's position*	*Reftone level*
		db.
Railway train, 60 m.p.h.	in corridor, windows open	84
,, ,, ,,	in carriage, windows open	74
,, ,, ,,	in carriage, windows shut	69
,, ,, ,,	sleeping compartment	64
Tube train, London .	in train	See Table 6, p. 89.

TABLE 14. *American Train Noises* [90]

Source	*Observer's position*	*Reftone level*
		db.
Railway train (Limited)	in Pullman car	65
Subway (New York)	in train (express)	100
,, ,, ,,	in train (local)	95
Elevated Railway, N.Y.	15 to 20 ft. away	95
,, ,, ,,	in train	80

TABLE 15. *Traffic Noise Measurements in London* [124]
Microphone suspended above pavement

Location	*Average reftone level*	*Peak reftone level*
	db.	db.
In front of St. Paul's Cathedral . .	74	77
Lombard St.	74	80
Mansion House	73	78
Victoria St.	73	77
Trafalgar Square	72	. .
Adelphi	62	66
Fleet St. (Law Courts)	62	70
Temple Gardens	53	67
Regents Park (quiet period) . .	52	. .

TABLE 16. *Specific Street Noises in London* [124]

Location	*Reftone level*
	db.
Tram entering Kingsway tunnel .	90
Pointsman's whistle	100
Tram at 30 m.p.h. 6 ft. from meter .	91

TABLE 17. *Miscellaneous Noises* [63, 90]

Source	*Observer's position*	*Reftone level*
		db.
Whispering. . . .	5 ft.	24 to 40
Normal conversation . .		50 to 65
Church bells . . .	1,200 ft. away	65
Thunder	1 to 3 miles away	70
Dog barking in street . .	20 ft. away	70
London restaurant . .	within	54 to 84
Typists' office . . .	within	75
Lion roaring in N.Y. Zoo .	18 ft. away	90
Loud applause in N.Y. street	in crowd	95

TABLE 18. *Permissible Noise Levels in Buildings*

Type of building	*Permissible noise level*
	db.
Broadcasting and film studios	11 to 15
Hospitals	13 to 17
Music studios . . .	15 to 20
Homes	15 to 25
Theatres, cinemas, libraries, lecture rooms . . .	17 to 29
Public offices, banks . .	30 to 45

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