Alternator tonal noise target setting

ALTERNATOR TONAL NOISE TARGET SETTING

S. J. Walsh

Department of Aeronautical and Automotive Engineering,

Loughborough University, Loughborough, LE11 3TU, UK.

I. Robinson

Ford Motor Company,

Small and Medium Vehicle Centre, Laindon, Basildon, SS15 6EE, UK.

G. Stimpson

Institute of Sound and Vibration Research,

University of Southampton, Highfield, Southampton, SO17 1BJ, UK.

3 Copies Submitted

17 Manuscript pages

13 Figures

1 Table

ADDRESS FOR CORRESPONDENCE:

Dr S. J. Walsh

Department of Aeronautical and Automotive Engineering

Loughborough University

Loughborough, LE11 3TU, UK

Summary

The aim of the research reported in this paper is to develop a procedure to determine target levels for the tonal noise emitted by a vehicle alternator. The investigation begins with a study into the contribution of the alternator to the noise inside the vehicle. This is followed by the description of an experiment to determine subjectively threshold levels for alternator tonal noise. From the results of these tests alternator noise target levels are derived. Finally, the derived alternator target noise levels are compared with current alternator performance.

1. Introduction

The increasing level of competition in the motor industry and the increasing level of customer expectations has led a general trend towards quieter and more refined cars. The interior noise of a car is made up of contributions from many sources, and is influenced by many factors. Low frequency noise, below 500 Hz, is mostly generated through structure-borne vibration emanating from the powertrain and transmitted through the various connection points to the vehicle body and into the passenger compartment. This noise contribution has been reduced dramatically over the past few years resulting in a much quieter passenger compartment. However, a consequence of this is that high frequency noise has become much more intrusive because of the reduction in the masking effect of low frequency structure-borne noise. High frequency noise comes from a variety of sources, and is generally airborne rather than structure-borne. Broad-band noise sources include wind and tyre noise. However, possibly more annoying to the driver are narrow-band high frequency noises, classified as 'whine'. These are mainly attributable to radiation from the powertrain and the various ancillary components attached to it. Of all the ancillary components the principal noise source at high frequency is generally the vehicle alternator.

By the nature of its design and operation, the alternator will always produce high frequency noise at various frequencies related to its specific design. At low rotational speeds the noise is dominated by vibrations produced by alternating magnetic forces, an effect which increases with increasing load on the alternator. The frequency of these noises is related to the interaction between the rotor and the stator, and is typically of 30th, 36th and 42nd alternator rotational order. These vibrations also excite resonances in the alternator structure that are perceived as peaks in the overall noise at the various resonance frequencies. Techniques are now being developed [1,2,3] to predict the noise generated by alternating magnetic forces and, hence, to reduce the radiated noise [4]. The other main source of alternator noise is aerodynamic noise generated by the various rotating parts of the alternator. The dominant contributors to aerodynamic noise are the cooling fans, which induce noise in two ways: broad-band noise which is produced by vortex shedding due to turbulent air flow at the tips of the fan blades and tonal noise which is produced by interactions between the fan blades and some stationary object. Aerodynamically generated noises dominate at higher rotational speeds of the alternator, typically above 5500 revolutions per minute (r.p.m.). Research has been conducted by, among others, Frederick and Lauchle [5] to identify the sources of aerodynamic noise in an alternator. There are several other sources, such as the bearings and the brushes, but these are generally insignificant. An illustration of the sources of alternator noise is shown in Figure 1.

Typically, a maximum allowable overall noise level from the alternator is specified in an attempt to minimise the intrusive effect if the alternator. However, Mesaric and Boltezar have shown [6] that the tonal nature of the alternator noise produces a subjectively unacceptable sound even though the alternator meets the specified overall noise level. Clearly what is needed is a means of giving the alternator manufacturers guidance on the levels of pure tones that are acceptable. This paper reports on the development of a methodology to derive such tonal noise target levels [7]. In section 2 the contribution of the alternator to the overall interior noise level in the vehicle is established. The predicted noise levels are obtained by using the volume velocity of the alternator combined with transfer functions from the alternator location to the driver's ear position. The experimental apparatus used to measure the noise from the alternator is described and the technique used to measure the vehicle transfer functions explained. Predictions of the interior noise due to the alternator are compared with measured interior noise levels. In section 3 an experiment to determine threshold levels for alternator noise is described. The results of subjective listening tests are presented and from these results alternator tonal noise target levels are derived. The application of the derived target levels is illustrated on an existing alternator noise problem.

2. Prediction of the contribution of the alternator to vehicle interior noise

An illustration of the way alternator tonal noise is perceived by the occupants of a vehicle passenger compartment is shown schematically in Figure 2. It can be seen that tonal noise produced by the alternator is modified by the vehicle body on its way to the passenger compartment. The masking noise inside the passenger compartment of the vehicle is made up of contributions from structure-borne and air-borne sources. Thus, the tonal noise perceived by the vehicle occupants is a combination of the modified alternator tone masked by the noise from other sources. To indicate the contribution of the alternator, predictions of vehicle interior noise were made using the measured volume velocity of the alternator and transfer functions measured between the alternator location and the driver's ear position. The level of the masking noise was established by taking measurements of the overall sound pressure level inside the vehicle.

2.1. Experimental apparatus and method

To measure the transfer function from the alternator location to the driver's ear position a suitable noise source should be placed in the engine compartment at the alternator mounting position, y. The response at the driver's ear position, x, can then be measured and a transfer function calculated directly from the ratio of sound pressure at the driver's ear position, p(f,x), to the acoustic source volume velocity at the alternator location Q(f,y). Thus,

$$H(f) = \frac{p(f,x)}{Q(f,y)}, \tag{1}$$

where, f, is the frequency in Hz. However, in order to simplify the measurement procedure the principle of acoustic reciprocity [8,9] can be invoked:

$$\frac{p(f,x)}{Q(f,y)} = \frac{p(f,y)}{Q(f,x)} \tag{2}$$

where Q(f,x) is the volume velocity of the source located at the driver's ear position and p(f,y) is the resulting sound pressure level at the alternator location. Thus, for the transfer function measurements reported in this paper the noise source was positioned at the driver's ear position and the response was measured with a microphone at the alternator location in the engine compartment.

The vehicle used for these experiments was a 2.0l saloon car which for this model type had a standard production alternator fitted at the bulkhead side of the engine. The alternator had a cooling fan with 11 blades, a rotor with 6 poles, and a stator with 36 windings. Measurements were also made on an older and noisier design of alternator with an external cooling fan constructed with 13 blades.

An omni-directional noise source was used which produced sufficient sound over the entire frequency range, 100 - 10000 Hz, of a typical alternator. The source used was a combination of loudspeakers and compression driver units which were directed into a single conical output nozzle tapering to a small outlet aperture. Small outlet dimensions maintained reasonable omni-directivity over the required frequency range. The output was monitored by a microphone positioned at the output nozzle. A diagram of the source is shown in Figure 3.

The volume velocity of the source was calculated from measurements of sound pressure made in free-field conditions. Sound pressure was recorded at a number of points on a sphere around the source at a distance of 0.5 m. These results were averaged and the volume velocity calculated using the following relationship:

$$Q(f) = \frac{2rp_r}{\rho f} \tag{3}$$

where p_r is the sound pressure at the radius distance, r, and ρ the density of air. Simultaneously, the sound pressure was measured with the microphone located at the source output nozzle. From this ratio of sound pressures a value of the volume velocity could be calculated during transfer function measurements.

To measure the vehicle transfer function the noise source was positioned in the passenger compartment and the response was measured at the alternator position in the engine compartment. The sound levels produced by the source were monitored using the nozzle microphone. Hence, a value of volume velocity was calculated from the free-field volume velocity measurements and the ratio of sound pressures between the nozzle and far-field microphones derived previously. To obtain a good signal to noise ratio in the transfer function measurements a swept-sine input signal was used. For clarity of presentation the results were converted into 1/3 octave bands.

To test the assumption of acoustic reciprocity, the transfer function was also measured directly. Thus, the source was placed at the alternator position in the engine compartment and the response was measured with a microphone at the driver's ear position inside the vehicle. To enable the sound to be positioned in the engine compartment a long flexible tube was connected to the end of the source so that the omni-directional output nozzle could be placed at the desired location.

Predictions of the contribution of the alternator to the overall interior noise level were made by multiplying the reciprocally measured transfer function, H(f), by the volume velocity of the alternator, Q(f,y). Thus, the sound pressure at the driver's ear was predicted by rearranging equation (1):

$$p(f,x) = H(f)\, Q(f,y) \tag{4}$$

A diagram of the experimental apparatus used to measure the volume velocity of the external fan alternator is shown in Figure 4. The alternator was driven via a belt from a large electric motor located in the housing underneath the reflecting plane. The speed of the alternator was increased from 1000 r.p.m. to 15000 r.p.m. at a constant rate over a 5 second period with spectral readings taken at increments of 100 r.p.m. This procedure allows noise levels to be measured in accordance with the guidelines set out in reference [10] for a sound source with hemispherical propagation. However, this design is not ideal as there may be leakage of noise through the belt aperture. Thus, an alternative alternator noise rig was designed which minimised any reflections and, thus, allowed spherical propagation of the sound. In this design the alternator was driven by via a belt from a small electric motor. However, the simplicity of the design did not allow any load to be applied to the alternator.

2.2. Results

Noise from the external fan alternator and the standard production alternator was measured on the hemispherically propagating alternator noise rig shown in Figure 4. The sound pressure level from the external fan alternator measured at one of the microphone positions is displayed in waterfall form in Figure 5, where the variation of alternator sound pressure level with alternator speed and frequency is shown. The data indicate high sound pressure levels corresponding to the 6th and 13th rotational orders of the alternator.

A comparison between directly measured and reciprocally measured acoustical transfer paths is shown in Figure 6, where for simplicity the data have been shown as receiver sound pressure level minus source sound pressure level. The data indicate good agreement between the direct and reciprocal transfer functions below 1250 Hz. The differences at higher frequencies may be due to some lack of omni-directivity of the source, or the sensitivity of the transfer function measurements to the exact microphone position.

The contribution of the standard production alternator to the overall vehicle interior noise is shown in Figure 7. Measurements of the total noise in the interior of the vehicle were made with the vehicle on a chassis dynamometer in a semi-anechoic chamber. The overall A-weighted noise levels (solid lines) in dB were calculated from a number of microphone positions in the vehicle interior. Recordings were made whilst the vehicle was in 2nd gear under full load. The alternator contributions (dashed lines) were calculated using equation (4) by multiplying the reciprocally measured transfer function by the appropriate alternator volume velocity. The contribution of the alternator to overall interior noise was calculated for a number of discrete engine speeds: Figure 7(a) shows the alternator contribution at 6450 r.p.m.; Figure 7(b) the contribution at 3850 r.p.m.; and Figure 7(c) the contribution at 1300 r.p.m. It can be seen in Figure 7 that the total noise levels in the vehicle interior (solid lines) do not indicate any spectral peaks due to the alternator. This result is supported by subjective examination, since the tonal noise from the alternator is generally not perceived within the background noise level.

However, the predicted contributions (dashed lines) indicate that at high engine speeds and high frequencies the alternator makes a significant contribution to the overall interior A-weighted sound pressure level. For example, in the predicted data shown in Figure 7(a), the spectral peak due to the 6th alternator order is 51 dB. This compares with a total interior noise value of 55 dB at that frequency. Similarly the spectral peak due to the 11th alternator order is 48 dB and the total interior noise value is 51 dB at the same frequency. The 6th and 11th alternator orders are also marked in Figure 7(b). In this example the spectral peak due to the 6th alternator order is 47 dB and the total noise 51 dB at the same frequency. For the 11th alternator order the predicted and total noise levels are 41 and 48 dB, respectively. The predicted contribution of the alternator is less evident at the lower engine speed shown in Figure 7(c).

The predicted contribution of the alternator given above is based upon the assumption of a monopole source. However, for an aerodynamic source, such as the alternator, the radiated sound pressure may vary with direction. Thus, to investigate any differences in the noise radiated from the different sides of an alternator a microphone scan of the standard production alternator and the external fan alternator was carried out on the spherical propagation rig. Readings were taken at a distance of 0.5 m at 10° intervals in three planes with the alternator running at 15000 r.p.m. The frequency content of the radiated noise was assessed by taking $^1/_3$ octave spectra at each of the measurement points. The 1/3 octave band centred at 2500 Hz contains frequencies between 2223 Hz and 2787 Hz which covers the alternator rotational orders between 8.89 and 11.15. This particular alternator has cooling fans with 11 blades, thus, the majority of the noise in this frequency band can be attributed to the fans. The results of a horizontal sweep of the standard production alternator are shown in Figure 8, where the overall sound pressure level (solid line) is compared to the sound pressure level in the 2500 Hz band (dashed line). The data indicate that the total sound pressure level remains approximately constant with direction. However, the sound pressure level in the 2500 Hz band varies cyclically around the alternator with four distinct peaks being indicated. The lowest levels of fan noise are at angles of 45° to the main axis of the alternator.

Hence, the noise radiated from the alternator exhibits a directivity pattern in the frequency band associated with the 11^{th} alternator order. Thus, the values of the predicted contribution in this frequency band may not be accurate. Nether-the-less, the trend of the data shown in Figure 7 gives a clear indication that the alternator is likely to be a significant contributor to the overall noise level at high engine speeds and high frequencies.

3. Subjective determination of the alternator threshold noise level

3.1. Experimental apparatus and method

In order to determine target levels for alternator noise, a number of subjective listening tests were undertaken. The objective of these tests was to determine a threshold level for alternator tonal noise. To achieve this a method of superimposing a pure tone onto the overall interior noise level was developed. This equipment was based on a compression driver unit with a lower frequency limit of approximately 500Hz. A long tube was attached to the noise source which allowed the noise to be introduced at a suitable position in the engine compartment and provided a small omni-directional outlet for the sound. A schematic representation of the test equipment is shown in Figure 9. The superimposed sine-wave was linked to alternator rotational order via an alternator speed reading obtained with the optical sensor. Thus, as the subject changed the engine speed the frequency of the superimposed sine-wave changed, which simulated the effect of alternator noise. The frequency of the superimposed tonal noise is also dependant upon the drive ratio of the alternator. In this case the drive ratio was 2.34:1.

The experiment was conducted using the method of adjustment [11]. In this method the listener is asked to adjust the gain control on the power amplifier and, thus, the level of the superimposed tonal noise inside the vehicle until the threshold noise level was reached. A gain control without locating features was used, and the starting point was varied by the experimenter between tests to avoid problems of biasing due to control position. Testing was carried out with the standard production alternator remaining in the vehicle. Except at high alternator speeds, the tonal noise from this alternator was subjectively masked by the overall level of background noise in the vehicle. After initial trials a matrix of test conditions was established based on five different engine speeds and five different alternator orders. These test conditions are shown in Table 1. The number of tests was set such that it was possible for a complete assessment to be carried out in 30 minutes.

To conduct the assessment each subject was asked to set the alternator order and to obtain the correct engine speed using the accelerator pedal. Each subject was then required to adjust the gain on the amplifier up and down until the threshold level for the superimposed tone was reached. The level on the ammeter was then recorded by the experimenter on the pro-forma illustrated in Table 1. The engine speed was then changed and the procedure repeated. This was done at all five engine speeds. The alternator order was then reset and the test repeated again at all engine speeds. To check that the results were repeatable, the subject was asked to repeat one or two of the test conditions. The vehicle and test facility were available for three days during which time 13 subjects performed the assessment.

The volume velocity of the tonal noise source was calculated using the same procedure as used for the wideband omni-directional source described earlier. Thus, the source was removed from the vehicle and reassembled in free-field conditions. The alternator was replaced by an electric motor to provide the speed signal. The amplifier was set to the respective gain values obtained during the subjective listening tests. Measurements were taken of the sound pressure level at the source nozzle and at a distance of 0.5 m. Thus, for each amplifier gain setting the source volume velocity could be derived. Alternatively, the sound pressure level at a distance of 0.5 m from the source could be used directly as a target level for alternator noise measurements.

3.2 Results

Threshold sound pressure levels at 0.5 m were derived for all thirteen subjects. From these values a linear average was calculated. The mean and plus and minus one standard deviation data are shown in Figure 10 for each engine speed and alternator order. Third order polynomials were fitted to the mean data to allow an interpolation of the threshold values at regular frequency intervals. The derived threshold target levels are displayed as a contour plot in Figure 11. The threshold values are shown over a frequency range of 1800 to 6000 Hz and over engine speeds ranging from

3000 to 6000 r.p.m. This mid to high frequency range was identified in section 2 as being the most significant region for alternator noise. The data in Figure 11 indicate a shallow maximum in the threshold values at 2750 Hz for the higher engine speeds. As expected the threshold levels increase with increasing engine speed. This pattern reflects the predicted contribution of the alternator to interior noise in the vehicle shown previously in Figure 7.

From the data shown in Figure 11 it is possible to derive target values for each rotational order of an alternator for a given drive ratio. This data can then be compared to measured alternator noise. Figure 12 shows a comparison of the derived target values and measurements of the sound pressure level recorded at 0.5 m from a large diameter alternator. The measurements were made on the hemispherical alternator noise rig shown in Figure 4. Thus, the target values were adjusted for hemispherical propagation by increasing the previously derived spherical propagation values by 3 dB. Figure 14(a) shows the 6th alternator order, Figure 14(b) the 12th alternator order and Figure 14(c) the 24th alternator order. The derived target values are based on a drive ratio of 2.5:1. The data in Figure 12 indicate a potential interior noise problem at higher alternator speeds due to the 6th and 24th alternator orders.

Figure 13 shows a comparison of the derived target values with measurements of alternator sound pressure level for an existing "noisy" alternator. For this alternator the vehicle interior noise was considered to be unacceptable at low engine speeds with a high electrical load. The alternator was modified and acceptable levels of alternator noise achieved. Measurements of sound pressure level were made for the original alternator and the modified version using the hemispherical noise rig shown in Figure 4. Alternator noise associated with electrical load is typically related to the 36th alternator order. Hence, a target level was derived for the 36th alternator order. Figure 13 shows the measured sound pressure level for the original alternator (dashed line), the modified alternator (dotted line) and the target level (solid line) for the 36th alternator order. The data in Figure 13 indicate that the modified "quiet" alternator meets the target level, while the original "noisy" alternator exceeds the target level.

4. Discussion of results

To measure the volume velocity of the alternator, two experimental rigs were used both of which assumed that the alternator sound propagates spherically from the source. However, the supporting structure of the spherical noise propagation rig inevitably induced some reflections in the radiated sound field. The hemispherical noise propagation rig assumed a perfectly reflecting plane beneath the alternator. However, the actual reflecting surface contained gaps for the alternator drive mechanism and, thus, did not provide a perfect reflection. In practice it was found to be more convenient to use the hemispherical noise propagation rig as the control equipment and a larger drive motor could be mounted underneath the reflecting plane.

The prediction of the contribution of the alternator to the overall interior noise level was based upon multiplication of the alternator volume velocity with the reciprocally measured transfer function from the alternator location to the driver's ear position. This simplification is best justified for omni-directional sources and receivers or in reverberant spaces where the directionality of the direct field is buried by the diffusivity of the reverberant space. However, investigation of the alternator directivity pattern revealed that this assumption was violated in certain frequency bands. For an arbitrary vibrating structure, such as the alternator, a more accurate prediction of interior noise could be made by discretising the structure into a number of volume velocity point sources as described in references [12] and [13].

The derivation of the alternator tonal noise target levels relied upon a subjective determination of the threshold level of the tonal noise at a particular alternator order. Inevitably, the threshold noise levels varied from subject to subject. Hence, the final target levels are derived from an average taken from of a number of subjects. The number of subjects chosen for this study was based upon a compromise between the need for a sufficiently large sample of subjects and the total time available for the experiment. A larger number of subjects could be expected to produce better estimates of the derived target levels.

5. Conclusions

A number of conclusions can be drawn from the research reported in this paper:

- At high engine speeds the alternator makes a significant contribution to the high frequency noise level in the passenger compartment. At low engine speeds and low frequency the contribution of the alternator is less significant.
- Alternator noise target levels have been derived based upon subjective determination of threshold levels for tonal noise.
- Initial results have shown that a vehicle fitted with an alternator which meets the derived target has an acceptable interior noise level. Conversely, when the vehicle was fitted with an alternator which did not meet the derived target the interior noise level was unacceptable.

References

1. P. G. Blaschke, D. J. Ewins: Vibro-acoustic model for the noise reduction of a car alternator. Proceeding of the International Modal Analysis Conference, IMAC '96, 1356-1361, (1996).
2. N. Saga, Y. Iwaki, Yoshiyuki, M. Nakazawa: Study on electromagnetic noise of an alternator (Noise source identification using modal analysis). Transactions of the Japan Society of Mechanical Engineers, **61**, Part C, 3532-3537, (1995).

3. S. J. Suh, J. Chung, B. D. Lim, C. H. Hwang: Case history - Noise source identification of an automobile alternator by r.p.m. dependent noise and vibration spectrum analysis. Noise Control Engineering Journal, **37(1)**, 31-36, (1991).
4. T. Nagai, D. K. Lieu: Acoustic noise reduction in automobile alternator by constrained layer damping of the structure. Society of Automotive Engineers, S.A.E. Technical Paper Series, Paper No. 920407, (1992).
5. D. M. Frederick, G. C. Lauchle: Aerodynamically-induced noise in an automotive alternator. Noise Control Engineering Journal, **43(2)**, 29-37, (1995).
6. M. Mesaric, M. Boltezar, A. Kuhelj: The influence of the unsymmetrical alternator fan blade spacing to the total sound pressure level and spectra of aerodynamic noise. Proceedings of Internoise '96, Liverpool, U.K., 30 Jul. - 2 Aug. 1996, 207-210, (1996).
7. I. Robinson: Accessory tonal noise target setting. M.Sc. Thesis, Loughborough University, (1998).
8. F. J. Fahy: The reciprocity principle and applications in vibro-acoustics. Proceedings of the Institute of Acoustics **12**(1), 1-20, (1990).
9. I. L. Vér, R. W. Oliphant: Acoustic reciprocity for source-path-receiver analysis. Sound and Vibration, March 1996, 14-17, (1996).
10. I.S.O. 3745 - 1977(E). Determination of sound power levels of noise sources. Precision methods for anechoic and semi-anechoic rooms. International Standards Organisation, (1977).
11. S. A. Gelfand: Hearing - An introduction to psychological and physiological acoustics. Marcel Dekker, New York, (1990).
12. J. A. Mason, F. J. Fahy: Application of a reciprocity technique for the determination of the contributions of various regions of a vibrating body to the sound pressure at a receiver point. Proceedings of the Institute of Acoustics **12**(1), 469-476, (1990).

13. J. Zheng, F. J. Fahy, D. Anderton: Application of a vibro-acoustic reciprocity technique to the prediction of sound radiated by a motored I. C. engine. Applied Acoustics **42**, 333-346, (1994).

FIGURE CAPTIONS

Figure 1. Illustration of the sources of vehicle alternator noise.

Figure 2. Schematic representation of alternator tonal noise propagation in a vehicle.

Figure 3. Diagram of the omni-directional wideband noise source.

Figure 4. Diagram of the experimental apparatus used to measure alternator noise.

Figure 5. Variation of alternator sound pressure level with alternator speed and frequency.

Figure 6. Comparison of direct (solid line) and reciprocal (dashed line) acoustical transfer functions against 1/3-octave band centre frequency.

Figure 7. Predicted contribution of the alternator (dashed line) compared to total vehicle interior sound (solid line) against 1/3-octave band centre frequency at different engine speeds: a) 6450 r.p.m.; b) 3850 r.p.m.; c) 1300 r.p.m.

Figure 8. Variation of the overall alternator sound pressure level (solid line) and sound pressure level in the 2500 Hz band (dashed line) at an alternator speed of 15000 r.p.m.

Figure 9. Schematic representation of the equipment for the alternator threshold noise level experiment.

Figure 10. Mean (solid line) and plus and minus one standard deviation data (dashed lines) for threshold tonal noise levels at 0.5 m against alternator order and engine speed.

Figure 11. Threshold alternator tonal noise levels at 0.5 m against frequency and engine speed.

Figure 12. Comparison of measured alternator sound pressure level (dashed line) with target noise level (solid line): a) 6th alternator order; b) 12th alternator order; c) 24th alternator order.

Figure 13. Comparison of original alternator sound pressure level (dashed line) and modified alternator sound pressure level (dotted line) with target noise level (solid line) for the 36th alternator order.

Table 1.
First author: Walsh.

Engine speed [r.p.m.]	**Alternator order**				
	6	12	18	24	36
2000					
3000					
4000					
5000					
6000					

Table 1. Matrix of test conditions for the threshold noise level experiment.

Figure 1.
First author: Walsh.

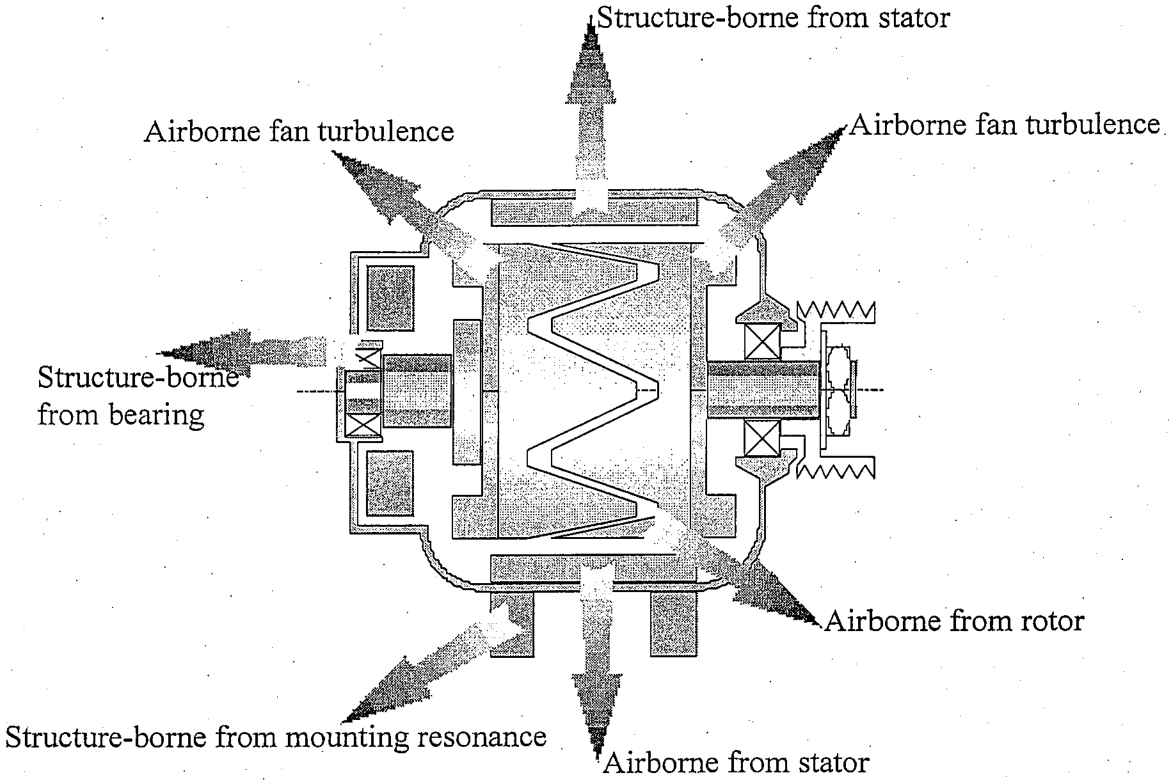


Figure 2.
First author: Walsh.

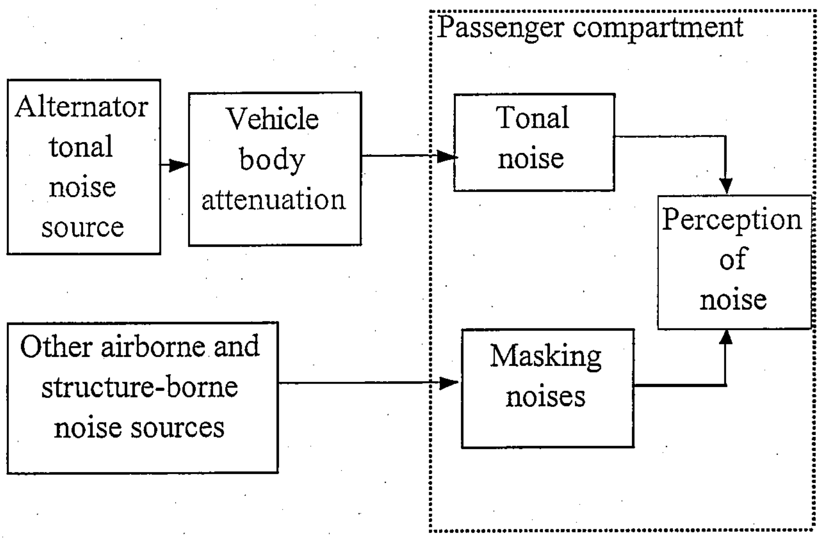


Figure 3.
First author: Walsh.

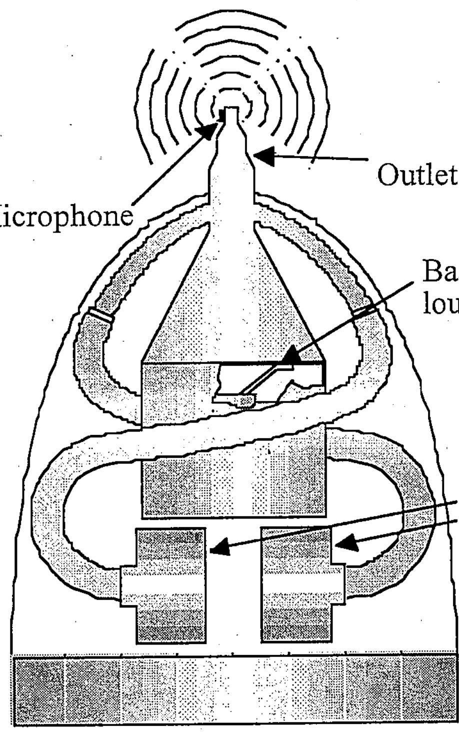


Figure 4.
First author: Walsh.

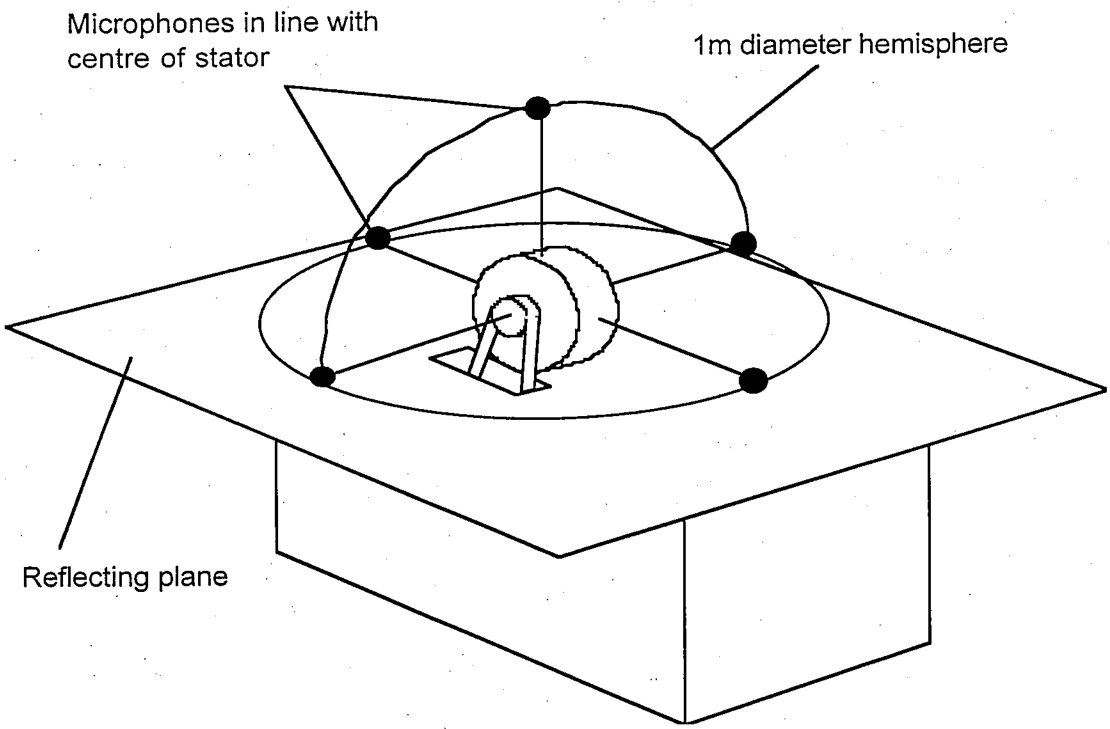


Figure 5.
First author: Walsh.

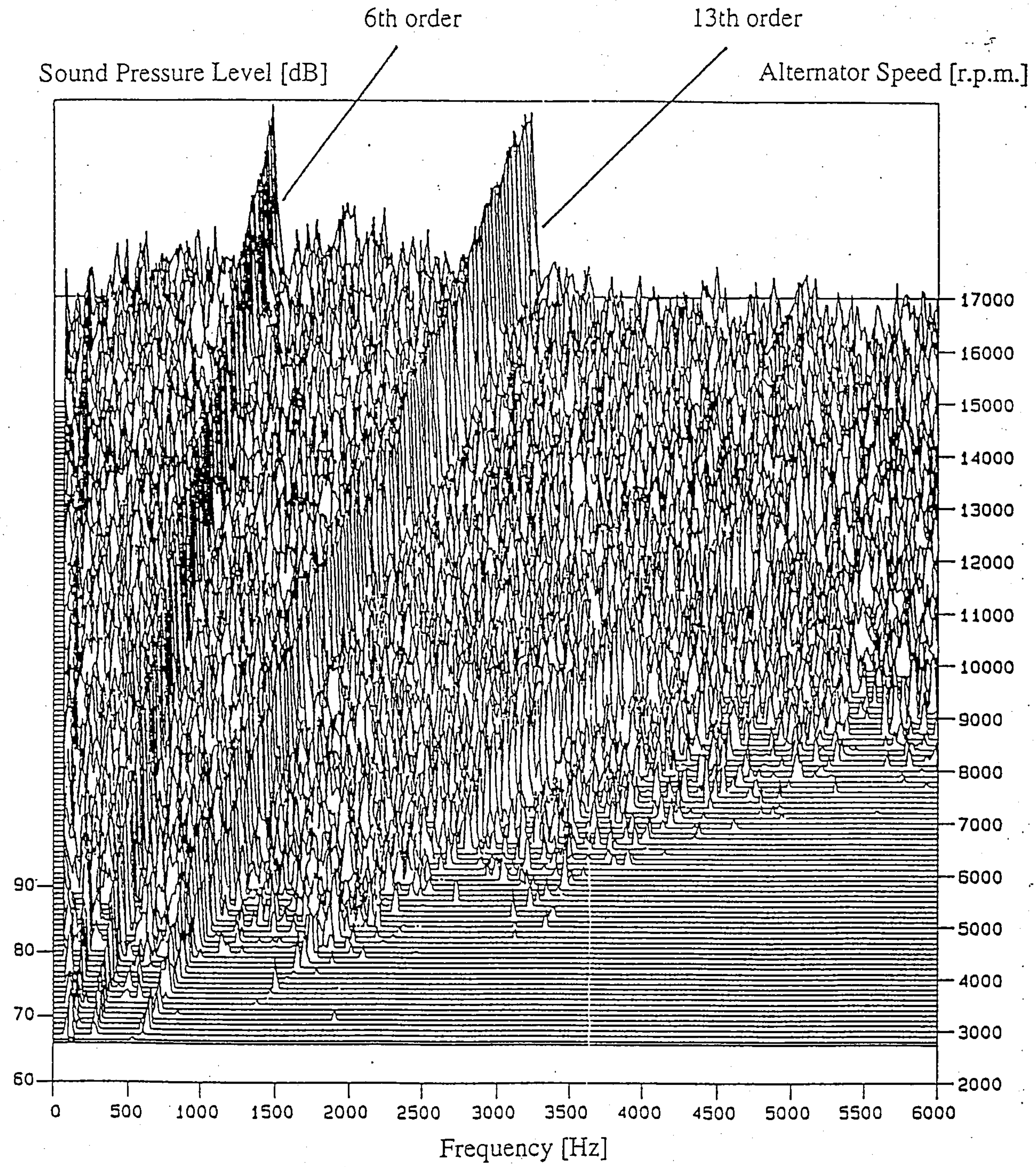
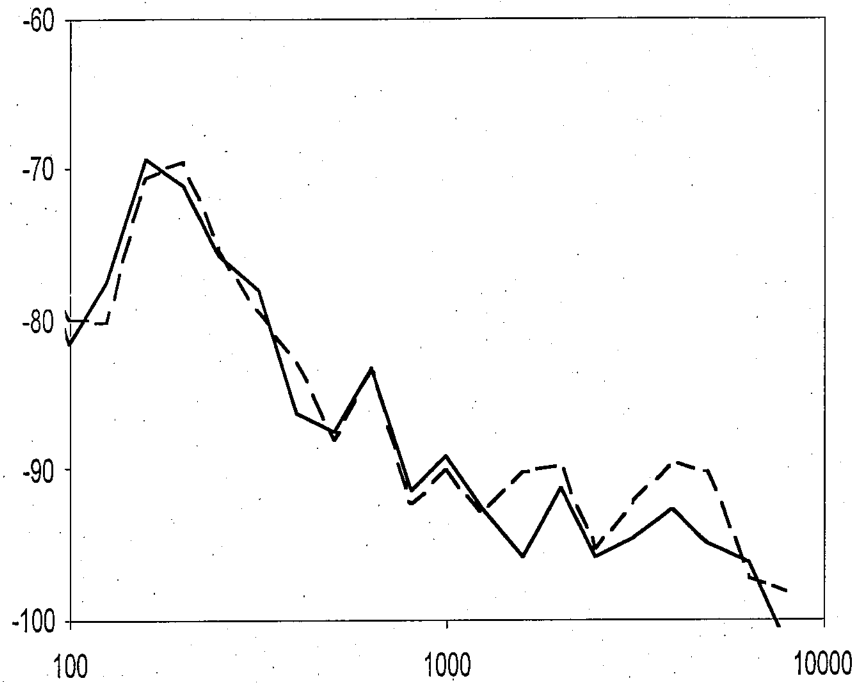


Figure 6.
First author: Walsh.

Receiver Sound Pressure Level - Source Sound Pressure Level [dB]



Frequency [Hz]

Figure 7.
First author: Walsh.

a) Engine speed: 6450 r.p.m.

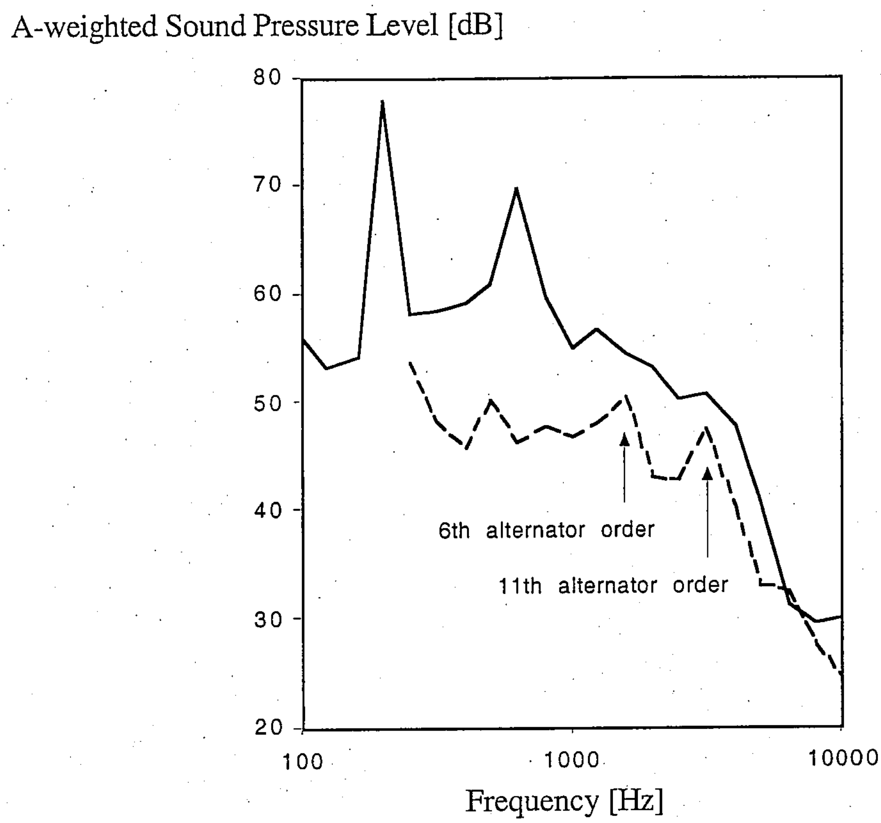
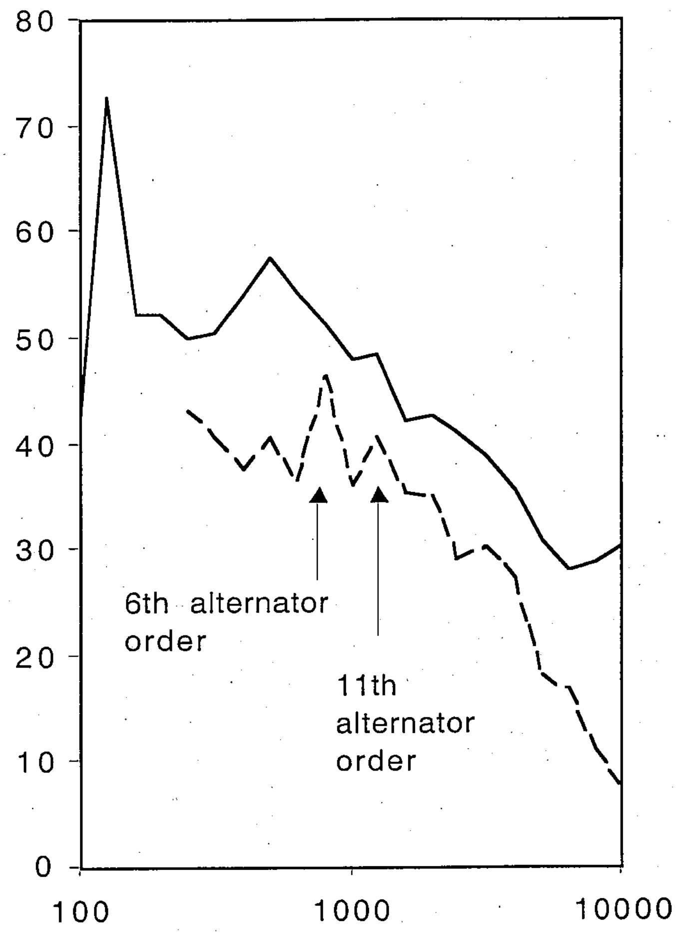


Figure 7.
First author: Walsh.

b) Engine speed: 3850 r.p.m.

A-weighted Sound Pressure Level [dB]



Frequency [Hz]

Figure 7.
First author: Walsh.

c) Engine speed: 1300 r.p.m.

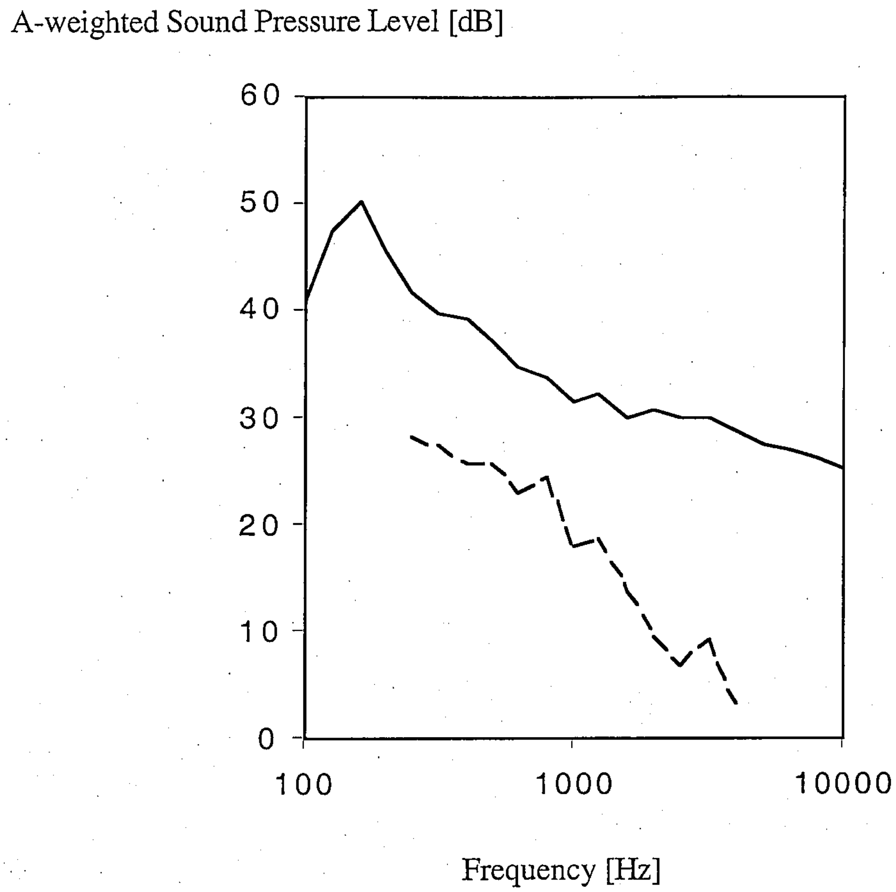


Figure 8.
First author: Walsh.

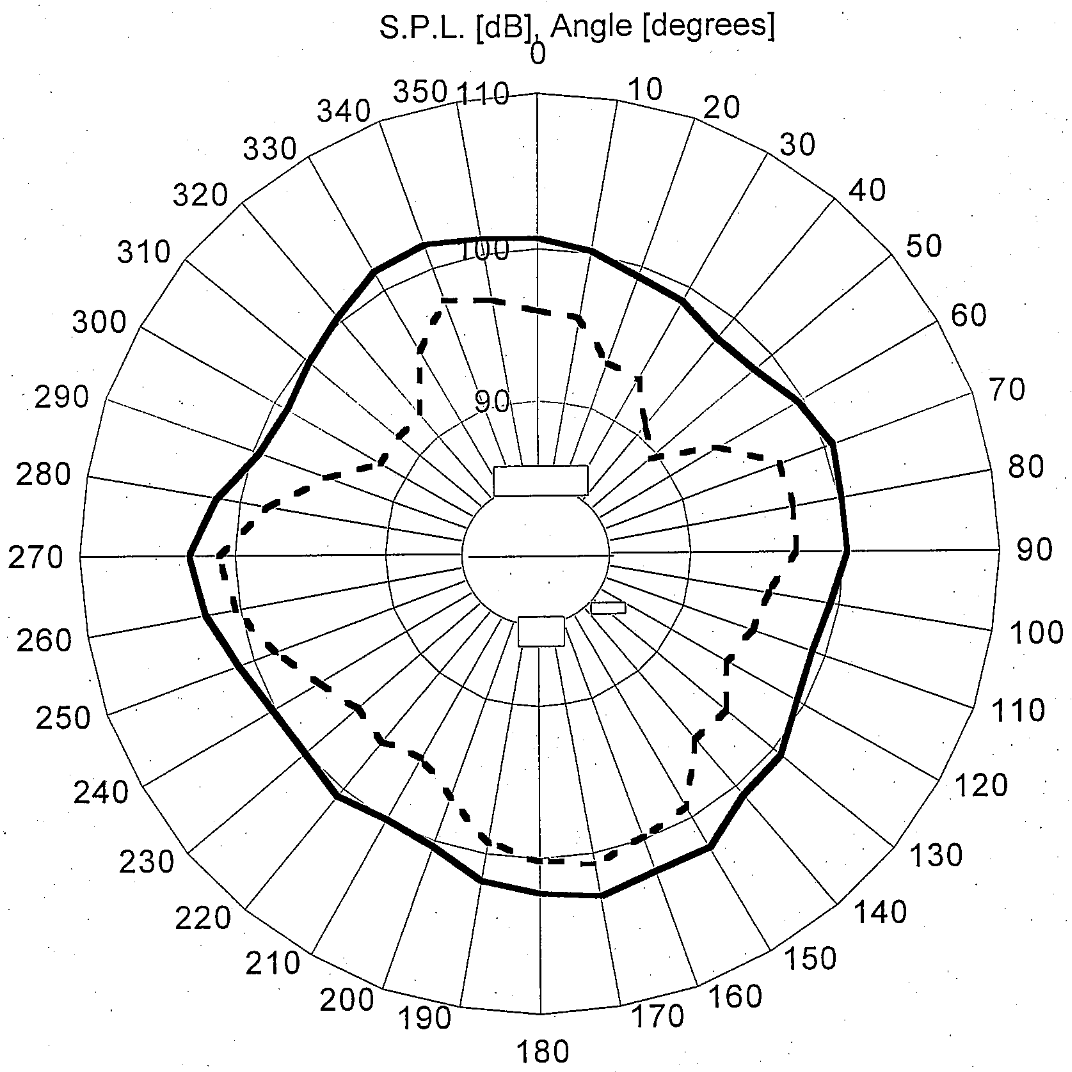


Figure 9.
First author: Walsh.

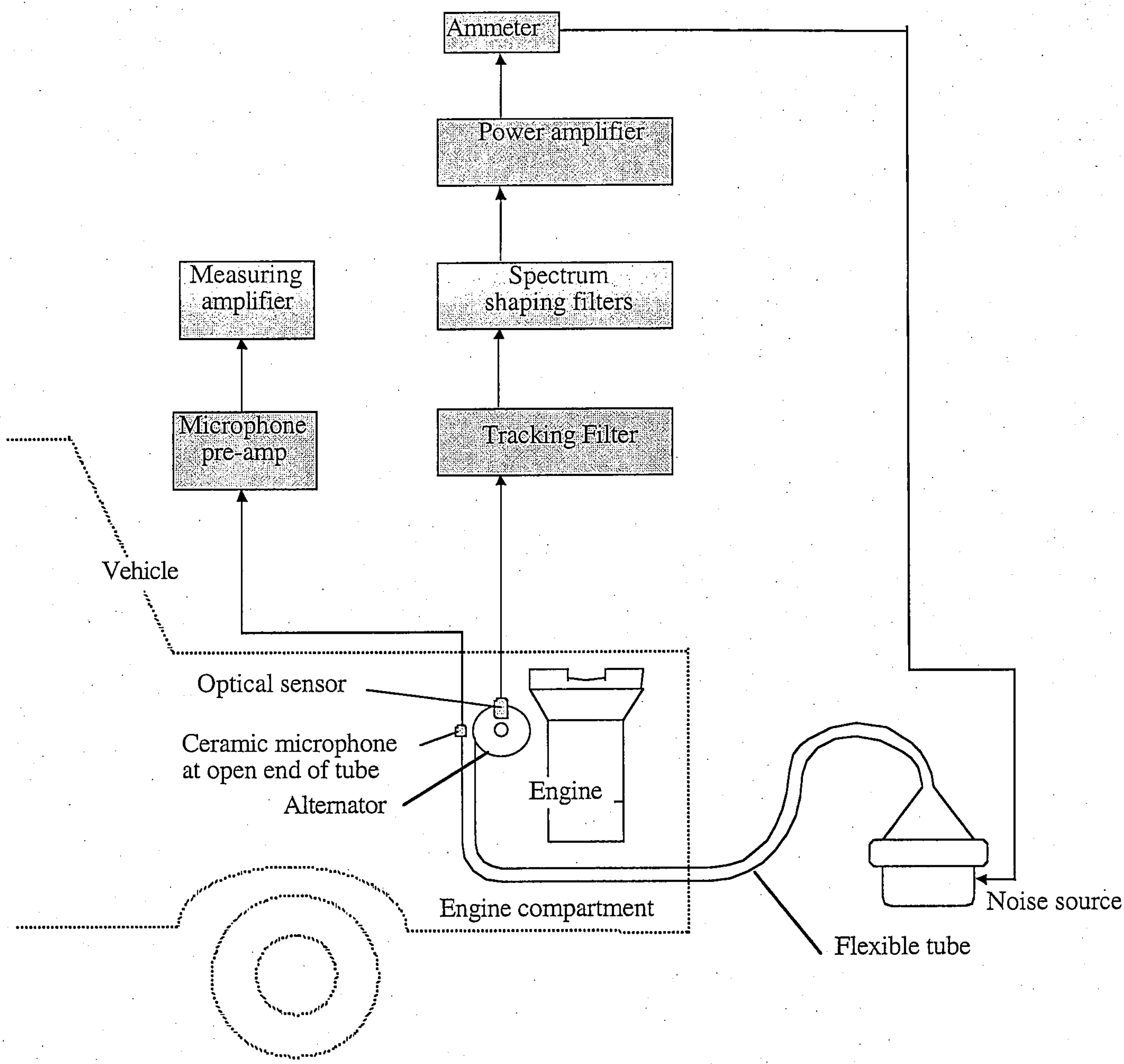


Figure 10.
First author: Walsh.

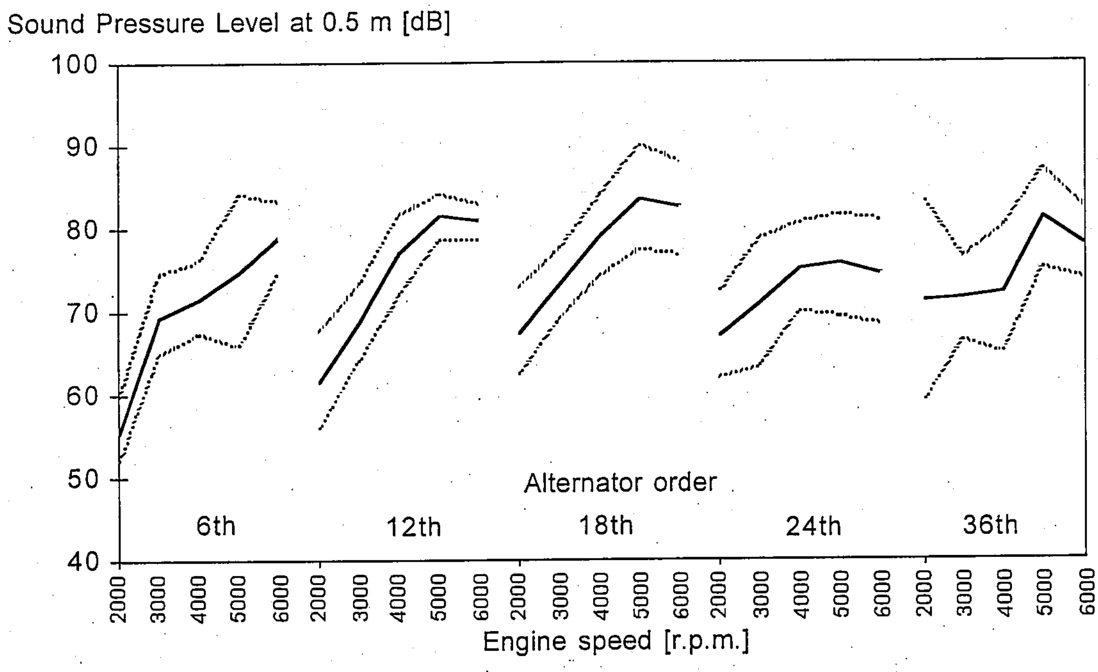


Figure 11.
First author: Walsh.

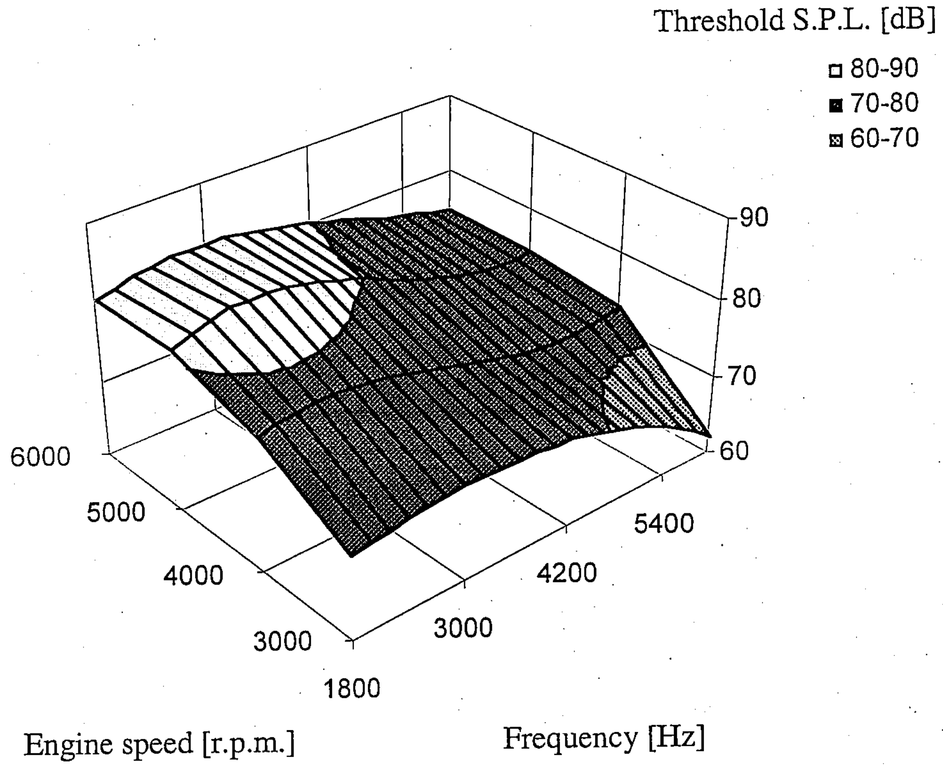
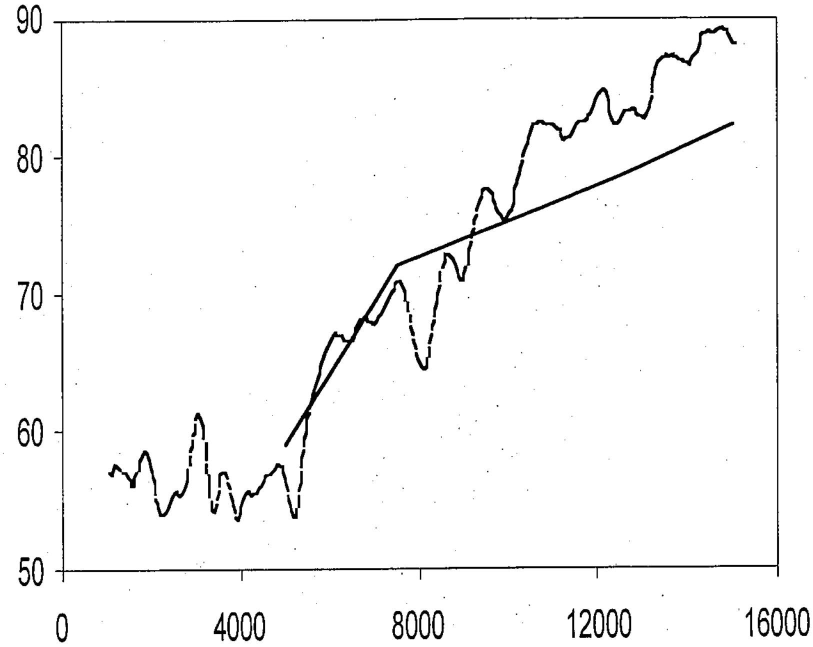


Figure 12.
First author: Walsh.

a) 6th alternator order

Sound Pressure Level at 0.5 m [dB]

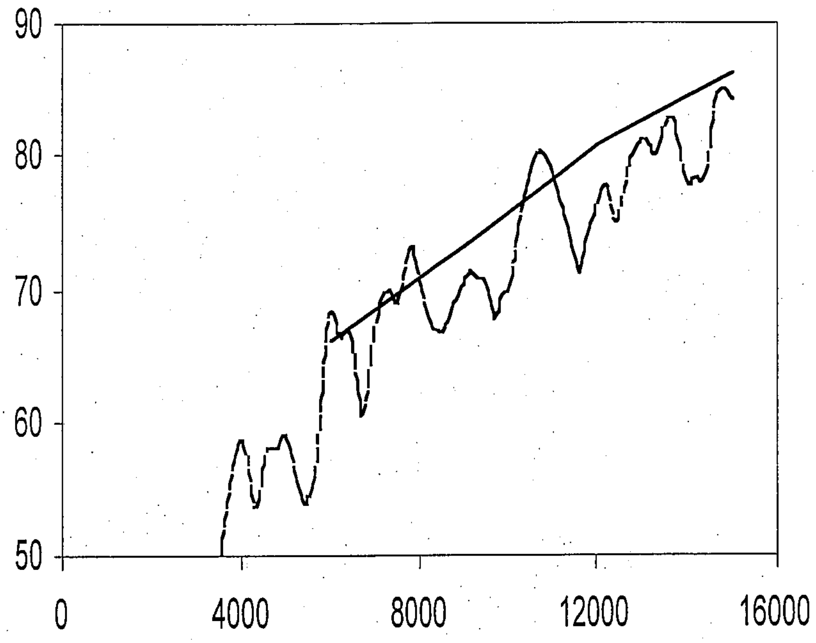


Alternator speed [r.p.m.]

Figure 12.
First author: Walsh.

b) 12th alternator order

Sound Pressure Level at 0.5 m [dB]

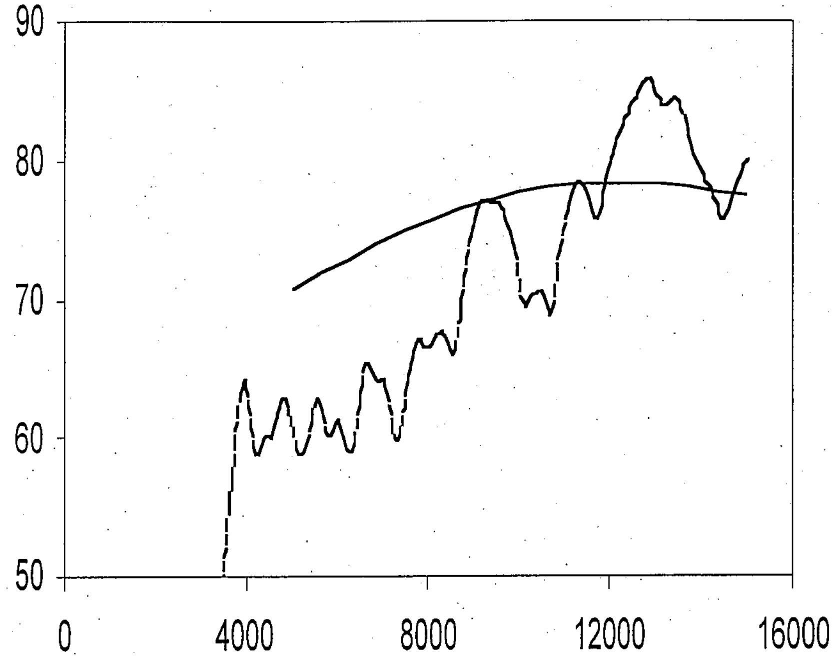


Alternator speed [r.p.m.]

Figure 12.
First author: Walsh.

c) 24th alternator order

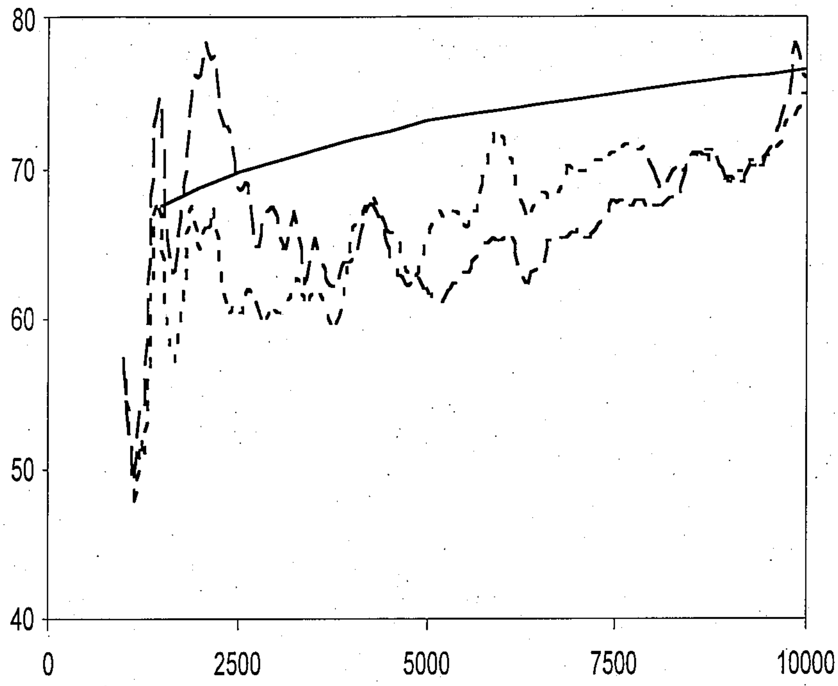
Sound Pressure Level at 0.5 m [dB]



Alternator speed [r.p.m.]

Figure 13.
First author: Walsh.

Sound Pressure Level [dB]



Alternator speed [r.p.m.]