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AN INVESTIGATION OF VEHICLE ACCESSORY NOISE USING THE PRINCIPLE OF ACOUSTIC RECIPROCITY

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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 by control of the vibration levels generated by the powertrain, and engine mount isolation, so minimising the forces transmitted to the vehicle body. Body structures have also improved, resulting in a very much quieter passenger compartment. The 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. There are broad-band high frequency noise sources, which include wind and tyre noise, but possibly more annoying to the driver are narrow band high frequency noises, classified as 'whine' noises, the majority of which are attributable to noise radiated from the powertrain and the various auxiliary components attached to it. Engine radiated noise has also been reduced significantly over recent years, which means that the contribution of auxiliary components has become more important.

This paper presents the results of an investigaion into the influence of the alternator on vehicle interior noise. The aim of the investigation being to establish fundamental information about the nature of the contribution of the alternator to overall interior noise. Specific objectives are to consider the directionality of the alternator noise and to determine the best position within the engine compartment for the alternator. The investigation is based on detailed transfer function measurements carried out using a wideband sound source and utilising the principle of acoustic reciprocity. The contribution of an automotive alternator to overall interior noise is discussed, along with the effects of the directivity of the alternator radiated noise. However, the conclusions of the work could apply to any accessory located in any vehicle engine compartment.

2. THEORY

The acoustic transfer function, H, between the alternator position in the engine compartment and the driver's ear position can be calculated directly from the ratio of response sound pressure level (SPL) to acoustic source volume velocity:

$$H = \frac{SPL(x)}{q(y)} \qquad (1)$$

where SPL(x) is the sound pressure level at the driver's ear position and q(y) is the volume velocity (m^3/s) of the source at the alternator position. Alternatively, the well known acoustic reciprocity relationship may be invoked [1,2]:

$$\frac{SPL(x)}{q(y)} = \frac{SPL(y)}{q(x)} \tag{2}$$

where q(x) is the volume velocity of the source at the located at the driver's ear position and SPL(y) is the resulting sound pressure level at the alternator location. Thus, the sound pressure at the driver's ear position may be predicted using the formula:

$$SPL(x) = H.q(y) \tag{3}$$

where q(y) is the operational alternator volume velocity.

3. METHOD AND EQUIPMENT

As a first step towards deciding what investigations should be carried out, it is necessary to examine the means by which tonal noise is perceived in the passenger compartment. This can be described by the diagram in Figure 1, which identifies the aspects of the system which can be considered independently:

- i Alternator noise can be measured in isolation from the vehicle on a custom-made rig, which can also be used for directivity investigations.
- ii Noise transfer functions can be measured between the alternator position and the passenger compartment which will quantify the sound attenuation attributable to the vehicle body.
- iii These data can then be combined to calculate the contribution of the alternator to vehicle interior noise. This should highlight the frequency ranges over which the accessory noise is of most concern, and will therefore indicate the aspects of the accessory design which will influence these frequencies. It should also identify frequencies at which the vehicle body structure contributes to the perception of high frequency noise in the vehicle.

To establish the transfer functions a suitable omnidirectional noise source is needed with the capability of providing a known signal over the range of frequencies of interest. Ideally the source should be placed in the engine compartment at the alternator mounting position. The response at the driver's ear position could then be measured and a transfer function derived. In order to make instrumentation and measurement easier it was felt that the principle of acoustic reciprocity could be used, whereby the noise source could be positioned inside the passenger compartment and the response measured in the engine compartment. This should give the same result as having the noise source at the alternator position and measuring the response at the driver's ear. Detailed transfer function measurements to be taken at different positions around the alternator so that the effects of directivity of alternator noise could be assessed.

The source used for this work is a prototype system developed by the Automotive Design Advisory Unit at the Institute of Sound and Vibration Research, University of Southampton [3]. In order to provide sufficient power at all frequencies a combination of loudspeakers and compression driver units is used. The output of the drivers and speaker are combined into a single conical output nozzle tapering to a single small outlet aperture. Small outlet dimensions maintain omnidirectivity over the required frequency range. The source output is quantified by volume velocity which is obtained from a calibration test, performed by operating the source in free field conditions and measuring the sound pressure at a number of points on a 1m radius sphere centred at the output. These results are averaged, and the volume velocity calculated as follows:

$$q = \frac{2rP_r}{\rho f} \tag{4}$$

where P_r is the sound pressure at radius r, ρ is the density of air (=1.19 kg/m^3), q is the volume velocity and f is the frequency in Hz.

To check that the reciprocal method would give the same results as a direct method, a single horn driver unit was used, fitted with a long tube with a suitably sized nozzle on the end so that the source noise could be introduced into the engine compartment. Response was measured in the passenger compartment and a transfer function derived. This was compared with a transfer function derived with the source and receiver positions reversed. The vehicle used for this investigation was a production saloon car with the alternator fitted at the bulkhead side of the engine.

In order to measure the alternator noise, a simple rig was built on which to mount a typical alternator such that access was not obstructed nor radiated noise significantly influence by the structure. The alternator was driven using an electric motor via a long drive belt. Measurements were taken at 10° intervals in three planes round the machine to assess fully the directivity of the noise.

4. RESULTS

The most appropriate position at which to mount an accessory was determined by measuring the response at various positions within the engine compartment. This showed which possible mounting position could lead to greatest interior noise. Figure 2 shows the layout of this test. Narrow band transfer functions were measured with the vehicle in a semi-anechoic chamber and are expressed as the measured engine compartment SPL divided by the volume velocity of the source. For clarity, the corresponding $^1/_3$ octave transfer functions are plotted in Figure 3. The main point to note here is the behaviour at around 3kHz. This is a frequency which is known to contribute strongly to tonal noise concerns. It is apparent that mounting the alternator at the bulkhead side of the engine will give rise to increased interior noise at this frequency. A position at the bottom of the engine would be worst, possibly because the vehicle was right hand drive, and there is a possible noise path through the steering column bush near that position.

Transfer functions were also established at various locations around the existing alternator position (Figure 2, position A) to determine if noise radiated in any one direction could be a particularly significant contributor to interior noise. A small piezo-electric microphone was used so that measurements could be taken in the small spaces around the alternator, and transfer functions were derived for all the measurement positions. Generally it was seen that there was little difference between these functions. However, the transfer functions were now available so that their influence on the alternator's contribution to interior noise could be assessed. Figure 4 shows the transfer functions derived during the check on the validity of the reciprocal method. In this figure the transfer functions are calculated as the ratio of receiver SPL to source SPL. It can be seen that there is general agreement between the two methods although there are some slight variations. This is possibly due to some lack of omnidirectionality of the source at high frequencies, or the sensitivity to the exact positioning of the source and receiver, particularly at high frequencies. However, the degree of agreement was considered sufficient to proceed with the reciprocal method for the remainder of the work. Initially a broadband signal was produced at the source, but because of the high attenuation of the vehicle body, the signal to noise ratio at the receiver was poor, and so coherence of the transfer function was low. This was greatly improved by using a swept sine wave input, although it meant that processing time was increased as the wideband frequency response had to be built up from a series of narrower frequency bands due to processing limitations in the equipment.

Alternator radiated noise was then measured on the rig. Readings were taken at 0.5m distance at 10° intervals in three planes around the alternator. The frequency content of the radiated noise was assessed by taking $^1/_3$ octave spectra at each of the measurement points. In order to assess which are the dominant frequencies, the data for a horizontal sweep at 15000rev/min were plotted in 3D form, and are shown in Figure 5. This clearly shows that the $^1/_3$ octave band centred at 2500Hz forms the dominant contribution. This band contains frequencies between 2223Hz and 2787Hz which covers alternator rotational orders between 8.89 and 11.15. This particular alternator has cooling fans with 11 blades, and so the majority of the noise in this case can be attributed to the fans, as there is no other feature in the alternator which could produce rotational orders in this range. The peaks seen at 250Hz and 500Hz correspond to 1^{st} and 2^{nd} orders and are probably attributable to rotating out-of-balance of the rotor. It is also interesting to note that the 2500Hz level varies cyclically round the alternator with four distinct peaks being seen. This is demonstrated more clearly in Figure 6 which shows that the fan noise is lowest at angles of about 45 degrees to the main axis of the alternator. Similar plots can be obtained for the other two planes, and show similar behaviour. This is due to the orientation of the ventilation slots around the casing of the alternator. It is also interesting to note that at this speed the contribution of the fans is at a similar frequency to the peak in transfer function seen in Figure 3 at the lowest position near the bulkhead, which would lead to higher levels of noise at this frequency should the alternator be mounted at this position. The rig measurements were all carried out with the alternator unloaded, and so only the effects of aerodynamically generated noise will be seen. This is generally sufficient when considering alternator speeds above about 5-6000 rev/min (engine speeds of around 2000 rev/min). Below this speed it is known that noise due to magnetically induced vibrations in a loaded alternator can lead to significant levels of 36^{th} alternator order, and this should be considered separately.

The contribution of the alternator noise to overall interior noise was then calculated using equation (3). The data from the scans round the alternator were averaged to provide data for each of the six sides of the alternator in directions corresponding to the transfer functions previously derived, and converted to volume velocity. These volume velocities were then multiplied by the transfer functions to determine the interior noise contributions from each side of the alternator. The results obtained at 15000 rev/min are shown in Figure 7, which shows that there is in fact little difference between the noise contributions from the six sides of the alternator. The overal alternator noise calculated from the sum of all contibutions is also shown. In order to compare the contribution of the alternator to overall interior noise at different engine speeds, the total alternator contribution was calculated for a suitable number of speeds. Figure 8 shows this data in comparison with measurements of overall interior noise made with the engine running. It can be seen that the alternator contributes very significantly to the high frequency interior noise at higher engine speeds with the effects of the 6^{th} and 11^{th} alternator rotational orders being obvious. The effect of the alternator is less pronounced at low engine speeds.

5. SUMMARY AND CONCLUSIONS

This paper has reported on a detailed investigation into the contribution of the alternator to vehicle interior noise, although the conclusions could apply to any engine mounted accessory. It has been shown that the principle of acoustic reciprocity can be successfully used for this type of investigation, although for accurate results, particularly at high frequency, care has to be taken in the positioning of the microphones. The work has led to a number of conclusions which will help the further understanding of tonal noise issues, and their resolution.

- The positioning of accessories within the engine compartment is important in terms of their contribution to interior noise. A location towards the front of the vehicle is preferred.
- At higher engine speeds the alternator makes a major contribution to the overall interior noise of the vehicle at high frequencies.
- The directivity of alternator radiated noise was not an important factor in its contribution to interior noise in this instance.

6. REFERENCES

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[2] IL VER & RW OSIPHANT. 'Acoustic reciprocity for source-path-receiver analysis'. Sound and Vibration, March 1996, pp14-17, (1996.)

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7. FIGURES

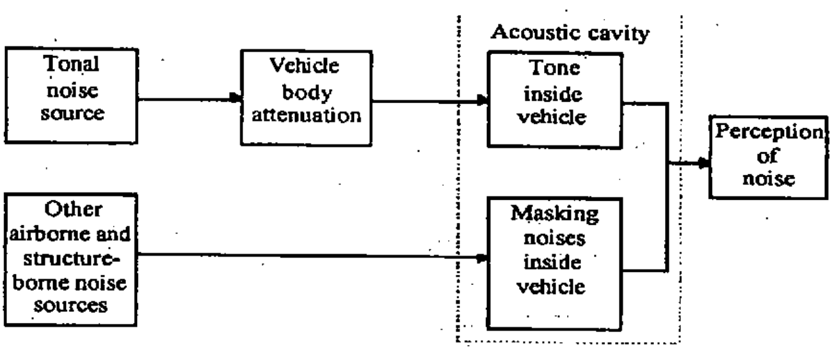

Figure 1: Tonal noise paths for a vehicle

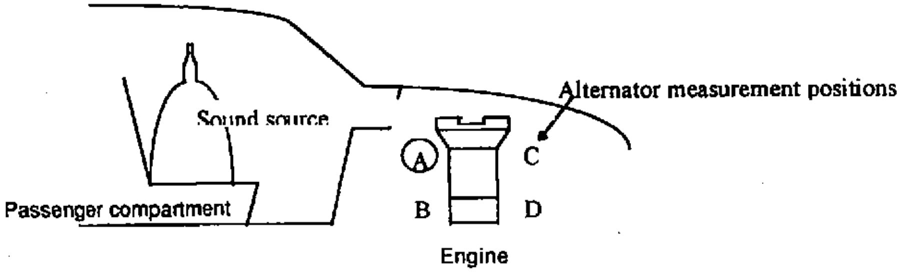

Figure 2: Alternator measurement positions

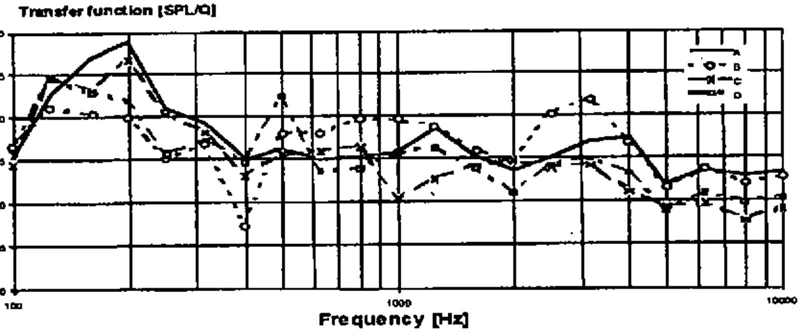

Figure 3: Transfer functions for four possible alternator positions

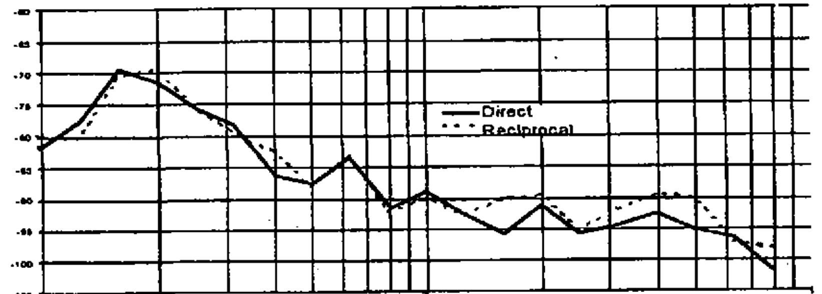

Figure 4: Comparison of direct and reciprocal transfer functions

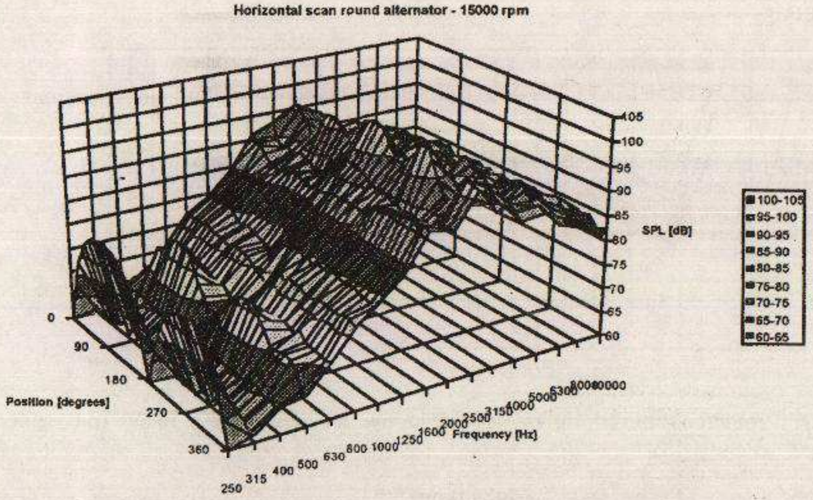

Figure 5: SPL verses frequency from a horizontal scan around alternator - 15000 rpm

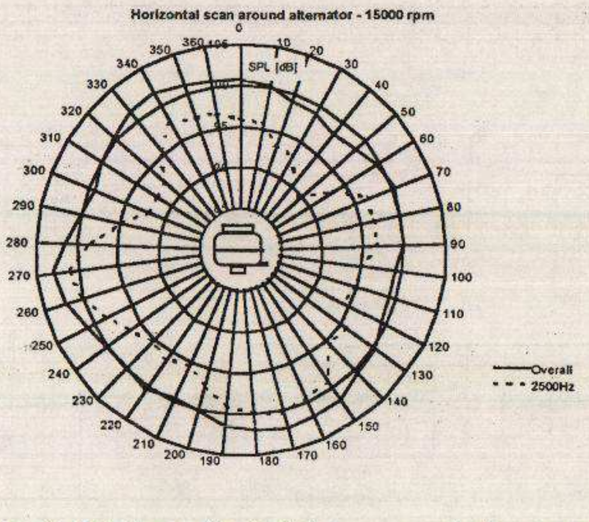

Figure 6: SPL from a horizontal scan around alternator -15000 rpm

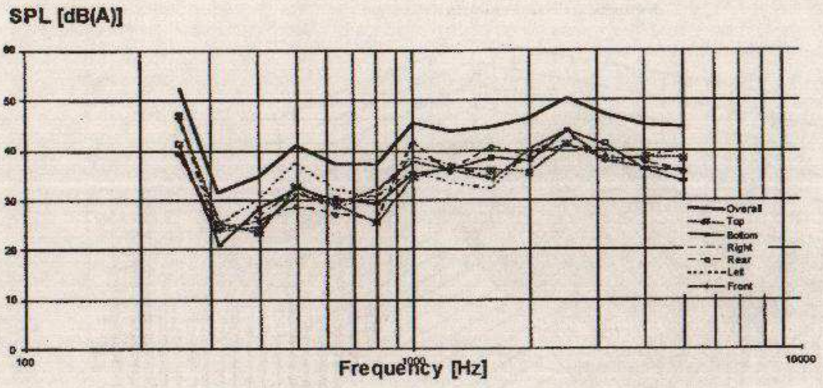

Figure 7: Predicted interior noise generated by the alternator - 15000 rpm speed

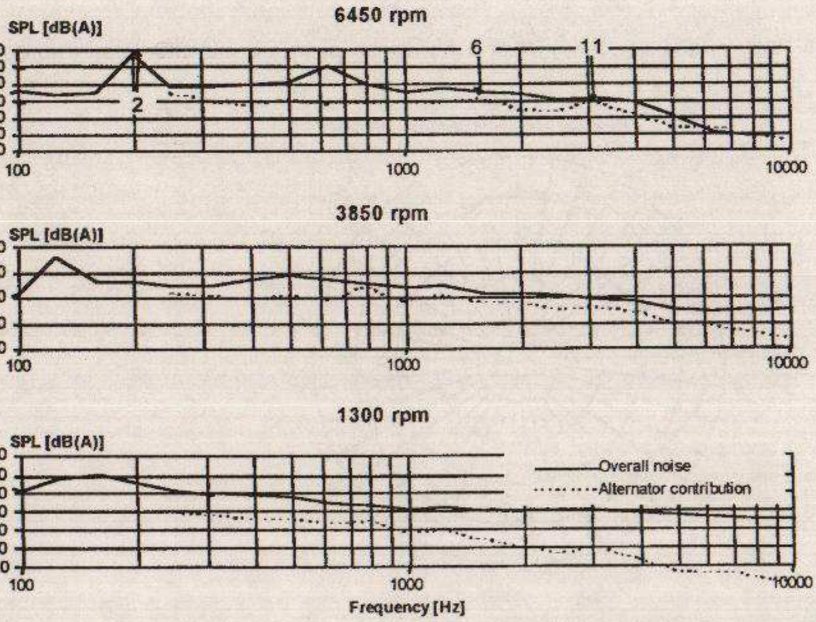

Figure 8: Predicted interior noise generated by the alternator at different alternator speeds