under the worst conditions of ambient noise. A recent investigation was carried out by the Coal Board to determine the suitability of various devices to signal the impending start of coal face machinery. It was found that bells, hooters and sirens were all about equally effective in being heard above coal face noise.

In this case the electro-acoustic conversion efficiency was not considered.

The tone transducer has been tested in a similar way by comparing it with a telephone bell in a noisy location. This was a room housing punched-card accounting machines producing a noise level of about 90 phons. The transducer was operated over a range of frequencies and power inputs and it was found that even when operating on lower power than the bell, the transducer gave a sound output that was more easily distinguishable than that of the bell against the background noise.

Noise and Vibration Control in Engineering*

By

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FROM METROPOLITAN-VICKERS

Introduction

THE PROBLEMS of noise and vibration control in engineering are many and varied. When faced with excessive noise or vibration the engineer has sometimes a difficult task to decide which of the many possible causes is the main offender. Having determined the cause, he can then set about attempting to reduce the noise, if possible, at the source, or he may decide to take steps to reduce the transmission of the noise from the source to the area with which he is concerned.

The fact that a machine is noisy does not necessarily mean that its efficiency is low, for the energy radiated as sound is normally small, but it may mean that some part is not functioning correctly, as a well made machine normally runs smoothly and quietly. However, in many cases, a quiet machine will be larger and more costly than its noisy counterpart.

In making an intelligent attack on his noise problems, and also to assess progress, the engineer requires a reliable method of measuring the noise and vibration. To appreciate this aspect of the problem it will be necessary to examine the fundamentals of the subject more closely.

Noise Measuring Equipment

Consider a noise consisting of a single pure tone. There are many physical attributes which can be used to describe the level of this tone, but the most usual is the oscillatory pressure. The pressure-range normally met in practice is very wide, say one to a million; and a logarithmic scale, the decibel scale, is used to cover this wide range. Thus the sound pressure level of a pure tone may be given as x dB above 0·0002 dynes/cm^2 where $x = 20 \log \frac{P}{0{\cdot}0002}$, P being the oscillatory component of pressure in dynes/cm.^{2} The value of 0·0002 dynes/cm^2 corresponds approximately to the threshold of hearing at 1,000 c/s. The frequency range involved in noise measurement is from approximately 20 c/s to 20,000 c/s, whereas for vibration lower frequencies may be important.

The loudness relation between tones of different frequencies is shown by the equal loudness contours which have been recently redetermined at the National Physical Laboratory (Robinson *et al.*, 1956). A simplified definition of the loudness level (B.S., 1936) of a noise in phons states that it is the sound pressure level of the 1,000 c/s pure tone which is judged by the average observer to have the same loudness. It is found, however, that this is not a satisfactory scale of loudness so the sone (Robinson *et al.*, 1957) scale has been devised as a scale of sensation. *Table I* gives the loudness of some noises on this scale.

Table I

LOUDNESS OF TYPICAL NOISES

	Loudness level: phons	Loudness: sones
Threshold of hearing	0	
Very quiet country district at night	20	0·25
Quiet office or home	40	1
Ordinary conversation	60	4
Busy traffic or Light engineering shop	80	16
Pneumatic road drill or Heavy engineering shop	100	64
Jet engine at 100 ft. (discomfort)	120	256
Close to jet engine (pain)	140	—

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* Given at the Annual Provincial Meeting of the Association on 15th July, 1958.

Table II

ERRORS OF SOUND LEVEL METER

Noise No.	No. of harmonic components	Component level	L.L.: phons	S.L.: dB	Errors
A	2	50	61	53	8
B	2	30	37·5	33	4·5
E	6	80	91	88	3
F	6	61	79	69	10
G	6	40	62·5	48	14·5
H	6	30	53	38	15
P	10	various	88	75·4	12·6
R	Saw tooth waveform		91	72	19
S	Saw tooth waveform		73	50	23
D.C. motor			85	72	13
D.C. motor			52	32	20
A.C. motor			78	59	18
A.C. motor			49	31	18

The determination of the loudness level of a noise in phons involves a subjective estimate whereas an objective method is normally preferred. The instrument usually used is the Sound Level Meter which consists essentially of a pressure sensitive microphone, an amplifier, attenuator and an r.m.s. output meter. Three weightings are provided, one giving a flat sensitivity and one each corresponding roughly to the 40 and 70 equal loudness contours. The summation law of the ear, however, is complex and this leads to large differences between the sound level and the loudness level in phons (King *et al.*, 1941). Some examples are given in *Table II.*

The problem of reducing the level of a noise often demands a knowledge of the frequency distribution of its components. This can be obtained by passing the amplified microphone output through suitable filters. These are generally either one third or one octave wide and permit an assessment of the frequency range in which the maximum energy lies. The identification of the source of major components is often simplified by a knowledge of their exact frequencies, which can be obtained using a narrow band analyser. A typical analysis is shown in *Table III.*

Vibration Measuring Equipment

The measurement of vibration is usually carried out by using similar equipment in which the microphone is replaced by a vibration pick-up. Several different types are on the market, which may measure oscillatory deflection, velocity or acceleration. *Table IV* shows the amplitude, velocity and acceleration of air particles in a sound field at a sound pressure level of 100 dB above 0·0002 dynes/cm^2. From this *Table* it can be seen that quite high sound pressure levels can be created by surfaces which are only moving distances of the order of millionths of an inch. Mechanical vibrographs are also on the market which are very useful in measuring low frequency vibrations.

Types of Noise Source

A very common source of noise is the vibration of a hard surface. In this case, the radiation depends not only on the frequency and amplitude of the vibration, but also on the area involved. Thus the tuning fork makes little noise unless in contact with a sounding-board. Examples of this type of noise in engineering include the bearing noise in electric motors where the vibration of a ball or roller bearing vibrates the end cover of the machine resulting in increased noise (70/80 dB). Or again the noise of riveting in a shipyard where the hammer vibrates a considerable area of hull.

Another class results from the release of a gas in a series of pulsations. The air raid siren is a deliberate example of this, while in the motor car exhaust efficiency is sacrificed in an effort to smooth out the pulsations resulting from the power strokes, before they are released at the tail pipe. Many fans too, create this type of noise when the moving blades are allowed to pass close to stationary members. This is a noise of definite pitch the frequency of which can be calculated from a knowledge of the speed and the number of fan blades (see *Table III*).

There is another type of noise from a fan, or propellor, which also occurs to some extent in all moving air streams, including the jet engine, and has a much less definite pitch. This noise arises from the generation and destruction of eddies.

Table III

TYPICAL SOUND ANALYSIS FOR GEARED TURBO-GENERATOR

Frequency: c./s.	Sound pressure level dB above 0·0002 dynes/cm.^2	Equivalent loudness: phons	Loudness: sones	Probable source
125 (125 × 1)	70	57	3·2	Turbine unbalance
199 (16·6 × 12)	75	69	7·5	Generator fan
1670 (16·7 × 100)	74	75	11·3	Generator slots
3,340 (16·7 × 200)	61	65	5·7	Generator commutator
3,740 (125 × 30)	75	80	16	Gear contacts
6,000 (16·7 × 360)	71	65	5·7	Gear phantom

Details of geared turbo-generator.
Turbine 7,470 r.p.m. = 125 r.p.s.
Gear pinion 30 teeth. Wheel 224 teeth.
Cutting table 360 teeth.
Generator 1,000 r.p.m. = 16·7 r.p.s. Slots = 100.
Commutator bars 200. Fan blades 12.

Table IV

AMPLITUDE, VELOCITY AND ACCELERATION OF PARTICLES IN SOUND FIELD HAVING A SOUND PRESSURE LEVEL OF 100 dB ABOVE 0.0002 DYNES/CM^2

Frequency, c./s.	10	100	1,000	10,000
Amplitude, inches $\times 10^{-3}$	3	0·3	0·03	0·003
Velocity, inches/sec.	0·19	0·19	0·19	0·19
Acceleration, g units	0·03	0·3	3	30

The steady discharge of air, or other gas, from a pipe, is not free from noise, for, even at moderate discharge velocities, the shearing action between the moving and stationary air, creates a wide spectrum noise. The intensity increases more and more rapidly as the relative velocity increases and eventually at high supersonic velocities may give rise to an intense pitched noise. At Mach. 1 the intensity of the sound is approximately proportional to the eighth power of velocity. These unpitched sources sometimes become pitched by resonance in a nearby cavity or pipe.

Common Sources of Vibration

Considering now some common sources of vibration in engineering, these may be impulsive as in the hammer blow, the pile driver or drop hammer, or repeated impulse as in the motor car or road drill, or steady state as in the electrical transformer and many others. Rotating or reciprocating machinery out of balance can produce oscillatory forces at the bearings which give rise to vibration of the whole machine and its foundations. This may be intensified by resonance or by running at a critical speed. So called slip-stick friction often gives rise to vibration and noise. This results from a variation in the friction force with velocity, frequently static and dynamic, which converts a steady retardation into an oscillatory one. Examples are the squeal of motor car brakes, the groaning of leaf springs and the music of a violin. These vibrations and the resulting noises frequently have a pitch due to the resonances of the system.

Another class of vibrations is the forced vibration, in which the motion of the body itself creates or releases a force to maintain the vibration. The steam engine is an example in which the piston motion moves a valve, which admits steam to drive the piston and maintain the motion. Another example is the swaying of power lines and suspension bridges in the wind, due to the action of the eddies produced which may become excessive when the driving frequency, called the Strouhal frequency, agrees with one of the natural frequencies of the line or bridge. This is sometimes referred to as an aeolian vibration as it is the action used in the aeolian harp.

Transmission Paths

Another important aspect of the control of noise and vibration is the study of the transmission paths from the source to the observer. In the case of vibration, this may be from the machine to its foundations and along the floor to the observer. This transmission can be reduced by providing a resilient break in the floor round the machine or by mounting the machine on resilient mountings of rubber or steel springs. It should be noted that this will normally increase the vibration of the machine itself, by reducing the total moving mass.

In the case of noise transmitted through the air, it is difficult to provide a break in the transmission path, and the most effective method is to box the machine in by some non-porous enclosure of metal, wood or brick. In this case, the reduction is mainly dependent on the weight per unit area of the wall (or ceiling). An increase in noise will result inside the enclosure which can be controlled by the introduction of acoustic absorption. " Silenced " ducts (Britain *et al.*, 1948) will generally be required for the supply of ventilating and cooling air. Sometimes a reduction in sound transmission is attempted by a partial barrier. These are not so effective as complete enclosures and should be of non-porous material sealed to the ground. An impervious barrier some 10 ft. above the line joining source and observer can give a reduction of about 10 dB.

General

It is difficult, in a complex subject like the control of noise, to lay down general rules. Each case has to be dealt with on its merits and a decision reached on whether to attempt to reduce the noise at its source, to cut down the radiation or to box the noise in and so reduce the transmission. In many cases, the reduction of noise will reduce accessibility and increase cost and a compromise solution has to be adopted. In some cases, the best solution is to remove the offending machine to another site or building.

The question of whether a particular machine is noisy or not will depend on the background noise which exists owing to other causes. In general, if the machine is 10 dB below the background it will not be obtrusive whereas if it is 10 dB above it will take control.

These remarks have been confined to the physical aspects of noise control, but the importance of the subjective aspect must not be overlooked. The question of whether a particular noise is excessive may depend on the attitude of the listener. Some people are disturbed by the complete absence of noise as in sound proof rooms.

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