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APPRAISAL OF TEST PROCEDURES APPLICABLE TO THE MEASUREMENT OF DIESEL ENGINE NOISE

D.T. ASPINALL and R.PETTITT

MOTOR INDUSTRY RESEARCH ASSOCIATION and PERKINS ENGINES

1. INTRODUCTION

The measurement of engine noise is necessary to determine whether standards can be met, to enable comparisons between engines to be made, and to assess the effect of design changes and modifications. For these purposes the noise measurement method should be as reliable and as simple as possible, consistent with giving results which are representative of the noise emission properties of engines in absolute terms.

There are numerous national and international noise measurement procedures (Refs 1, 2, 3, 4 and 5) in existence, or proposed, together with various procedures developed by individual engine manufacturers and institutions. Unfortunately this wide choice has led to noise levels being measured to different procedures, sometimes to an ambiguous and misleading interpretation of results, and difficulties in deciding the test method to use.

The main concern of this paper is to compare the available engine noise test procedures and show the relationship that has been found between them, and the main factors that appear to affect and limit measurement accuracy. It is hoped that this work will stimulate others to publish more measurement data so that more widely agreed and valid standard methods can be achieved for the benefit of the Industry and its Customers.

The subsequent sections examine various procedures and techniques used for determining the noise levels emitted by diesel engines in the 30 to 200 kW power range.

2. THE SOURCE

Engine noise is defined as the noise radiated by the engine surfaces and the ancillaries necessary for its operation. Intake noise, exhaust gas noise, cooling system noise are excluded, and as much as possible of the noise radiated by the flywheel is also excluded since it is, in most applications, enclosed in a housing.

The 'A' weighted spectrum of the noise emitted by I.C. engines is dominated by the frequency range from approximately 500 Hz to about 5 kHz with the highest spectrum levels occurring at about 2 kHz. The overall 'A' and 'C' weighted sound levels are usually very similar.

3. MEASUREMENT METHODS

Over the last 2½ decades, during which time engine noise has been of interest, a number of measurement methods have been developed for the determination of engine noise levels. At first, measurements of sound pressure were made at a fixed distance from the surface of the engine, the distance being dictated in many cases, by the size of the engine test cell in which the measurements were made; often the unshielded dynamometer was in the same cell. Many measuring distances were used, eg 2 ft, 3 ft and 1 metre, so that measurements could not be compared in absolute terms, but gradually the 1 metre distance has been accepted as a standard.

The UK Industry in the early 70s felt the need for tighter engine noise test specifications to ensure confidence in the accuracy and comparability of laboratory measurements. As a consequence the Industry cooperated in the design of a semi anechoic engine noise test cell. Nominally identical cells were built at MIRA and Ricardos, shortly followed by a test cell at Perkins Engines. These cells were large enough to allow sound pressure measurements to be made on a 3 metre radius hemisphere centred on the engine bed plate, to enable sound power to be determined with a small number of fixed microphone positions in order to overcome the problem of having to decide where to position the microphones with respect to the engine. Provision was made in the cells to suppress intake and exhaust noise, a local underfloor engine cooling system was provided and the dynamometers were located in an isolated control room. The cells provided relatively ideal conditions for measuring engine noise.

An attempt was made to standardise test procedures and microphone positions but this proved to be almost impossible at this early stage and it was resolved to compare a number of sound pressure methods which were in use at the time with methods giving a measure of sound power. Comparisons were made between the sound power determined from 6 microphones on a 3 m hemisphere (Fig 1a and Appendix 1) and the results from procedures using various numbers of microphones positioned at a variety of 1 m microphone positions. Some indication of the variety of specifications for 1 m microphone positions in various standards and procedures can be seen from the following examples:-

a) 3 microphones positioned at exhaust manifold height 1 m from the surface of an imaginary parallelepiped enclosing the engine.
b) 3 microphones positioned 1 m from the engine surface at the height of the crankshaft centre line, and one microphone 1 m from the centre of the top surface of the engine.
c) 3 microphones positioned 1 m from the engine surface at a height midway between the crankshaft centre line and exhaust manifold height.
d) 4 microphones at ½ the height of the rectangular parallelepiped measuring surface around the engine and 5 microphones on the top horizontal surface of the parallelepiped.
e) A number (depending on engine size) of microphones positioned 1 m from the sides of the engine midway between the crankshaft and the top of the cylinder head.

4. RESULTS

4.1 Noise Cell Acoustic Conditions

The results quoted in this paper were obtained in either the MIRA or Perkins noise test cells which are to the same design. The cells have a volume of 200 m^3 with 0.3 m long foam wedges on the walls and ceiling resulting in a nominal cut-off frequency of 200 Hz. The acoustic performance of each test cell has been determined. The MIRA cell was evaluated by measuring the noise level of an engine in the cell and then repeating the measurements outside in true hemispherical free field conditions. The results of these tests are plotted in Fig 2 which shows very good agreement between the two measurement environments.

The Perkins noise cell was evaluated using a calibrated sound power source (Bruel and Kjaer Type 4205). Sound pressure levels were measured both in the cell and in true hemispherical free field conditions at 3 m radius. From the measured sound pressure levels sound power levels were calculated (see Appendix 1) and compared with the calibrated levels of the sound source. The results of this comparison are shown in Table 1. The results show good correlation throughout the frequency range.

TABLE 1 COMPARISON OF SOUND POWER LEVELS (dB re 1 pW)

Condition	Octave Band Centre Frequency (Hz)						
	125	250	500	1000	2000	4000	8000
Calibrated Level of Sound Source	95.0	95.0	95.0	95.0	95.0	95.0	95.0
Noise Cell	95.9	95.0	95.0	94.7	95.0	95.3	95.8
Hemispherical Free Field	95.0	95.4	95.0	94.4	94.3	94.8	95.8

4.2 Sound Pressure Levels at 1 Metre

The sound pressure level, at 1 m, emitted from an engine varies over its surface. A typical example of this is shown in Fig 3. The sound pressure level gradually decreased as the microphone was raised from ground level up to the top of the engine. The 1 metre microphone positions adopted for the measurements reported in this paper are shown in Fig 1b.

4.3 Repeatability of Engine Noise Tests

To determine the repeatability, on the same engine, of engine noise tests, 4 microphones were positioned at 1 metre from an engine as shown in Fig 1b. The engine was run at a constant speed of 2000 rev/min, full load, and a total of 10 consecutive tests were carried out during an elapsed time of 30 minutes. The measurements were carried out with a digital real time analyser, 16 spectra being averaged for each microphone. The results from the 4 microphones were then averaged for each test. The standard deviation of the overall dBA level for the 10 nominally identical tests was 0.2 dBA, indicating that 95% of the measured data would be in the range ± 0.4 dBA.

The standard deviation of measured noise levels for several engines of the same type has also been determined. The noise levels of production engines were measured at their rated speed and power and the standard deviation about the mean level calculated. Table 2 summarises the results which show the variation in the measured standard deviations of noise levels from samples of a number of nominally identical engines. The results indicate that in 95% of cases a single example of an engine of one particular type could emit a noise level in the range from ±0.8 to ±1.6 dBA about the mean. The pooled estimate for the standard deviation was 0.59 which indicates that the noise levels of nominally identical engines are likely to fall, in 95% of cases, within

± 1.2 dBA about the mean. The distribution of the engine noise levels was shown to be Gaussian.

TABLE 2 STANDARD DEVIATIONS OF ENGINE NOISE LEVELS

Engine Type	Number of Engines Tested	Standard Deviations (dBA)
A	7	0.77
B	15	0.43
C	10	0.56
D	10	0.70
E	10	0.42
F	10	0.60
G	10	0.49
Pooled Estimate	72	0.59

4.4 Measurements on 3 Metre Radius Hemisphere

Measurements using arrays of 6, 12, 18, 24 and 30 microphones on the 3 m radius hemisphere on a number of engines have shown that increasing the number of microphones has little effect on the mean overall dBA levels. Some typical variations in overall levels are shown in Table 3. The effect on the ⅓-octave spectra was also found to be small as can be seen from the envelope of mean ⅓-octave measurements shown in Fig 4a.

The measurements referred to in Section 4.1 demonstrate the good agreement between the test cell measurements and measurements made in true hemispherical free space in the open air. The mean overall levels differed by less than 0.25 dBA, and at any one microphone the levels differed by less than 1.5 dBA.

4.5 Comparison Between 1 m and 3 m Measurements

Comparisons were made independantly at MIRA and at Perkins Engines between the means of measurements made at 1 m (front, top and two sides as shown in Fig 1b) and the means of six microphones on a 3 m radius hemisphere (Fig 1a). The results of these two sets of measurements are shown in Fig 5. It is to be noted that the equations of the regression lines for determining the sound power level of an engine from 1 m measurements given in the Figures differ slightly. However the good agreement between the results can best be appreciated by substituting values into the two regression equations; in both cells the sound power level of an engine is given by adding 12.1 dB to the mean 1 m measurements, within the important sound pressure level range of 85 - 100 dBA.
ie SWL ≡ Average SPL at 1 m + 12.1 dBA
In both cells the standard error in predicting SWL from 1 m measurements was approximately 0.6 dBA. The conversion factor of 12.1 dB can also be applied to the ⅓-octave spectrum values as shown in Fig 4b.

A total of 81 engines, both vee and in line, was used to determine the relationship between sound power and 1 metre sound pressure level.

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4.6 Comparison of Engine Noise Measuring Procedures

A 4 cylinder diesel engine was run at 2000 rev/min, full load, and its noise level determined to various procedures, the results of which are summarised in Table 3.

TABLE 3 THE EFFECT OF TEST PROCEDURE ON ENGINE NOISE LEVELS

Test Procedure	Number of Microphones	Average Sound Pressure (dBA re 20 uPA)	Sound Power (dBA re 1 pW)
BS 4196 (3 m hemisphere)	6 12 18 24 30	88.4 88.4 88.7 at 3 metres 88.9 88.8	105.9 105.9 106.2 106.4 106.3
MIRA/Perkins (1 metre)	4	93.5 at 1 metre	105.6
ISO 3744 (Parallelepiped)	9	91.5 at 1 metre	106.9
CIMAC and DIN 45635 (Parallelepiped)	6	92.6 at 1 metre	108.0
SAE J1074	3	91.6 at 1 metre	*
* A method for the determination of sound power is not given			

The ⅓-octave spectra of the engine sound power levels for the various test procedures are plotted in Fig 4b which shows that all the procedures give similar shaped spectra but the levels differ.

5. DISCUSSION

From the manufacturer and users points of view the measurement of the noise emitted by automotive size engines is not yet satisfactory. Different measurement procedures utilizing the 1 metre measurement distance can give different results. An example of this is given in Table 3 which shows that a particular engine was apparently 2 dBA quieter when tested to the SAE J1074 1 metre procedure when compared to the tests carried out to the MIRA/Perkins 1 metre procedure. The differences arise because of the different surfaces from which the 1 metre measurements were made, which effectively alters the distance of the microphone from the engine. The SAE procedure stipulates microphones at 1 metre from the surface of an imaginary parallelepiped completely enclosing the engine whereas the MIRA/Perkins procedure uses microphones at 1 metre from the surface of the engine itself.

Sound pressure measurements, at approximately 1 m from the engine surface, vary with distance at a rate of between -3.0 to -6.0 dBA/doubling of distance depending upon the engine and microphone position. This corresponds to a rate of change in the measured sound pressure level of 0.4 to 0.8 dBA/0.1m. Unfortunately it is often difficult to specify unambiguously the positions of the microphones to 0.1 m.

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It was thought that the use of sound power would overcome the problems encountered with the 1 metre procedures. However there are discrepancies among the sound powers of an engine determined with the 3 m radius hemisphere method and those obtained using the rectangular parallelepiped method as shown in Table 3. The detailed reasons for the discrepancies are not known, but one possible cause is that the surface area of the parallelepiped may not increase with distance, at the same rate as the sound pressure decreases. Thus, since sound power is the product of the average sound pressure and the area over which it is being radiated, it is possible for the sound power level of an engine to vary with the measuring distance. An example of this is shown in Fig 6 which shows that using a measuring distance 2 metres from the engine, instead of 1 metre, could change the sound power by between +1.3 to - 1.7 dBA compared with that obtained at 1 metre. On the other hand sound power is less sensitive to uncertainties in the distance measurement. Unfortunately the standards and draft standards for determining sound power are very time consuming to carry out because of the number of microphone positions required, and the time taken to locate them and determine the surface area of the resulting rectangular parallelepiped. However, the sound power of automotive sized engines can be found easily, and with reasonable accuracy (± 1 dB) by adding 12.1 dB to the average 1 metre measurements. This result will only apply in test cells which simulate hemispherical free field conditions, use an engine crankshaft height 1 metre above the ground and use microphones positioned as shown in Fig 1b.

6. CONCLUSIONS

1) The existing procedures for rating the noise emitted by engines are unsatisfactory. Its determination according to existing procedures is time consuming, the results obtained vary significantly with the procedure used, and not all procedures offer the means for determining sound power.
2) Sound power provides a means for reducing the uncertainty in the rating of the noise emitted by engines. The single figure rating provided is useful for comparing with intensity measurements and sound power from vibration measurements.
3) Sound power can be determined relatively simply and to a satisfactory degree of accuracy on conventional automotive engines mounted at a crankshaft height of 1 metre by the addition of 12.1 dB to the mean of four sound pressure measurements obtained at 1 metre from the surface of the engine.

REFERENCES

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APPENDIX 1

Calculation of Sound Power Level and Directivity Index from Microphones Positioned on the Surface of a 3 m Radius Hemisphere.

$$SWL = SPL_A + 10 \log_{10} 2\pi r^2 \quad (dB)$$

where SWL = Sound Power Level (dB re 1 pW)

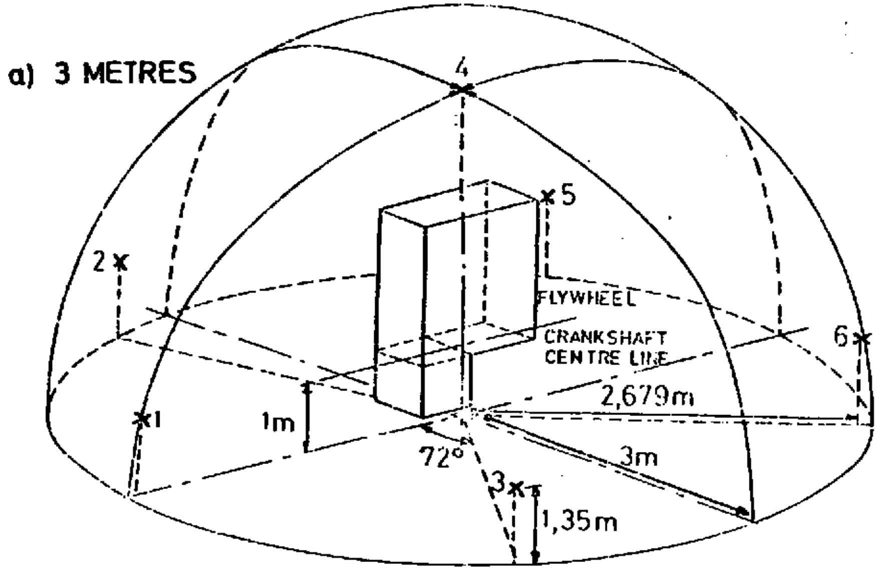
SPL_A = Average Sound Pressure Level (dB re 20 μPa)

$$= 10 \log_{10} \frac{1}{n} \left[\text{antilog}_{10} \frac{SPL_1}{10} + \ldots\ldots\ \text{antilog}_{10} \frac{SPLn}{10} \right]$$

where n = number of microphones
r = radius of hemisphere (m)

when r = 3 metres,

$$SWL = SPL_A + 17.5 \text{ (dB)}$$



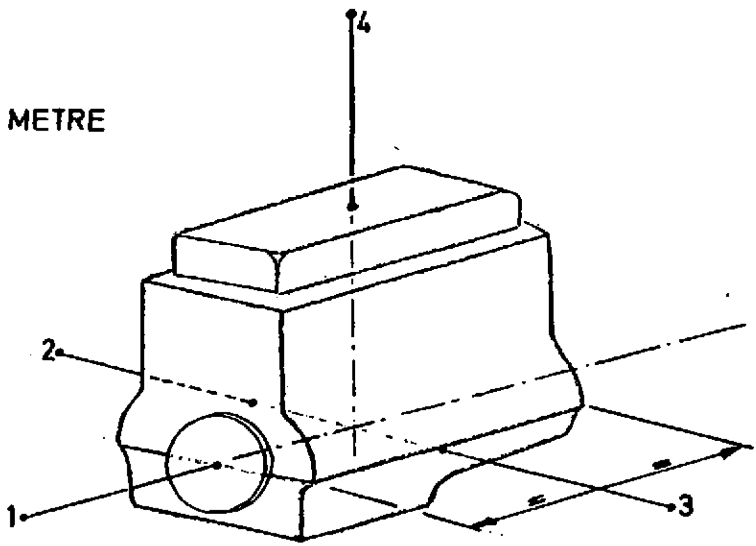


FIG 1 MICROPHONE POSITIONS

Appraisal Of Test Procedures Applicable To The Measurement Of Diesel Engine Noise.

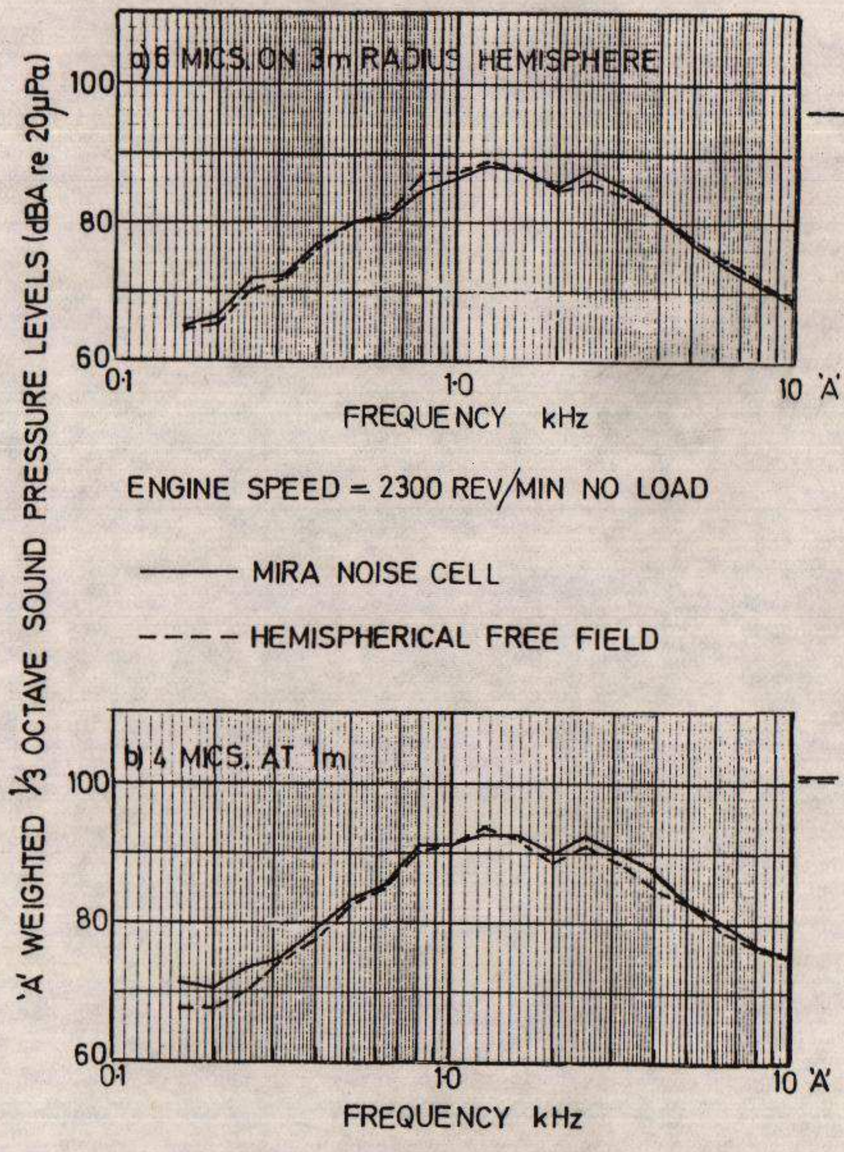


FIG 2 NOISE CELL & HEMISPHERICAL FREE FIELD COMPARISON

Appraisal Of Test Procedures Applicable To The Measurement Of Diesel Engine Noise.

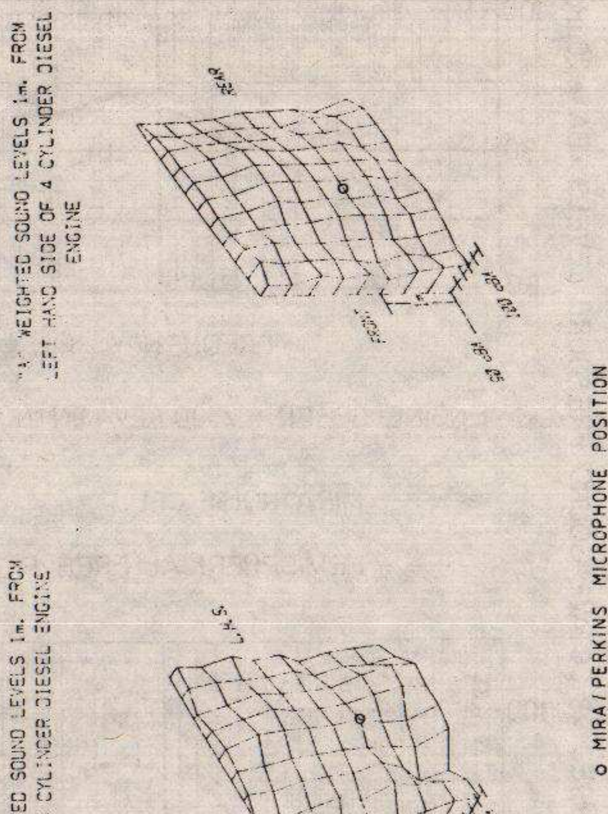


FIG 3 VARIATION IN SOUND PRESSURE AT 1m FROM ENGINE

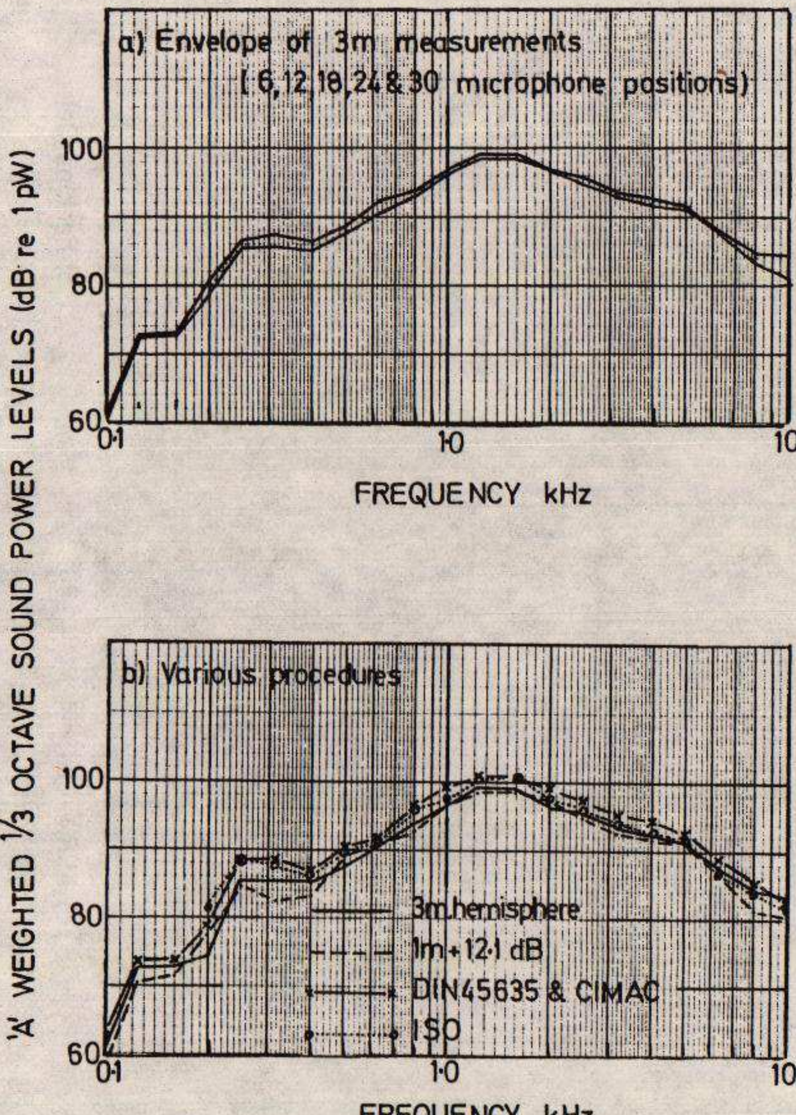


FIG 4 ENGINE SOUND POWER SPECTRA

Appraisal Of Test Procedures Applicable To The Measurement Of Diesel Engine Noise.

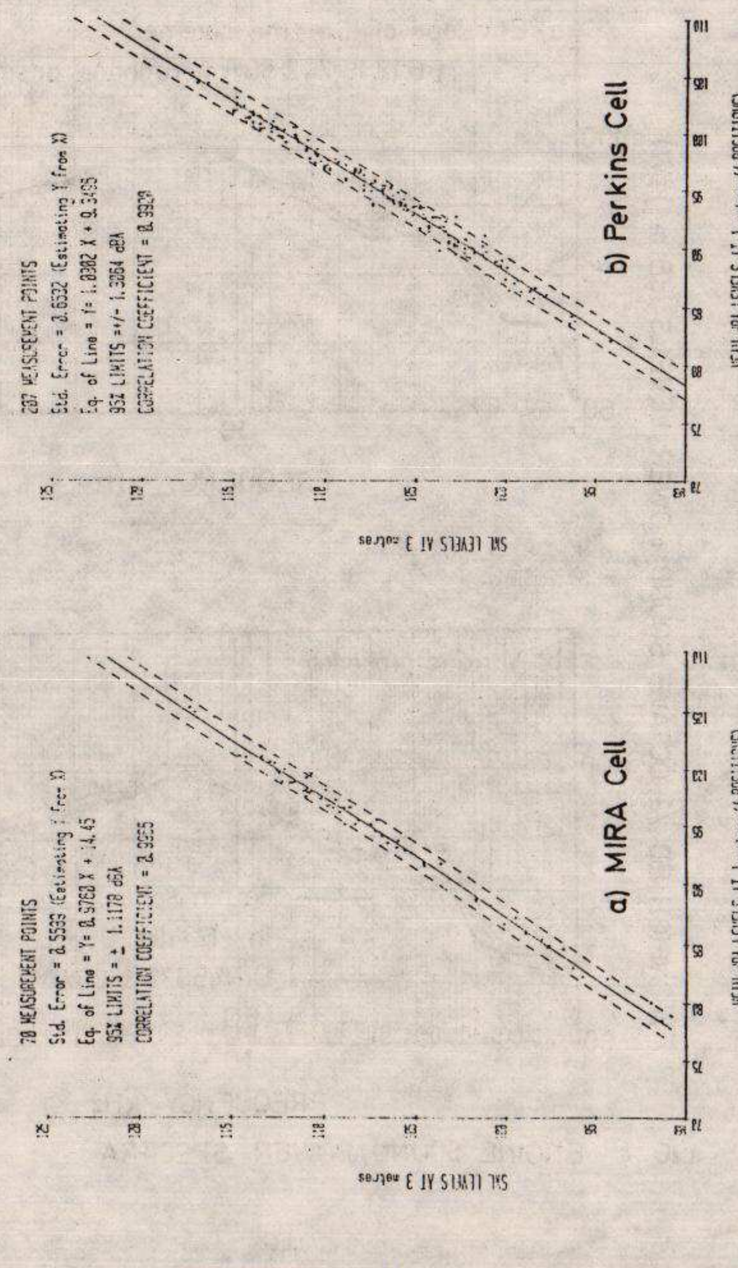


FIG 5 CORRELATION BETWEEN SOUND POWER CALCULATED FROM 3m MEASUREMENTS

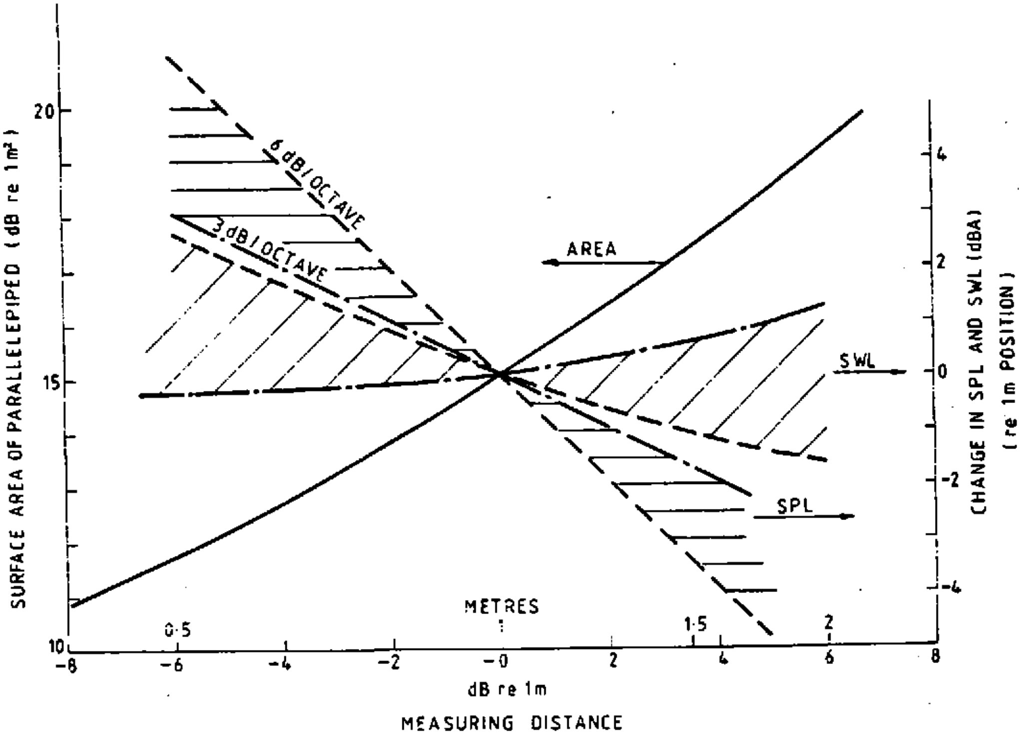


FIG 6 VARIATION IN PARALLELEPIPED SURFACE AREA, SPL AND SWL AGAINST DISTANCE FROM ENGINE