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EXPERIMENTAL METHODS OF IDENTIFYING SOUND SOURCES ON A MACHINE

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There are many existing methods to identify noise sources and paths and some newer methods have also been recently developed. Several existing techniques have been used to identify noise sources on machines for many years. None are completely satisfactory. They are usually inaccurate, expensive, time consuming and often need special acoustic facilities. The most commonly used technique is perhaps the selective-wrapping or lead-wrapping approach. Recently, fast Fourier transform (*FFT*) minicomputers have become widely available and theory has been published for the calculation of acoustic intensity from two simultaneously measured signals. Two new techniques have been investigated by a number of research workers. These two techniques are: the surface intensity approach (microphone-accelerometer) and the acoustic intensity approach (two-microphone). These two new techniques can be used to study sound sources and sound paths and will be discussed in this paper in some detail. The paper begins with a brief review of some of the earlier methods, continues with a description of other methods of noise source identification and concludes with a discussion of the newer intensity and coherence techniques to identify machinery noise sources and paths.

1. Introduction

The use of road vehicles has now become so widespread in industrialized countries that their gaseous emissions have become a health hazard and their noise unbearable for a large fraction of the population in many large cities [1, 2]. In addition, the noise in some industrial plants is so intense that large numbers of workers in many countries have suffered permanent hearing loss.

The reduction of vehicle and machinery noise has become a priority item for many governments and several countries have produced noise regulations for industrial machinery and vehicles. In order to reduce machinery and vehicle noise it is important first to gain some knowledge of noise sources. Once this knowledge is obtained, then it may be possible to make engineering changes to reduce the strength of different sources or interfere with the paths of noise propagation by use of absorption, enclosure or vibration-isolation.

In most such machinery noise control problems, a knowledge of the dominant noise sources in order of importance is very desirable so that modifications can be made in a logical way. In a complicated machine, such noise source information is often difficult to obtain and many noise reduction attempts are made based on inadequate data so that frequently expensive or inefficient noise reduction methods are employed. Information on noise paths is also needed so that the most suitable path noise control techniques mentioned above can be attempted, and the whole noise control solution optimized.

2. Review of classical methods of identifying sources

The sound field produced by a noise source is normally quite complicated and several of its properties are of interest. These include: variation of the sound pressure magnitude and sound power with frequency, directivity of the sound field and variation of sound pressure level with distance from the source and with time.

Several noise source identification methods have been used on machinery for a long time. A brief review of these methods follows.

2.1 *Subjective assessment*

With practice the ear can often distinguish between sounds more accurately than can sophisticated measuring equipment. The ear should always be used as the first noise source identification approach. However, it does not give quantitative results.

2.2 Selective operation

Selective operation is also a useful approach [3]. Sometimes with a complicated machine it is possible to operate the machine with some parts disconnected and simultaneously to measure the noise of the machine. Providing such a procedure does not alter the operation of the machine significantly, it can often be used to indicate the contribution of the different parts to the complete machine noise when all the parts are operating simultaneously. However, great care must be used with this approach.

2.3 Selective wrapping

Selective wrapping has often been used with vehicles and engines. It is often used in conjunction with selective operation. Fig. 1 shows the contributions of different sources on an International Harvester truck, during a drive-by test, which were obtained by a combination of the selective operation techniques [4]. With the truck, the engine was wrapped, the exhaust suppressed with an oversize muffler and the cooling fan removed. The selective wrapping technique is also often used on engines. Usually a heat resisting, absorbing material is used, enclosed with a massive material such as lead. However, the selective wrapping technique is tedious and time consuming and there has been a search for quicker, more convenient methods of source identification.

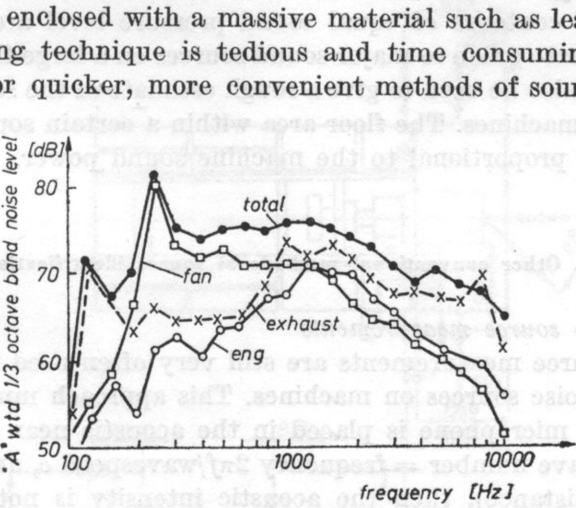

Fig. 1a. One-third octave analysis of truck total and other noise

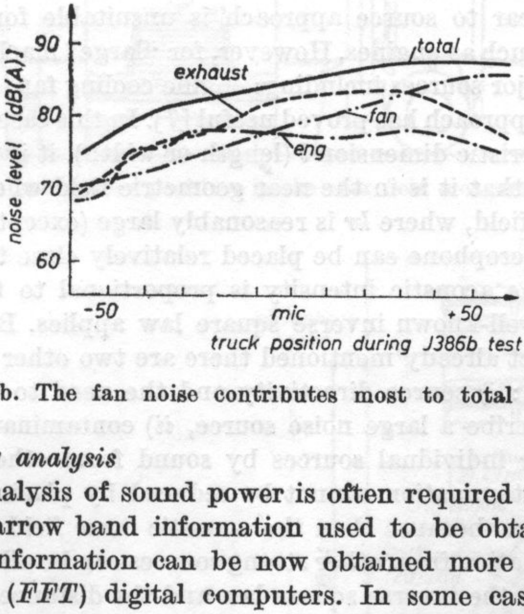

Fig. 1b. The fan noise contributes most to total noise

2.4 Frequency analysis

Frequency analysis of sound power is often required to describe a noise source properly. Narrow band information used to be obtained using analog equipment. Such information can be now obtained more quickly using fast Fourier transform (*FFT*) digital computers. In some cases a narrow band frequency analysis can also be used to identify pure tone sources of sound. Engine-firing, fan-blade-passage, and gear-meshing frequencies can all be calculated and identified. As the vehicle (or engine) speed is changed, such frequencies will normally change as predicted. If peaks in the frequency spectrum do not change with speed this suggests that they are caused by resonance frequencies o efficient transmission or radiation at such frequencies [3, 5].

2.5 Mapping

Mapping of contours of equal sound pressure level around a source is a useful approximate guide to major sound sources on a large fixed machine [6]. This method can also be used to give a rough estimate of the sound power emitted by different machines. The floor area within a certain sound level contour is approximately proportional to the machine sound power.

3. Other conventional methods of source identification

3.1 Near to source measurements

Near to source measurements are still very often used in an attempt to identify major noise sources on machines. This approach must be used with extreme care. If microphone is placed in the acoustic near field where kr is small (k is the wave number = frequency $2\pi f$/wavespeed c, and r is the source to microphone distance), then the acoustic intensity is not proportional to sound pressure squared and this gives misleading results. This is particularly true at low frequency. The acoustic near field is reactive; the sound pressure is almost completely out-of-phase with the acoustic particle velocity.

Thus, this near to source approach is unsuitable for use on relatively "small" machines such as engines. However, for "large" machines such as vehicles with several major sources including: engine cooling fan, exhaust, inlet, etc., the near to source approach has proved useful [7]. In this case where the machine is large, of characteristic dimension l (length or width), it is possible to position the microphone so that it is in the near geometric field where r/l is small, but in the far acoustic field, where kr is reasonably large (except at low frequency). In this case the microphone can be placed relatively close to each major noise source and now the acoustic intensity is proportional to the sound pressure squared and the well-known inverse square law applies. Besides the acoustic near to source effect already mentioned there are two other potential problems with this approach: *i*) source directivity and the need to use more than one microphone to describe a large noise source, *ii*) contamination of microphone signals placed near individual sources by sound from other stronger sources. Unfortunately, contamination cannot be reduced by placing the microphones closer to the sources because then the acoustic near field effect is increased. However, contamination from other strong sources can be allowed for by empirical correction using the inverse square law and the distance to the contaminating source.

Despite the various potential problems with the near to source method, Wang and Crocker have used it quite successfully to identify the major noise sources on a large diesel engine truck [7]. By placing microphones near each major noise source (Fig. 2) and then extrapolating to a position 14.5 m from the truck (Fig. 4) good agreement could be obtained with earlier selective operation and selective wrapping drive-by measurements (Figs. 4 and 5). Averaging over five positions near each source and correcting for contaminating sources gave quite good agreement (Fig. 6).

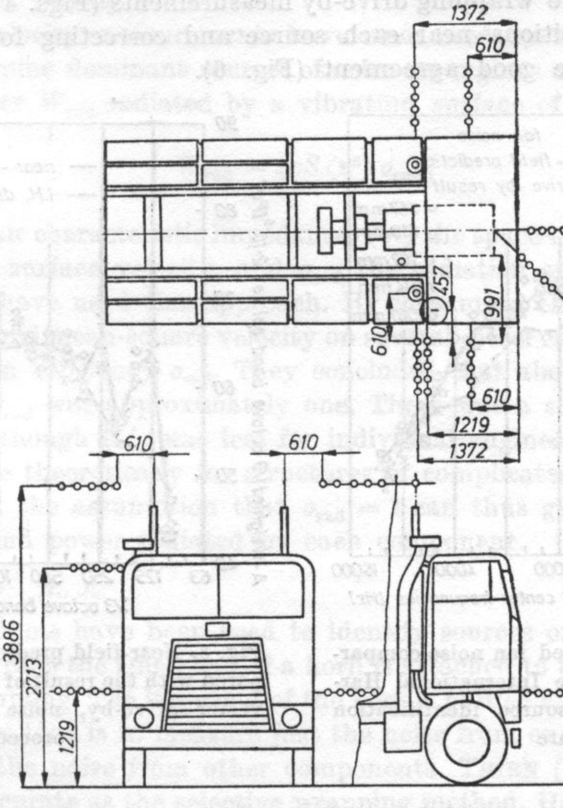

Fig. 2. Microphone positions in the near-field measurement

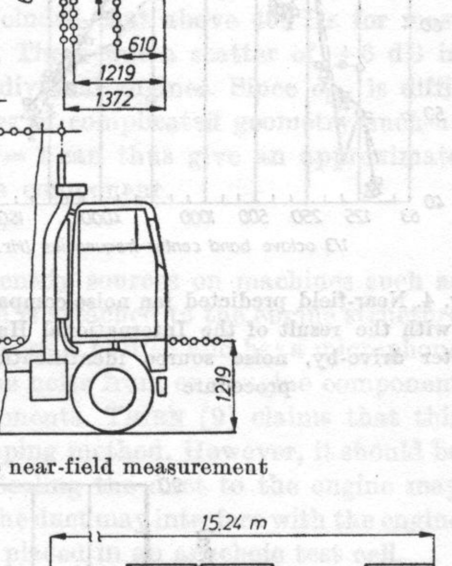

Fig. 3. The position of the track on the sound pad when the truck engine reached its governed speed of 2100 rpm with 6th gear in the International Harvester noise source identification test

ration and selective wrapping drive-by measurements (Figs. 4 and 5). Averaging over five positions near each source and correcting for contaminating sources gave quite good agreement (Fig. 6).

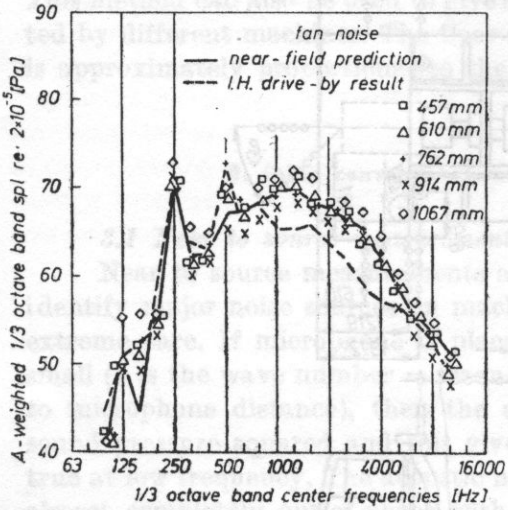

Fig. 4. Near-field predicted fan noise compared with the result of the International Harvester drive-by, noise source identification procedure

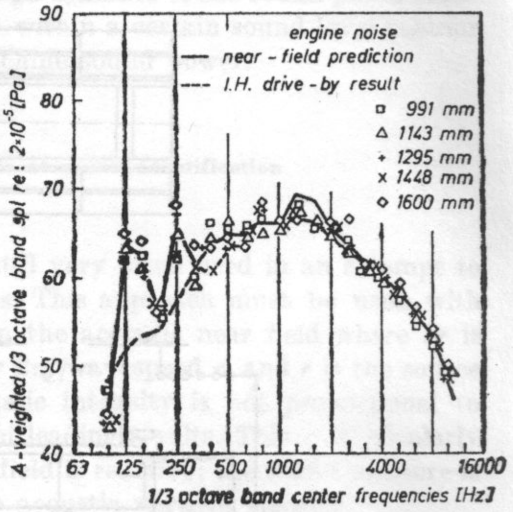

Fig. 5. Near-field predicted engine noise compared with the result of the International Harvester drive-by, noise source identification procedure

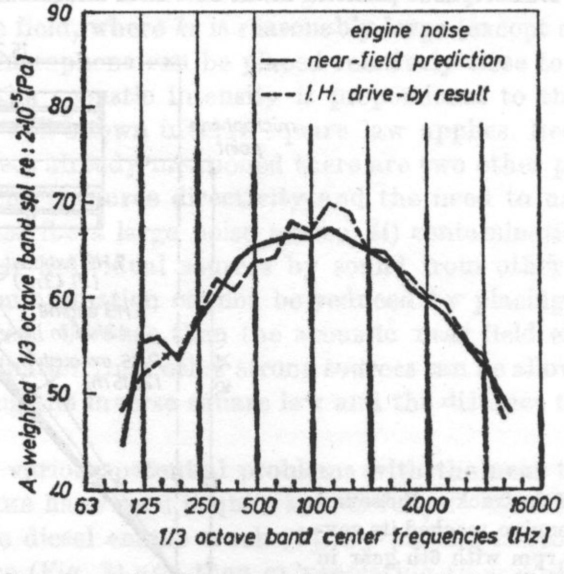

Fig. 6. The predicted engine noise after corrections are made to eliminate the contribution from the exhaust system noise, compared to the International Harvester drive-by result

3.2 Surface velocity

Surface velocity measurements have been used by several investigators to try to determine dominant sources of noise on engines and other machines. The sound power W_{rad} radiated by a vibrating surface of area S is given by

$$W_{\text{rad}} = \varrho c S \langle v^2 \rangle \sigma_{\text{rad}}, \tag{1}$$

where ϱc is the air characteristic impedance, $\langle v^2 \rangle$ the space-average of the mean-square normal surface velocity, and σ_{rad} the radiation efficiency. CHAN and ANDERTON [8] have used this approach. By measuring the sound power and the space-averaged mean-square velocity on several diesel engines they calculated the radiation efficiency σ_{rad}. They concluded that above 400 Hz for most diesel engines σ_{rad} was approximately one. There was a scatter of ±6 dB in their results, although this was less for individual engines. Since σ_{rad} is difficult to calculate theoretically for structures of complicated geometry such as a diesel engine, the assumption that $\sigma_{\text{rad}} = 1$ can thus give an approximate idea of the sound power radiated by each component.

3.3 Acoustic ducts

Acoustic ducts have been used to identify sources on machines such as engines. In this case the small end of a horn is attached to the engine structure by a flexible coupling. The large end of the horn is baffled and has a microphone placed in it. The idea is to measure just the noise from one engine component and to isolate the noise from other components. THIEN [9] claims that this method is as accurate as the selective wrapping method. However, it should be noted that there are potential problems. Sealing the duct to the engine may be difficult with different size components; the duct may interfere with the engine radiation and ideally the engine should be placed in an anechoic test cell.

Problems with cost, time and accuracy of the previous source identification methods have led to a continued search for other faster, more accurate alternative methods of source and path identification on machines. The introduction of the fast Fourier transform minicomputer has recently made several of these reasonably successful and they are now discussed. It is becoming common to use the new techniques in conjuction with the older more conventional ones to give added confidence in the noise source information. In some cases the new techniques are sufficiently developed so that they have supplanted older methods.

4. Coherence technique of source and path identification on machines

Correlation and coherence techniques in noise control date back over twenty years to the work of GOFF [10] who first used the correlation technique to identify noise sources. Although correlation has often been used in other applications it has not been widely used in noise source and path identification. One exception is the work of KUMAR and SRIVASTAVA who reported some success with this technique in identifying noise sources on diesel engines [11]. Since the ear acts as a frequency analyzer, the corresponding approach in the frequency domain (coherence) instead of the time domain is usually preferable. CROCKER and HAMILTON have recently reviewed the use of the coherence technique in modelling diesel engine noise [5]. Such a coherence model can also be used in principle. Fig. 7 shows an idealized model of a multiple-input, single-output system. It can be shown [5] that the auto spectrum of the output noise S_{yy} is given by

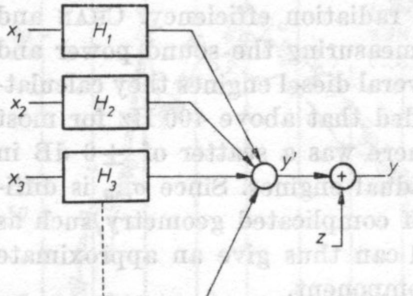

Fig. 7. A multiple input, single output system with uncorrelated noise at the output

$$S_{yy} = \sum_{i=1}^{N} \sum_{j=1}^{N} S_{ij} H_i H_j^* + S_{zz}, \tag{2}$$

where N is the number of inputs, S_{ij} are cross spectral densities between inputs, H_i are frequency responses and S_{zz} is the autospectral density of any uncorrelated noise z present at the output. Note that the S and H terms are frequency-dependent.

If there are N inputs, then there will be N equations,

$$S_{iy} = \sum_{j=1}^{N} H_j S_{ij}, \quad i = 1, 2, 3, \ldots, N. \tag{3}$$

The frequency responses $H_1, H_2, H_3, \ldots, H_N$ can be found by solving the set of N equations (3). The multiple coherence function $\overline{\nu_{xy}^2}$ is defined to be

$$\nu_{xy}^2 = S_{y'y'}/S_{yy}, \tag{4}$$

where $S_{y'y'}$ is the output noise coherent with all the inputs and is the first term on the right of equation (2);

$$S_{y'y'} = \sum_{i=1}^{N} \sum_{j=1}^{N} S_{ij} H_i H_j^* . \tag{5}$$

The multiple coherence function $\overline{\nu_{xy}^2}$ represents the fraction of the output which is coherent with all the inputs. From equations (2), (4) and (5)

$$\overline{\nu_{xy}^2} = 1 - (S_{zz}/S_{yy}) . \tag{6}$$

The value of $\overline{\nu_{xy}^2}$ falls between 0 and 1.

CHUNG, SEYBERT, CROCKER and HAMILTON have used the coherence approach to model diesel engine noise [5, 12-14]. This approach appears to give useful information on a naturally aspirated diesel engine which is combustion-noise dominated and where the N inputs are $x_1 \ldots x_N$, the cylinder pressures measured by pressure transducers in each cylinder (see Fig. 7). In this case, H_i, the frequency response (transfer function between the ith cylinder and the far field microphone) can be calculated. Provided proper frequency averaging is performed, the difficulty of high coherence between the cylinder pressures can be overcome because the phasing between the cylinder pressures is exactly known [15]. In this case the quantity $S_{ii}|H_i|^2$ may be regarded as the far field output noise contribution by the ith cylinder. This may be useful noise source information for the engine designer.

HAYES, SEYBERT and HAMILTON in further research at Herrick Laboratories have extended this coherence approach to try to separate combustion noise from piston-impact noise in a running diesel engine [16].

WANG and CROCKER showed that the multiple coherence approach could be used successfully to separate the noise from sources in an idealized experiment such as one involving three loudspeakers, even if the source signals were quite coherent [17, 18]. However, when a similar procedure was used on the more complicated case of a truck which was modeled as a six input system (fan, engine, exhaust (s), inlet, transmission) the method gave disappointing results and the simpler near to source method appeared better [7, 17]. The partial coherence approach was also used in the idealized and truck experiments. It is believed that contamination between input signals and other computational difficulties may have been responsible for the failure of the coherence method of identifying truck noise sources.

Some workers have recently used the coherence approach with the simplifying assumption that all the sources are incoherent. In this case the cross spectral terms S_{ij} in equation (2) are zero and only the autospectral densities S_{ji} are retained. This simplified approach is sometimes known as the ordinary coherence function method. It has been applied with most success where the sources are definitely incoherent, e.g. where there are many independent machines [50].

5. Noise source and path identification using intensity technique

5.1 *Intensity in a sound field*

The intensity I is the net rate of flow of sound energy per unit area. The intensity I_r in the r direction is

$$I_r = \langle p u_r \rangle, \tag{7}$$

where p is the instantaneous sound pressure, u_r is the sound particle velocity in the r direction and $\langle\ \rangle$ denotes a time average. The sound power W radiated by a source can be obtained by integrating the component of the intensity, I_n, normal to any surface S enclosing the source,

$$W = \int_S I_n dS. \tag{8}$$

5.2 *Noise source identification using the surface intensity technique*

The surface intensity technique which uses an accelerometer mounted on a vibrating surface and a microphone located close to the accelerometer has been under development since about 1974. MACADAM described the use of this technique in the measurement of the sound power radiated from room surfaces in lightweight buildings [19, 20]. HODGSON also discussed this technique and its use on a large centrifugal chiller machine [21]. CZARNECKI *et al.* [22] successfully compared the sound power of a pure-tone excited, rigid, circular, baffled piston source obtained from surface intensity measurements, the conventional reverberation room method, as well as the free-field method and theory. BRITO investigated theoretically and experimentally the case of a vibrating rectangular flexible panel and obtained good agreement [23, 24]. KAEMMER and CROCKER [25, 26, 27] measured the sound power of a vibrating cylinder using the surface intensity method and compared it with the reverberation room method and theory. They obtained good results when they carefully accounted for phase shifts between the microphone and accelerometer signals.

In the case of surface intensity measurements, the particle velocity u_n normal to the vibrating surface area S can be found by integrating the signal from an accelerometer. The pressure p can be measured by a microphone close to the accelerometer. If the instrumentation or the finite distance between accelerometer and microphone introduces a time delay Δt between pressure and velocity signals, this is related to a phase shift Φ by $\Delta t = \Phi/2\pi f$, where f is the frequency, in Hz. The intensity is usually computed in the frequency domain by feeding the velocity and pressure signals into an *FFT* analyzer, since the spectral distribution of sound power is usually required. The acoustic intensity may be shown to be [25, 26]:

$$I_n = \int_0^\infty [C_{up}(f)\cos\Phi + Q_{up}(f)\sin\Phi]\,df, \tag{9}$$

where C_{up} is the co-spectrum (real part) and Q_{up} is the quad-spectrum (imaginary part) of the one-sided cross-spectral density between velocity and pressure G_{up};

$$G_{up}(f) = C_{up}(f) - iQ_{up}(f). \tag{10}$$

McGary and Crocker continued development of the surface intensity technique [28-31]. They then applied it successfully to the determination of the sound intensity radiated from the different surfaces of a Cummins NTS 350 diesel engine [28, 29, 31]. This work is described in section 6.4 of this paper. Use of the velocity signal in this analysis, however, is rather inconvenient, since an along integrator is needed to integrate the signal produced by the accelerometer. It is simpler to eliminate use of the velocity signal through mathematical techniques and use instead the acceleration signal. The equation for intensity, I, then becomes

$$I = (1/2\pi)\int_0^\infty (1/f)(Q_{pa}\cos\Phi + C_{pa}\sin\Phi)\,df, \tag{11}$$

where Q_{pa} is the imaginary part of the one-sided cross-spectral density between pressure and acceleration, C_{pa} the real part of the one-sided cross-spectral density between pressure and acceleration and Φ the instrumentation phase shift. This was the approach used by McGary and Crocker in the measurements described in section 5.4 of this paper.

5.3 Noise source identification using the lead-wrapping technique

The selective-wrapping approach used in conjuction with the selective-operation approach have been the basic methods used to noise-source identify engines and other machines until very recently. Since the normal procedure now is to use a lead barrier enclosure with acoustic absorbing material between the lead and the engine, the approach is often also called lead-wrapping. It has been assumed by many people until recently that this approach will give the most reliable method of identifying noise source on the surface of a machine and it has been used as a baseline against which other approaches are compared.

In the work by Crocker *et al.* [28, 29, 36, 37, 40, 51] described in the present paper, measurements on a diesel engine using the lead-wrapping approach were used as a baseline against which to compare measurements made with the intensity techniques. The floor of the Herrick Laboratories semi-anechoic room was covered with fiberglass wedges and a hoop was rotated around a Cummins NTC 350 HP diesel engine. First the intensity I was obtained at thirty measurement points on the hoop traverse by assuming the far field approximation

$$I = p_{\mathrm{rms}}^2/\varrho c, \tag{12}$$

where p_{rms}^2 is the mean square sound pressure measured, ϱ is the air density and c is the speed of sound. Then, the sound power W was obtained by summation over the spherical area S covered by the hoop traverse around the engine using equation (8), where dS is the incremental area associated with each microphone position.

It has been shown during the present research that the lead-wrapping approach has several serious drawbacks. First, the lead-wrapping method is time-consuming, tedious and expensive. Second, a special facility: an anechoic engine-test cell is really required to obtain accurate, reliable results. Third, the method fails at low frequency (below about 200 to 300 Hz) because the lead becomes "transparent" to engine noise. This is obvious if mass law transmission loss theory is studied. In addition, since the lead is situated close to the engine wall it may act as a tight-fitting enclosure and actually amplify the engine noise at low frequency. See the measurements of the sound power of the bare engine and fully-wrapped engine given in Fig. 8. The net effect is that at low frequency it is difficult to separate the noise of one engine part from the total engine noise. See, for example, the measured sound power of the oil pan (sump) in Fig. 9. The oil pan is a strong source on this engine. A fourth and related drawback is that the lead-wrapping method works well only for the stronger noise source on the engine surface. When a surface, which is only a moderate or weak source of sound, is exposed it is difficult or impossible to determine its contribution accurately except in the very high frequency range (several thousand Hz). See, for example, Fig. 10 which shows the sound power of the fuel and oil pumps (a weak source on this engine). The measurements in Figs. 8-10 were made by rotating microphones on a hoop around a lead-wrapped Commins NTC 350 diesel engine in the semi-anechoic room at Herrick Laboratories (see Fig. 11). The engine was mounted at a height of about 1.5 m above the foor so that the hoop could be easily rotated around it [28, 29, 36, 37, 40, 51].

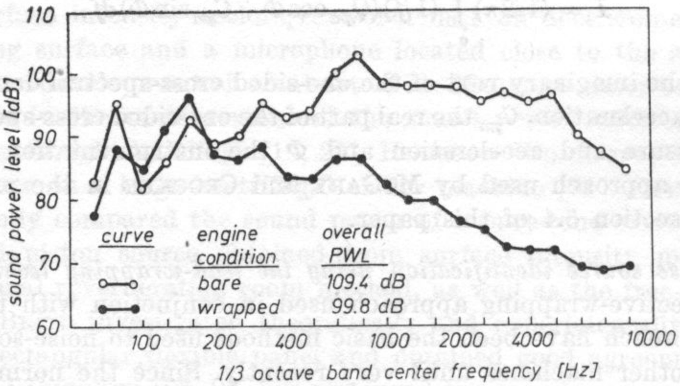

Fig. 8. Comparison of the sound power level of the bare engine and the fully-wrapped engine measured at 1500 rpm and 542 Nm load

5.4 Comparison between surface intensity and lead-wrapping measurements

The sound power radiated from 5 different surfaces of the Cummins engine was measured using the surface intensity technique and compared with the sound power radiated from the same surfaces determined from the lead-wrapping approach [28, 29].

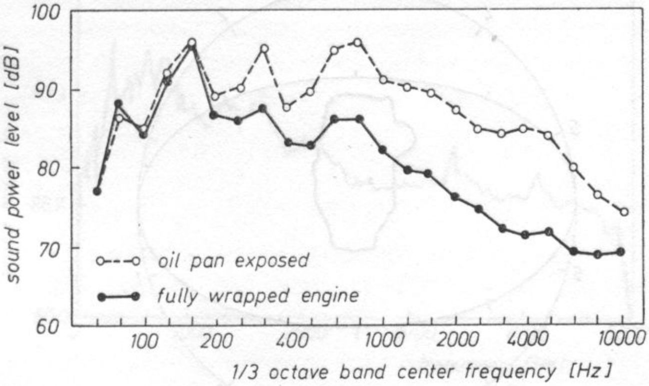

Fig. 9. Comparison of the sound power level of the oil pan and the fully-wrapped engine measured at 1500 rpm and 542 Nm load

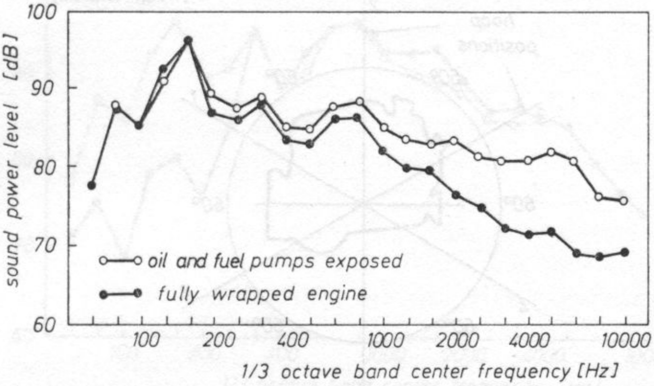

Fig. 10. Comparison of the sound power level of the fuel and oil pumps with that of the fully-wrapped engine measured at 1500 rpm and 542 Nm load

The five parts chosen for surface intensity measurements were: 1) the oil pan, 2) the after-cooler, 3) the left block wall, 4) the right block wall, and, 5) the oil filter and cooler. The exhaust manifold and cylinder head were not investigated because of the intense heat radiated by these parts. High surface temperatures can make acceleration readings difficult or inaccurate and are somewhat dangerous for investigators moving the accelerometer from location to location. The front of the engine was not examined either, because pulleys there made it very difficult to mount an accelerometer and locate the microphone. Figs. 12 and 13 show the sound power obtained by summing over 24 locations on the oil pan using equation (8). Fig. 12 shows narrow band results, while Fig. 13 shows the narrow band sound power results presented in Fig. 12 summed into one-third octave bands. The curve with symbols *O* was obtained from the lead-wrapping method, while the curve with symbols *S* was obtained from the surface intensity technique. The results for the other four surfaces examined on the engine are given in references [28, 29].

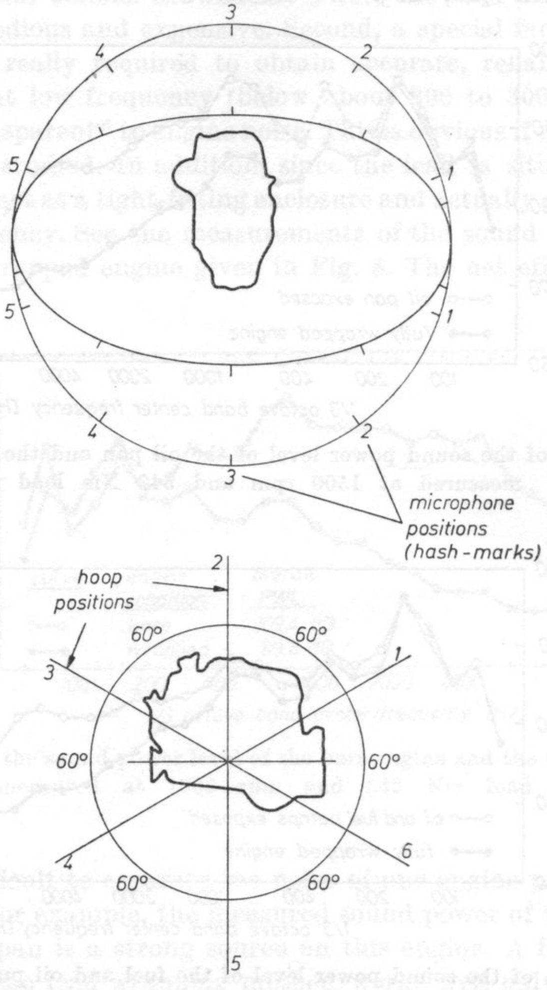

Fig. 11. Microphone positions on hoop which was rotated around engine for sound power measurements

It is seen in Fig. 13 that the agreement between the two methods is good except at very low frequency (below 315 Hz). At low frequency the lead becomes "transparent" to sound as already discussed and the surface intensity method is less accurate because of calibration difficulties [30]. The trend for the lead-wrapping results to be higher than the surface intensity results in the lower frequency region was observed for all the five parts examined and is as expected.

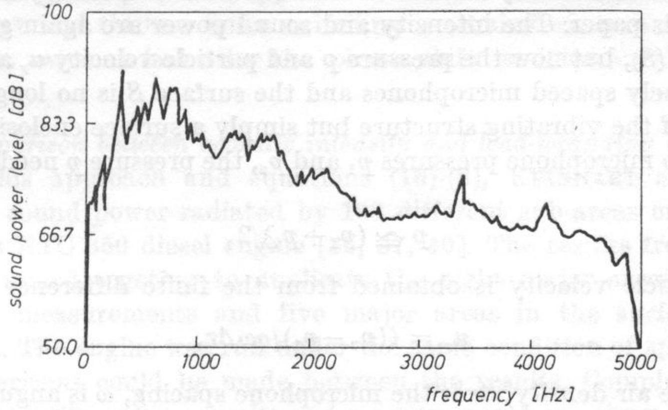

Fig. 12. Narrow band sound power level determined from surface intensity method summed over 24 sub-areas of the surface of the oil pan measured at 1500 rpm and 542 Nm load

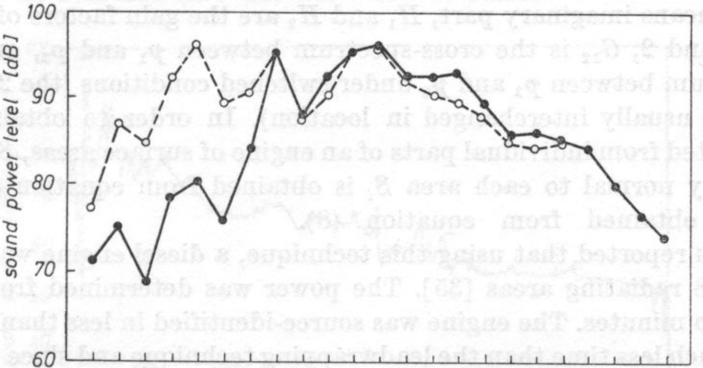

Fig. 13. Comparison of sound power level determined for the oil pan from the spherical traverse lead-wrapping technique ○—·—○ and the sound power level from the surface intensity method ●——●

5.5 *Noise source identification using the acoustic intensity technique*

The measurement of acoustic intensity has been possible since the last century using Rayleigh's disc. However, Rayleigh's disc is impractical in noise work. In the last fifty years several workers have investigated the measurement of acoustic intensity using various two-microphone devices. Olsen in 1932 took out a patent for its measurement. At last it appears that the *FFT* analyzer has now made practical intensity measurements possible. Recent developments suggest that acoustic intensity measurements are quicker and at least as accurate as the selective wrapping approach in measuring engine noise sources.

FAHY [32, 33] and CHUNG [34, 35] have given the theory for the measurement of acoustic intensity similar to that for surface intensity in the previous section of this paper. The intensity and sound power are again given by equations (7) and (8), but now the pressure p and particle velocity u_r are determined with two closely spaced microphones and the surface S is no longer necessarily the surface of the vibrating structure but simply a surface enclosing the source. From the two microphone pressures p_1 and p_2, the pressure p needed in equation (7) is

$$p \cong (p_1 + p_2)/2, \tag{13}$$

and the particle velocity is obtained from the finite difference assumption

$$u_r = i(p_2 - p_1)/\varrho\omega\Delta r, \tag{14}$$

where ϱ is the air density, Δr is the microphone spacing, ω is angular frequency. By substituting equations (13) and (14) into (7), CHUNG [34, 35] showed that

$$I_r = \mathrm{Im}\{[G_{12}G_{12}^S]^{1/2}\}/\varrho\omega\Delta r\,|H_1|\,|H_2|, \tag{15}$$

where Im means imaginary part, H_1 and H_2 are the gain factors of microphone systems 1 and 2, G_{12} is the cross-spectrum between p_1 and p_2, and G_{12}^S is the cross-spectrum between p_1 and p_2 under switched conditions (the 2 microphone systems are usually interchanged in location). In order to obtain the sound power radiated from individual parts of an engine of surface areas, $S_1, S_2, \ldots, S_N$, the intensity normal to each area S_i is obtained from equation (15) and the power W obtained from equation (8).

CHUNG reported that using this technique, a diesel engine was subdivided into $N = 98$ radiating areas [35]. The power was determined from each area in about two minutes. The engine was source-identified in less than a day which involved much less time than the leadwrapping technique and since the intensity measurements were made only 20 mm above the engine surfaces, an anechoic or semi-anechoic room was unnecessary.

REINHART and CROCKER [36, 37] did not use the intensity formulation given in equation (15) but rather that suggested by KRISHAPPA [38] and ROLAND [39]. In this formulation the acoustic intensity is

$$I_r = \mathrm{Im}\{G_{12}\}/\varrho\omega\Delta r. \tag{16}$$

Corrections for phase shift between the two microphone channels are made using equation (17). The true cross spectrum G_{12} between the microphone signals is related to the measured value G'_{12} by

$$G'_{12} = G_{12}T_{12}/|H_1|^2, \tag{17}$$

where T_{12} is the transfer function between microphone channel systems 1 and 2 and (H_2) is the gain of microphone system 2. In this phase shift determination, the two microphones were mounted at the same longitudinal position at the end of a small tube which was excited by a white noise source from a small loudspeaker. In principle, this approach has some advantage over that suggested by FAHY and CHUNG. Since switching is eliminated, measurements can be made about twice as fast after the phase shift is determined and stored on the *FFT*.

5.6 Comparison between acoustic intensity and lead-wrapping measurements

Using this approach and equations (16)-(8), REINHART and CROCKER measured the sound power radiated by 103 different sub-areas on the surface of a Cummins NTC 350 diesel engine [36, 37, 40]. The results from groups of areas were summed together to duplicate the eight major areas used in the lead-wrapping measurements and five major areas in the surface intensity measurements. The engine was run under the same condition of speed and load so that comparisons could be made between the results. Complete details of the acoustic intensity engine results and measurements are given in [40]. Figs. 14 and 15 show the sound power obtained by summing over 25 locations on the oil pan. Fig. 14 shows narrow band results while Fig. 15 shows the results given in Fig. 14 summed into one-third octave bands.

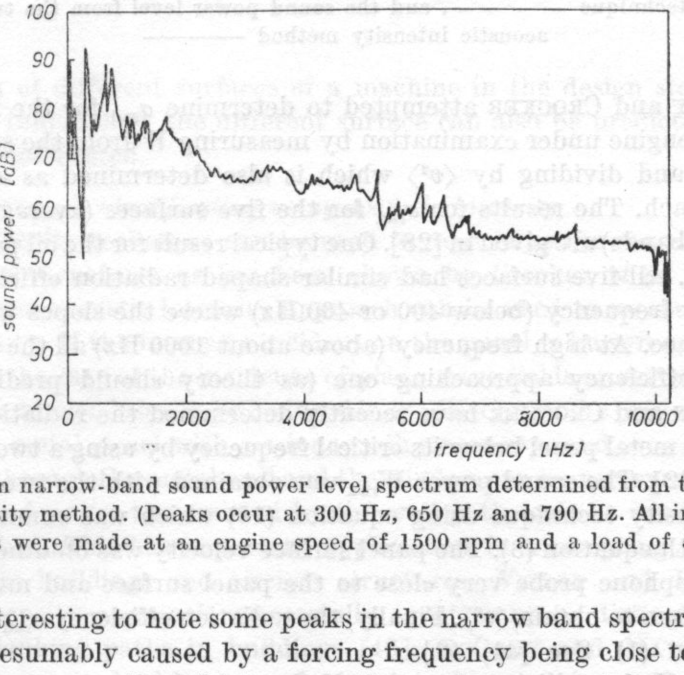

Fig. 14. Oil pan narrow-band sound power level spectrum determined from two-microphone acoustic intensity method. (Peaks occur at 300 Hz, 650 Hz and 790 Hz. All intensity measurements were made at an engine speed of 1500 rpm and a load of 542 Nm)

It is interesting to note some peaks in the narrow band spectrum in Fig. 14 which are presumably caused by a forcing frequency being close to a structural resonance frequency. Also of interest is the good agreement between the lead-wrapping and the acoustic intensity results in Fig. 15 for frequencies at and above 315 Hz. This result is similar to that for the oil pan when the lead-wrapping and the surface intensity results were compared in the previous section of this paper. The results for the other major engine surfaces are given in [37] and [40].

5.7 Radiation efficiency of different machine surfaces

The sound power W_{rad} radiated by a vibrating surface of area S is given by equation (1) in section 3.2 of this paper.

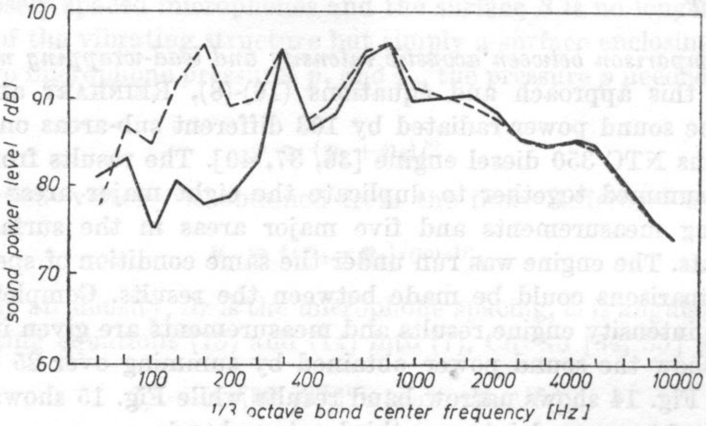

Fig. 15. Comparison of sound power level determined for the oil pan from the spherical lead-wrapping technique — — — —, and the sound power level from the two-microphone acoustic intensity method ———

McGary and Crocker attempted to determine σ_{rad} for the five surfaces of the diesel engine under examination by measuring W from the surface intensity method and dividing by $\langle v^2 \rangle$ which is also determined as a by-product of this approach. The results for σ_{rad} for the five surfaces (averaged over one-third octave bands) are given in [28]. One typical result for the oil pan is presented in Fig. 16. All five surfaces had similar shaped radiation efficiency curves, except at low frequency (below 400 or 400 Hz) where the slopes were different for each surface. At high frequency (above about 1000 Hz) all the surfaces had a radiation efficiency approaching one (as theory should predict).

Forssen and Crocker have recently determined the radiation efficiency of a vibrating metal panel below its critical frequency by using a two microphone method [41, 42]. The sound power W_{rad} was obtained with the two microphone acoustic intensity technique using equation (16) which was summed over the panel area with equation (8). The panel surface velocity was obtained by placing the two-microphone probe very close to the panel surface and moving it over the panel surface to obtain $\langle v^2 \rangle$. Finally, the radiation efficiency σ_{rad} was calculed from equation (1). See [41, 42].

Such radiation efficiency curves, if they can be accurately predicted or measured, can be very useful in machine design in a number of ways. They enable an experimentalist to determine the sound power radiated by each machine surface, simply by measuring the space-averaged mean-square velocity (as a function of frequency) on that surface. This can easily be accomplished using an accelerometer rather than making a complicated or sophisticated intensity or sound power measurement. Also, in principle, if theory can be used to predict the vibration of different surfaces of a machine in the design stage, then the sound power radiated by the different surface can also be predicted before the machine is constructed.

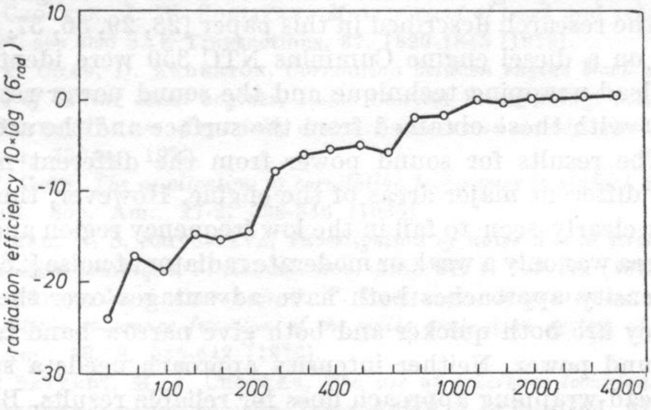

Fig. 16. Radiation efficiency of the oil pan determined at an engine speed of 1500 rpm and a load of 542 Nm

5.8 Noise path identification using acoustic intensity

The intensity technique can be used to determine the sound transmitted through panel structures as has been shown by Crocker *et al.* [43-47]. The two-microphone acoustic intensity approach can be used to measure the transmitted intensity. If the intensity incident on the panel is known or can be measured (e.g. in the case of the incidence of plane wave fields or reverberant fields) then the transmission loss can be deduced immediately. In the case of a composite panel (e.g. a metal panel with a window) the intensity (and thus sound power) transmitted through the metal wall and the window can be measured separately. Thus the sound power transmitted by the wall path and the window path can be distinguished. This has important applications in attempting to determine noise paths in buildings and aircraft structures. Villot and Roland have used this intensity approach successfully to attempt to distinguish between direct and flanking paths in buildings [48]. McGary and Hayes [49] have successfully separated airborne and structure-borne noise paths in aircraft-like structures using the intensity approach.

6. Conclusions

The earlier methods of identifying noise source and paths reviewed in this paper are still useful. However the new intensity techniques promise to become very important in identifying noise sources and paths. The surface intensity (accelerometer-microphone and acoustic intensity (two-microphone) techniques of identifying noise sources have been investigated and further developed in the research described in this paper [28, 29, 36, 37, 40]. The major noise sources on a diesel engine Cummins NTC 350 were identified using the conventional lead-wrapping technique and the sound power results were compared directly with those obtained from the surface and the acoustic intensity techniques. The results for sound power from the different methods agreed quite well for different major areas of the engine. However, the lead-wrapping approach was clearly seen to fail in the low frequency region and also when the noise source area was only a weak or moderate radiator of noise [28, 29, 36, 37, 40].

The intensity approaches both have advantages over the lead-wrapping approach. They are both quicker and both give narrow band frequency information on sound power. Neither intensity approach needs a special anechoic room as the lead-wrapping approach does for reliable results. Both approaches can be used to measure the noise better than lead-wrapping in the lower frequency region and when the source areas are weaker noise radiators. Of the two intensity approaches, the acoustic intensity approach is clearly quicker if the two-microphone array can be hand-held. For safety reasons this is not always possible. However, the surface intensity approach has the advantage over the acoustic intensity approach, in that radiated acoustic power, surface velocity and radiation efficiency information are obtained simultaneously. In addition, the velocity being determined from a transducer measurement in the surface intensity approach is not subject to the same low and high frequency errors as in the acoustic intensity approach (see equation (14)). At low frequency, difficulty with equation (14) is encountered since p_1 and p_2 are almost identical. At high frequency again equation (14) predicts erroneous results when $(\omega/c)\Delta r \to 1$. The two-microphone method can also be used to estimate the velocity of a vibrating surface and to determine the sound transmision paths through wall structures. The intensity techniques hold the promise of very wide application in many machinery noise problems.

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