PRACTICAL ASPECTS OF NOISE

BY

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FOREWORD

BY

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Machinery noise in naval vessels is an increasing problem and the subject has several aspects, each requiring different consideration. The main subdivisions of the problem are :—

(i) Underwater noise

(ii) Airborne noise.

The first is the most important operationally and has been well described (*Journal:* Vol. 8 ; No. 4, Oct., 1955) by Lieutenant-Commander J. M. B. Dathan, R.N. The second has become a serious problem partly because of its contribution in certain vessels to the underwater radiated noise but, more generally, because of its effects on communications, visual or telephonic, in machinery departments and on aircraft carrier bridges and flag-decks, and its fatiguing effect on machinery-space watchkeepers.

This article deals ably with the subjective aspect of airborne noise and gives a good grounding in the principles of airborne noise measurement. This should be helpful to engineering specialist officers in the Fleet who may have dealings with some of the noise measuring teams who nowadays often descend on ships during trials.

Finally, attention is directed to the short section dealing with acoustic enclosures because it is important that engineering specialists should know what can and what cannot be achieved by acoustic hoods.

Meanwhile the following extract from Richardson's *Technical Aspects of Sound* may help readers to appreciate the nature of the problem :—

'An excellent absorbing material absorbs, say, 90 per cent. It is often argued by laymen that such materials should be very effective for sound-insulation purposes, i.e. for the prevention of sound transmission from one room to another, since " practically all " sound energy disappears. This reasoning is almost completely wrong. If the remaining ten per cent should be transmitted entirely, the transmission loss would be only ten decibels (db), a rather poor result indeed. A wall having a good transmission loss of, say, 50 or 60 decibels only transmits 10^{-5} or 10^{-6} of the incident energy and the absorption coefficient should be as high as 99·99(9) per cent, if the absorption is to be the only reason of the transmission loss. This being practically impossible, it is clear that absorbing layers alone are almost useless for insulating purposes.

' Most practical constructions with a high transmission loss ($/t/^2$ very small) are almost completely reflecting ($/r/^2 \approx /$) so one might say that a low transmission is obtained by greatly increasing the reflection, whereas reflection is reduced as a rule by increasing the absorption.'

Introduction

The purpose of this paper is to explain in simple engineering terms some of the esoteric jargon of the acoustical engineer, some of the practical difficulties met in measuring engine noise, and to present to the ordinary Diesel user engine-noise problems in better perspective.

Engines have always made noises and the gentle rhythmical sound made by engines some thirty years ago was pleasant music to the engineer and told him a great deal about how the engine was performing. There have been, however, marked changes in materials and design over this period. Metals of superior ultimate and fatigue strengths have been developed and are employed in a much more efficient manner to produce the high-speed, light-weight engine of today. With this steady increase of power from less bulk of engine the noise intensity has increased until it is now realized that the noise level attained has, in some instances, become unacceptable.

The Nature of Sound or Noise

Sound is defined by the B.S.I. in its *Glossary of Acoustical Terms and Definitions* as a mechanical disturbance or radiation, in an elastic medium, of such a character as to be capable of exciting the sensation of hearing. Noise, on the other hand, is defined as sound which is undesired by the recipient. Both these definitions introduce the two characteristics of sound :—

(*a*) The physical nature of mechanical waves capable of being measured in absolute units

(*b*) The subjective nature denoted by the reaction of the hearer.

Here, then, is the first difficulty confronting the acoustical engineer ; the intensity of the wave propagation can be measured in clearly defined units but the noise is much less definite, being a matter of individual opinion. Further, that opinion is not invariant, for a noise heard under certain conditions may be acceptable but heard by the same individual under other conditions, it becomes quite unacceptable.

Sound is produced by longitudinal waves in any medium having mass and elasticity, the velocity of propagation being given by :—

$$C = \sqrt{\frac{E}{\rho}} \text{ for solids}$$

$$C = \sqrt{\frac{\gamma P}{\rho}} \text{ for gases}$$

where C is the velocity of propagation, E is the elasticity of the solid, ρ is the density of the medium, γ is the ratio of specific heats of the gas, P is the pressure of the gas. For propagation in air taking $\gamma = 1{\cdot}4$ the equation may be reduced to $C = 66\sqrt{T}$, where T is the absolute temperature in degrees centigrade, from which we obtain the velocity of sound in air at 15 degrees C. as 1,120 ft per sec. The pitch of a sound is determined subjectively as its position in the musical scale or its frequency in cycles per second (c.p.s. or c/s) and it follows from this that the wavelength of a progressive wave, the distance between successive points of maximum pressure, is the quotient of velocity of propagation and frequency. TABLE I gives the velocity and wave-length of sound of a few of the more common materials at 15 degrees C.

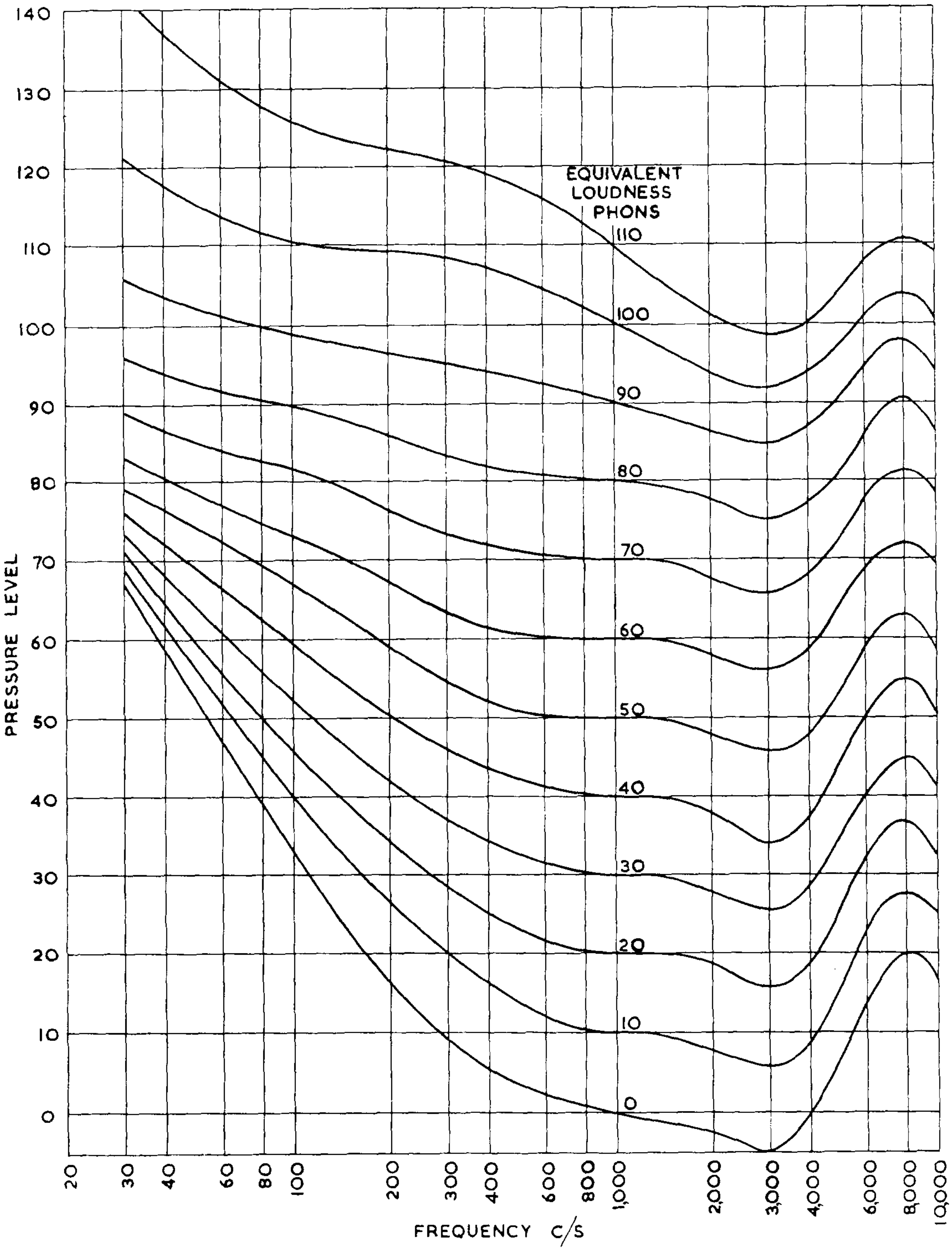


Fig. 1—Equal Loudness Relations for Pure Tones, determined under Field conditions, for various Intensity Levels at 1,000 C/S, i.e. Phons

TABLE 1

Medium	*Sound Velocity ft/sec*	*Wave Length (ft)*		
		25 *c/s*	500 *c/s*	10,000 *c/s*
Air	1,120	44·8	2·24	0·112
Water	4,850	194	9·70	0·485
Copper	11,800	472	23·60	1·180
Aluminium	16,900	676	33·80	1·690
Steel	16,750	670	33·50	1·675
Rubber (hard)	4,750	190	9·50	0·475
Rubber (soft)	230	9·2	0·46	0·023

Definitions

The intensity of a sound is expressed in terms of the oscillatory pressure in the wave, namely the root mean square value (R.M.S.), although other characteristics of the wave could be used. The pressure range between the threshold of audibility and the loudest noise is dependent upon pitch and exceeds $10^6 : 1$ at some frequencies. For convenience, therefore, a logarithmic scale called the ‘ decibel scale ’, devised originally for telephonic work, has been adopted. This is a ratio scale and expresses the sound pressure as a ratio to an arbitrary reference pressure. Using this scale the difference of two sounds of pressure P_1 and P_2 is:—

$$20 \log_{10} \frac{P_1}{P_2} \text{ decibels (db)}$$

The internationally agreed reference pressure is 0·0002 dynes/sq cm. R.M.S. and comparisons made to this reference level are referred to as sound pressure levels ; this is the same as intensity level in free field conditions. It will be seen from this that a pressure range of 10^6 to 1 will be represented by 120 db. This is the physical scale of sound but the db level does not necessarily represent the loudness of the sound as heard by a normal observer. Loudness is something very different ; sounds having the same energy or intensity do not have the same loudness if their frequencies differ. A subjective unit of loudness level has therefore been introduced called the ‘ phon ’, which is defined by the B.S.I. as being numerically equal to the sound pressure level of a standard tone of plane sinusoidal form coming from directly in front of an observer and having a frequency of 1,000 c.p.s. The listening should be done with both ears, the sound under measurement and the standard tone being heard alternately, and the tone being adjusted by the observer until it is judged to be as loud as the sound under measurement. A number of workers have produced curves showing the relationship between the loudness level of pure tones under free field conditions for a range of intensity levels at 1,000 c.p.s., i.e. phons. The best known are those made in America by Fletcher and Munson (adopted as an American Standard) and in this country by Churcher and King ; the latter curves are thought to be the more accurate and are shown in FIG. 1. These curves are very useful for comparing the importance of individual components of a complex noise but they are not a loudness scale ; for if a noise is reduced in loudness from, say, 100 phons to 95 phons it will not sound like 5 per cent but more like 30 per cent reduction of intensity. One further set of units is therefore required, these are called ‘ sones ’, to enable the loudness levels to be summed. The relation between phons and sones is shown in FIG. 2. Here it is seen that the relationship is approximately logarithmic, the greatest deviation occurring below a level of 70 phons. This curve, like that of FIG. 1, is a statistical average of a number of normal observers in a free field.

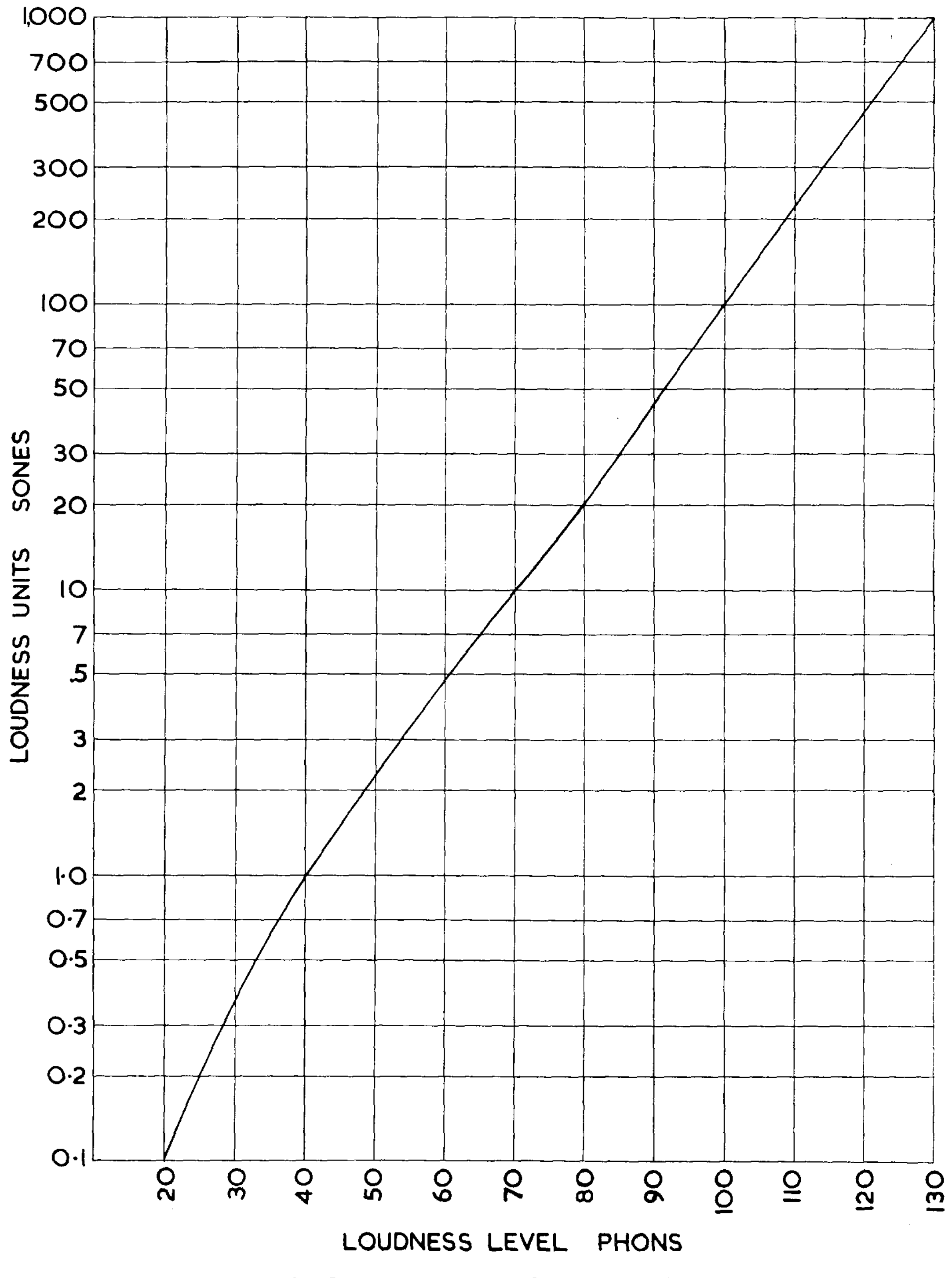


Fig. 2—Relation between Phons and Sones

The term 'free field' has been used when defining phons and sones, and presents the acoustical engineer with another difficulty. It is assumed that the sound waves generated are able to travel outwards from the source in an infinite isotropic medium, i.e. there will be no surfaces to distort the waves or cause reflections, no internal movement of the medium other than that caused by the wave, and no variations of density due to either pressure or temperature. These conditions can only be achieved in specially constructed test cells in which acoustical absorption has been provided on all the internal surfaces, otherwise the sound field set up is of a very complex nature.

Propagation of Sound

Before going deeper into the complex nature of the sound field observed under normal conditions, consider for a moment the manner of propagation of a sound wave under some simple conditions. First, assume a point source in a free field ; the waves will move outwards like the waves on the surface of a pond when disturbed by a falling stone ; instead of circles, however, the waves will be represented by the surfaces of spheres and this is called spherical propagation. The energy or intensity of the wave as it travels outwards will be distributed over a larger and larger area increasing as the square of the distance from the centre and the intensity measured will be inversely proportional to the square of the distance from the source. Secondly, assume a line source perpendicular to two flat parallel planes. Here the waves will travel outwards on the surfaces of cylinders the intensity this time being inversely proportional to the distance from the source and this is called cylindrical propagation. Lastly, consider a wave travelling along an enclosure of uniform section ; here the area of the wave remains unchanged and the intensity, within the limits of our assumptions, remains constant ; these are called plane waves.

Now consider the sound source in an enclosure ; the waves strike the boundary surfaces and are in part reflected and will continue to be reflected until the energy of the wave is absorbed in some way. In practice, absorption takes place at the boundaries and in the air itself by viscosity effect.

Consider now the noise caused by an engine in a normal test cell or shop ; we have all three forms of wave propagation when near to the engine and a build-up of sound pressure due to multiple reflection.

Under certain circumstances the wave-lengths of some frequencies are such that at specific points in the enclosure the pressure of the initial and reflected waves sum or cancel to cause high or low noise pressure areas. This is referred to as a standing wave, and a whole series of these may be present, each associated with a particular frequency and dimension of the room.

When measuring the noise of an engine it is therefore desirable to be some distance away from the nearest surface, approximately the longest dimension of the engine, and not at the trough or peak of a standing wave. If a closer approach is made the noise of one part of the engine will play an unduly larger part than it should. From this it will be seen that the noise energy measured near an engine, under normal practical shop conditions, is a function not only of the machine but also of the enclosure and the position of the measuring point.

The Character of Noises

To the research worker, therefore, the answer to the question ‘ how much noise does an engine make ?’ becomes a complex quantity stated in terms not only of pressure levels but also of conditions of measurement. Correlation between readings taken of one engine in a building with that in another building can, however, be made if, in addition to the engine noise, the acoustic characteristics of each building are also measured. In cases where it has not been practicable to measure the sound levels at a reasonable distance from the engine, it has been the practice of some investigators to measure a number of points around and above the engine and then to quote a mean reading.

The overall or total noise level so far discussed, whether quoted in phons or decibels, does not completely characterize the noise for, as stated earlier, the scales have been related to pure tones (sinusoidal waves) or mixtures of pure tones as a continuous wave train. Many noises are, however, of an impulsive

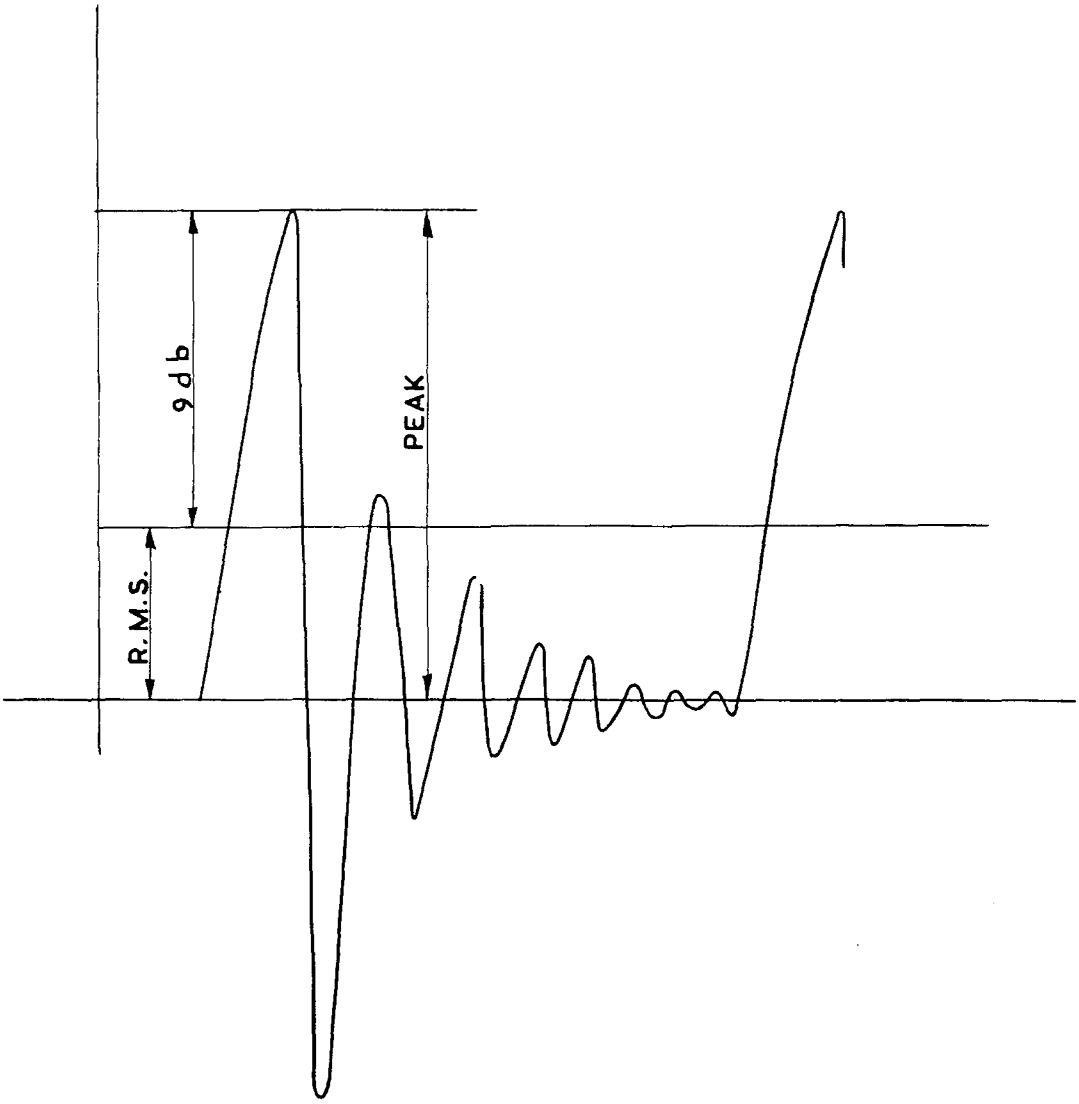


FIG. 3

nature rapidly repeated and, as readily seen from FIG. 3 which illustrates such a wave form, the R.M.S. value is small but the peak value of the wave is high so that, in addition to the R.M.S. readings, a peak reading is also taken.

It has been suggested that the degree of annoyance is associated with the peak intensity and endeavours have been made to relate the peak/R.M.S. ratio to an annoyance rating. Other factors come into such ratings and the results have not proved very useful. It is unfortunate that, apart from the complexity of the sound field occurring under normal test shop or engine room conditions, there is no simple way of measuring the subjective noise level, and in many cases this is the information that the engineer requires to know.

The conditions of test as laid down by the B.S.I. for determining the sound level in phons were not intended for engine noise measurements, for it is obvious that the noise of an engine cannot be shut off and an equivalent tone of 1,000 c.p.s. substituted for comparison as required by the definition. This does not mean that attempts to make subjective noise level meters have not been made, but it is generally agreed that they have limitations depending upon the type of noise for which they are used ; they require experienced operators and perferably a group of operators, to obtain an average value. It may well be asked ‘ Why bother with instrumental measurement and such complicated units when anyone can tell if a noise is loud or soft, annoying or tolerable ? ’ The answer is, of course, that no two persons hear alike and that, while the ear is very sensitive and discriminating in detecting sounds, it cannot translate these sensations into a quantitative form. The engineer describes most of his other quantities in terms of some measurement based on an accepted standard rather than upon a basis of the opinion of individuals and this is particularly important when attempting to fix limits for the sound level an engine or other piece of machinery is allowed to emit. However unbiased an observer may be, his own engine will be quieter than the engines of others and, further, no operator, however experienced, can remember loudness levels over a period of time.

Sound Measurement

To overcome some of the difficulties encountered in measuring phons directly, means of computing loudness levels have been devised by various investigators ; Churcher, King and others in this country and a somewhat similar method has recently been published by Mintz and Tyzzer in America based on earlier work of Beranek and others. All these methods are based on objective measurements, which are interpolated by curves similar to those of FIGS. 1 and 2. These methods call not for the overall magnitude of the noise but for the levels in finite frequency bands or of discrete frequencies. For this purpose filters are inserted into the measuring instrument or the signal is fed into a wave analyser. An analysis of a simple noise could be made from an oscillographic record but the more complex noises of non-harmonic form can be analysed practically only by electrical means which do not depend upon harmonic relationships of the components. Filters are usually of the octave type, that is, they permit a limited range of the noise spectrum to pass such that the upper frequency is twice the lower frequency. TABLE II shows the frequency bands usually employed.

TABLE II

	(a) Range I		*(b) Range II*	
Filter No.	*Frequency Band*	*c/s*	*Frequency Band*	*c/s*
1	37·5	75	50	100
2	75	150	100	200
3	150	300	200	400
4	300	600	400	800
5	600	1,200	800	1,600
6	1,200	2,400	1,600	3,200
7	2,400	4,800	3,200	6,400
8	4,800	9,600	6,400	12,800

The wave analyser most commonly used selects a narrow band proportional to the tuned frequency and the energy in that band is measured ; for example, a band width of ± 1 per cent may be used then, when the instrument is tuned to 100 c.p.s., the band width will be 2 cycles ; at 1,000 c.p.s. the band width is 20 cycles and at 10,000 c.p.s. 200 cycles ; this is known as constant selectivity. The degree of selectivity that can be employed will depend upon the unsteadiness of the noise source. Alternatively, a crystal gate of constant band width may be employed but these are unselective at low frequencies and very selective at high frequencies and hence are practically impossible to use on a fluctuating engine noise at the higher frequencies.

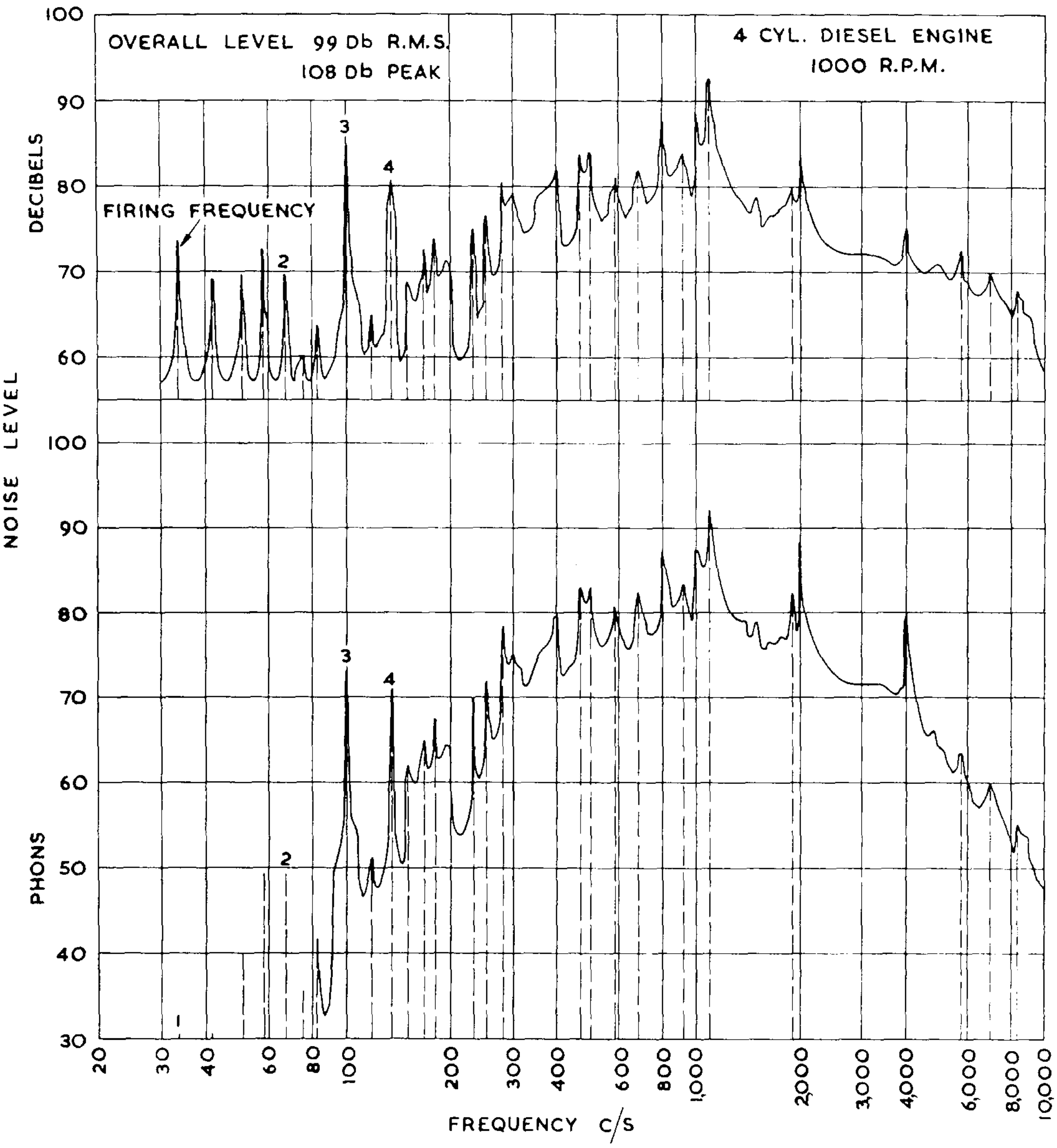


Fig. 4—Comparative Narrow Band Spectra

TABLE III

Type of Noise	*Noise Level in Phons*
Threshold of pain	130
Boiler shop	110—115
Pneumatic drill Engine room of a Diesel ship	105
Underground train	98
Dense traffic	90
Machine shop	87
Typing office	85
Moderate traffic	80
Average office	70
Ordinary conversation	65
Quiet office	62
Quiet street	45
Quiet house	25
Rustle of leaves	15
Threshold of hearing	0

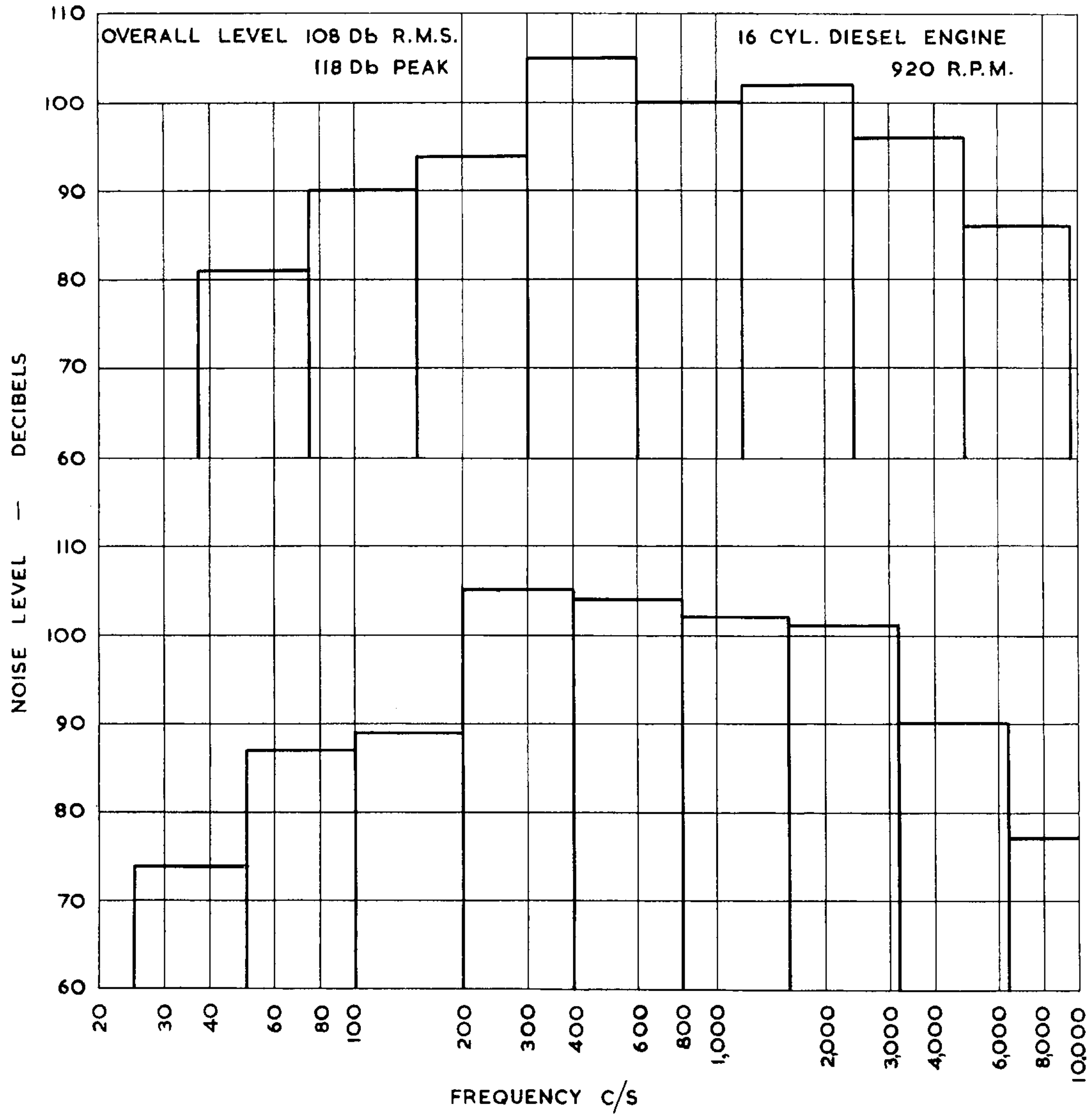
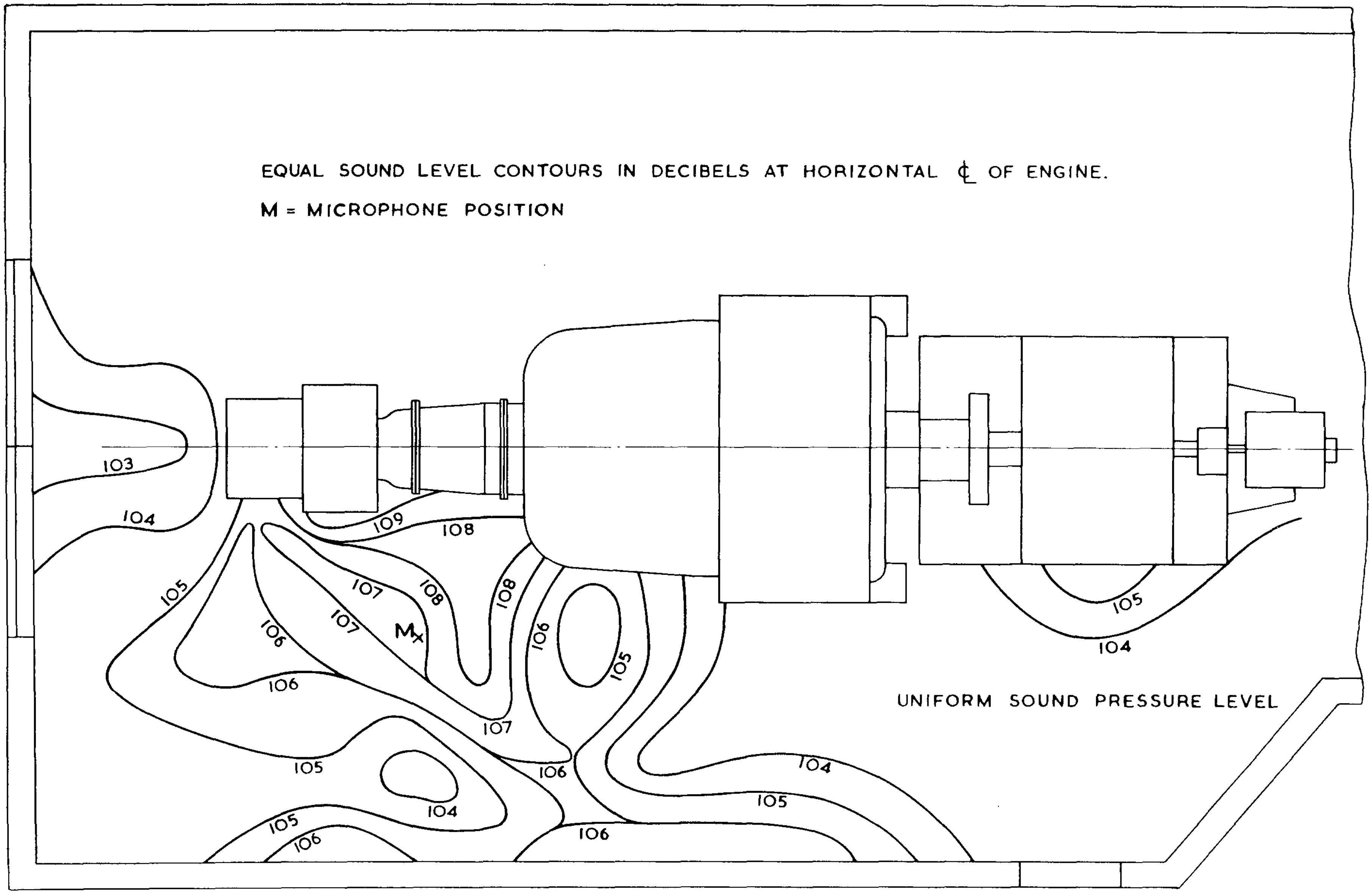


FIG. 5—OCTAVE FILTER DIAGRAM

In making noise measurements it is necessary to ensure that the background noise level is well below that of the noise to be measured ; the minimum difference in levels that can be tolerated depending upon the character of the noise to be measured and that of the background, 20 decibels difference being the usual desired minimum. Examples of the noise levels ordinarily met with are given in TABLE III. These are average values and wide variations can occur.

So far, the noise meter itself has not been discussed, not because it is a simple, well known and well tried piece of equipment for this is by no means the case. Noise measurements outside a laboratory were practically impossible until the invention of the thermionic valve, and during the last two decades great strides have been made in the electronic field. However, there still remains a wide gap between developments of commercial noise meters and what can be achieved with laboratory built units ; but the technical difficulties encountered in producing instruments are not appropriate to this paper.

Sufficient has been said to illustrate the practical difficulties of measuring and classifying noise in such a way as to enable an engine buyer to specify the limits of noise an engine may emit, or a manufacturer to state how little noise his engines make.


EQUAL SOUND LEVEL CONTOURS IN DECIBELS AT HORIZONTAL ℄ OF ENGINE.
M = MICROPHONE POSITION
UNIFORM SOUND PRESSURE LEVEL
M
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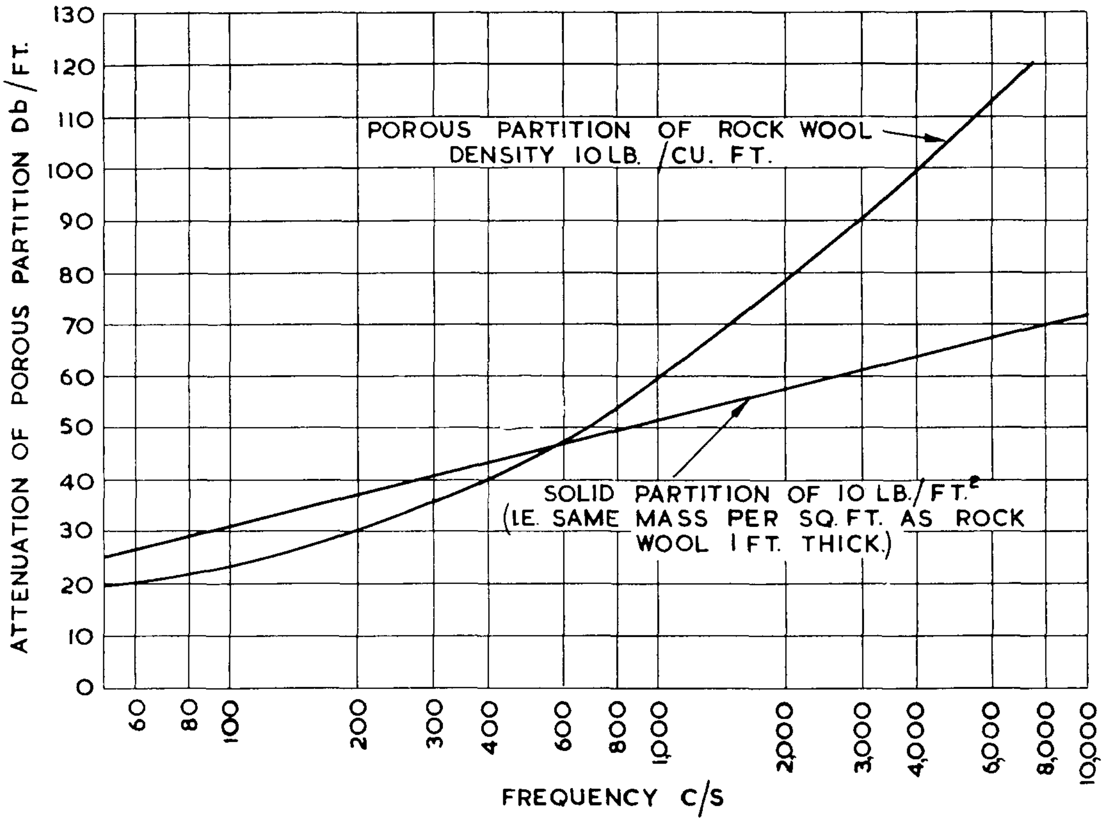

Fig. 7—Curves showing the Relative Sound Attenuation of Rock Wool and Solid Materials used as Partitions

Engine Noises

Fig. 4 shows two narrow band spectra obtained from a 4-cylinder Diesel engine running at 1,000 r.p.m. The upper curve gives the level of discrete components in decibels and the lower curve the same spectra modified by the equal loudness level curves of Fig. 1. It will be seen that the lower frequencies have become less important, particularly the firing frequency, while components at 2,000 and 4,000 c.p.s. become more prominent. These higher components can readily be detected when a recording of this engine noise is played. It is interesting to note that the loud tone at 1,100 c.p.s. was found to be due to a ringing of the rocker gear and the 4,000 c.p.s. note emanated from a hole in the flywheel case in which the clearance between the wheel and case was quite small.

Fig. 5. shows an octave filter analysis of a high duty 16-cylinder ‘ V’ Diesel engine running at 960 r.p.m. with a mechanically driven supercharger. The noise recorded here did not include induction or exhaust noise but, nevertheless, the major components are those associated with the mechanical blower ; these are readily seen.

Fig. 6 shows a typical sound field taken in a test cell ; lines of constant level have been drawn and illustrate the complex nature of the field. It is interesting to note that when this engine was installed in a large test house the sound pressure level decreased as the distance from the engine increased, similar to what would be expected under free field conditions when the level recorded at point M was 98 db while in the test cell, at the same distance from the engine, the noise level was 107 db.

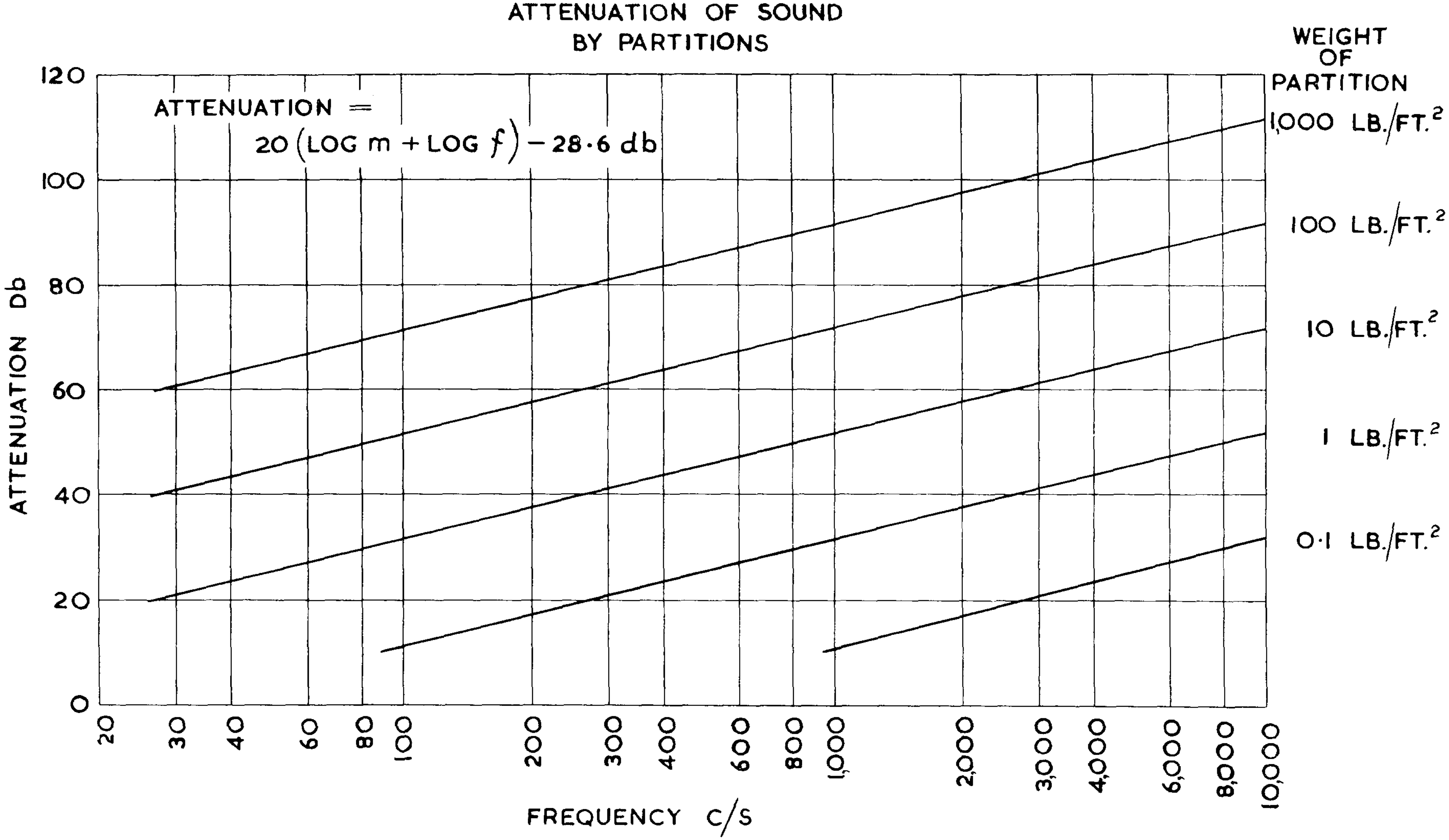

Fig. 8—Curves showing the Attenuation of Sound by Solid Partitions for various Surface Loadings

Noise Reduction

As will be seen from the spectrum shown in FIG. 4, the noise made by an engine is very complex. Many of the discrete frequencies recorded can be associated in some ways with parts of the engine ; for example, the firing frequency and the first four harmonics are shown. Higher harmonics undoubtedly exist, but it is difficult to ensure the exact relationship in this way when slight changes of engine speed occur. Such harmonic components, however, comprise only part of the noise, the remainder being inharmonic frequencies. It is interesting to note that it is the higher frequency components and higher harmonics that contain most of the noise energy. All the discrete components of the noise are generated by the vibration of surfaces and, at these higher frequencies, quite high noise levels are caused by vibrating surfaces whose amplitudes are very small.

The problem of reducing engine noise resolves itself into stopping the vibration of the engine. Before this can be done it is necessary to know the origin of the forces causing the movement and the manner in which these forces are transmitted throughout the structure. In stating the case in this form it is assumed that other aerodynamic noises due to the induction and exhaust have been adequately silenced. Very little research work has yet been done in this field, largely because the realization of the noise problem is of recent date, the whole art or science of noise in terms of the other sciences is young, and a vast field of enquiry would need to be covered before generalization of the results could be put into practice.

Acoustic Enclosures

Where items of machinery create excessive noise other methods than reduction of noise at source can be employed. If the item is small an acoustic hood may be fitted to enclose it completely. For larger sets of machinery requiring ready access, the building in which they are situated may be specially constructed to ensure that the noise is not transmitted to other parts of the building or to the neighbourhood. In designing these structures it is essential to ensure that the closure is complete, for quite small openings will transmit an unduly large part of the noise. Two types of problem are involved with airborne noise : (*a*) the absorption of the noise at the surface of the enclosure to prevent a build-up of energy by successive reflections and (*b*) sufficient resistance to the pressure waves to prevent transmission through the structure.

The isolation of the low frequency (sub-sonic) vibrations can be dealt with by flexibly mounting the engine or using a sprung bed.

The arrangements and types of acoustical linings are legion and most of these have been developed primarily to improve the acoustical properties of halls, theatres, etc. For engineering purposes any robust type of lining capable of dealing with the required frequency band is adequate. It should be noted that such linings absorb the noise energy principally in the higher frequencies, but linings in themselves do not prevent transmission of the noise. Solid partitions such as brick walls are much more effective than the equivalent thickness of lining as will be seen from FIG. 7 which shows the relative sound attentuations of rock wool and a solid partition of equal surface density. The porous material is less effective at the lower frequencies and superior at the higher frequencies ; it should be noted, however, that the rock wool is 12 inches thick compared with, say, $\frac{1}{4}$ in. steel plate of a solid partition. The attenuation expected from brick constructions is given by the equation :—

$$\text{Attenuation} = 20\,(\log m + \log f) - 28{\cdot}6\ \text{db.}$$

where m is the surface density of the wall in lb/sq ft and f is the frequency in cycles per second ; this is sometimes referred to as the mass law. Curves of attentuation against frequency are shown in FIG. 8. It must be remembered when designing these enclosures that they must be complete and that openings such as air inlets require adequate silencers. Doors should be of the same weight per square foot as the walls, and windows of special type, such as small panes of thick glass and double construction should be used and each properly sealed when closed.

Conclusion

It has not been possible in this short Paper to discuss all aspects of noise problems but it is hoped that enough has been said to illustrate some of the difficulties of defining the problems, measuring and interpreting the objective readings in terms of subjective hearing, and the limitations of present knowledge in specifying exact limits to the noise that may be emitted by machinery. If this has been achieved without causing confusion by the use of terms peculiar to the acoustical engineer, this Paper has served its purpose.

ACKNOWLEDGEMENT

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