PREDICTION OF THE SOUND OUTPUT OF AN ASSEMBLED MACHINE DRIVEN BY AN INTERNAL ELECTRIC MOTOR

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1. INTRODUCTION

In this paper an assembled machine is considered to consist of two substructures, an active internal component (in this case a motor) and the remaining passive parts of the machine (comprising panels, air cavities, pipes etc) which will be referred to as the 'frame'. The complete working machine is the 'assembly' of the component and frame. The aim of this work is to characterise separately the vibro-acoustic performance of the component and frame, and then to 'assemble' them in the computer to predict the overall noise output of the machine. Such techniques potentially have application to 'virtual acoustic prototypes' where the noise output of an assembly can be calculated and even heard without the need for physical assembly.

Both component and frame will be characterised by measurement, although it is possible in the future that the frame response could be calculated by numerical methods. In general, airborne, structure-borne (and for some other sources also fluid-borne excitation) may be present and need to be included, but here only airborne excitation is considered for simplicity.

The sound pressure around the assembled machine is expressed as:

$$\mathbf{p} = \mathbf{H}\mathbf{q} \qquad 1$$

where **p** is the vector of predicted sound pressure at any desired position, **q** is a vector of source strengths, and **H** is a matrix of transfer functions relating sound pressure output to source strength input. Ideally, **q** will be a property of the active component, independent of the frame, and conversely, **H** will relate to the frame only, and be independent of the source. It is crucial that the source is characterised in such a way as to maintain this independence, otherwise, the source data will not be applicable to other frames, nor the frame data to other sources.

The approach adopted here is to replace the real source with an equivalent source system made up of a number of elementary sources. The equivalent source system adopted for this study is a line of four monopoles on the motor axis as shown in figure 1. The elements of **q** are then the volume velocities of these monopoles. Sections 2 and 3 describe how values for **q** and **H** were obtained by measurement on the component and frame respectively.

2. CHARACTERISATION OF THE MOTOR

To characterise the motor, it was placed in an anechoic chamber, and the sound pressure around it measured by seven microphones as shown in figure 1. (It is assumed that the motor is an axisymmetric source.) The volume velocities **q** of the four monopoles were then calculated by solving the equation:

$$\mathbf{p_0} = \mathbf{H_0}\mathbf{q} \qquad 2$$

where $\mathbf{p_0}$ is the measured sound pressure, and $\mathbf{H_0}$ is the transfer function matrix relating the unknown monopole source strengths **q** to the measured pressure. Equations 1 and 2 are of the same form, but whereas equation 1 describes the motor installed in the machine frame, equation 2 describes it in free field. Since the measurements were conducted in free space the elements of $\mathbf{H_0}$ could be calculated by the well-known Green's function for a point source:

$$h_{0,RS} = -\frac{i\rho ck}{4\pi}\frac{e^{-ik(\mathbf{R}_R-\mathbf{R}_S)}}{(\mathbf{R}_R-\mathbf{R}_S)}$$

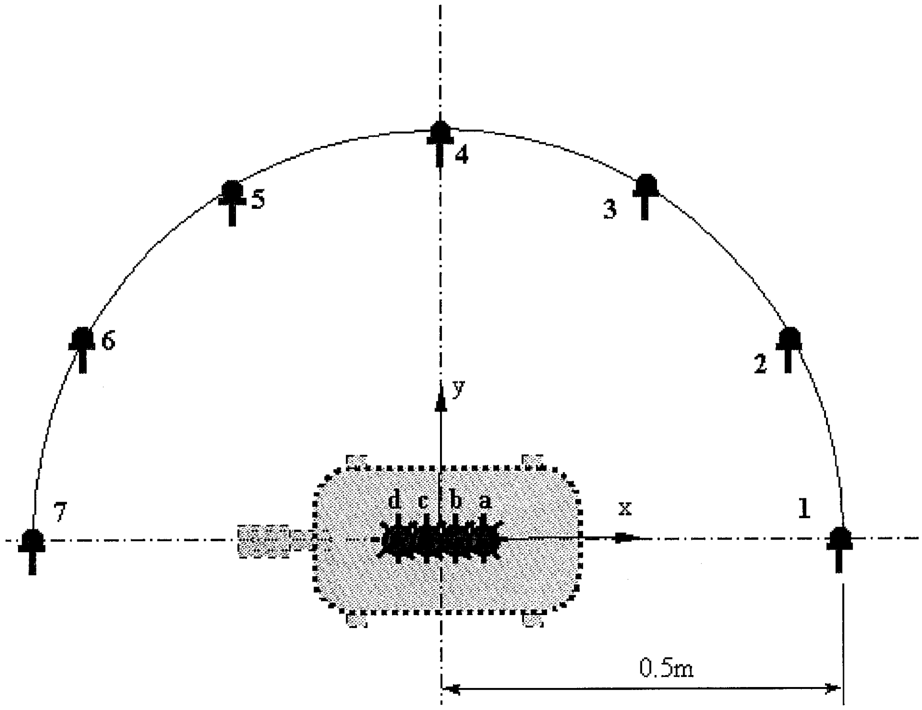

Fig 1 Positions of equivalent monopoles on motor axis and microphones for free field measurement

where $\mathbf{R}_R = x_R\mathbf{i} + y_R\mathbf{j} + z_R\mathbf{k}$, $\mathbf{R}_S = x_S\mathbf{i} + y_S\mathbf{j} + z_S\mathbf{k}$ are the vector co-ordinates of the source and response point respectively.

The solution of **q** from equation 2 is an inverse calculation, and in practice, special techniques have to be employed to avoid amplification of measurement errors. A singular value rejection method was used which will not be described in detail. The results of the inverse calculation are the source strengths of the four equivalent monopoles, given in units of volume velocity as shown in figure 2 (an arbitrary reference value is used for confidentiality reasons).

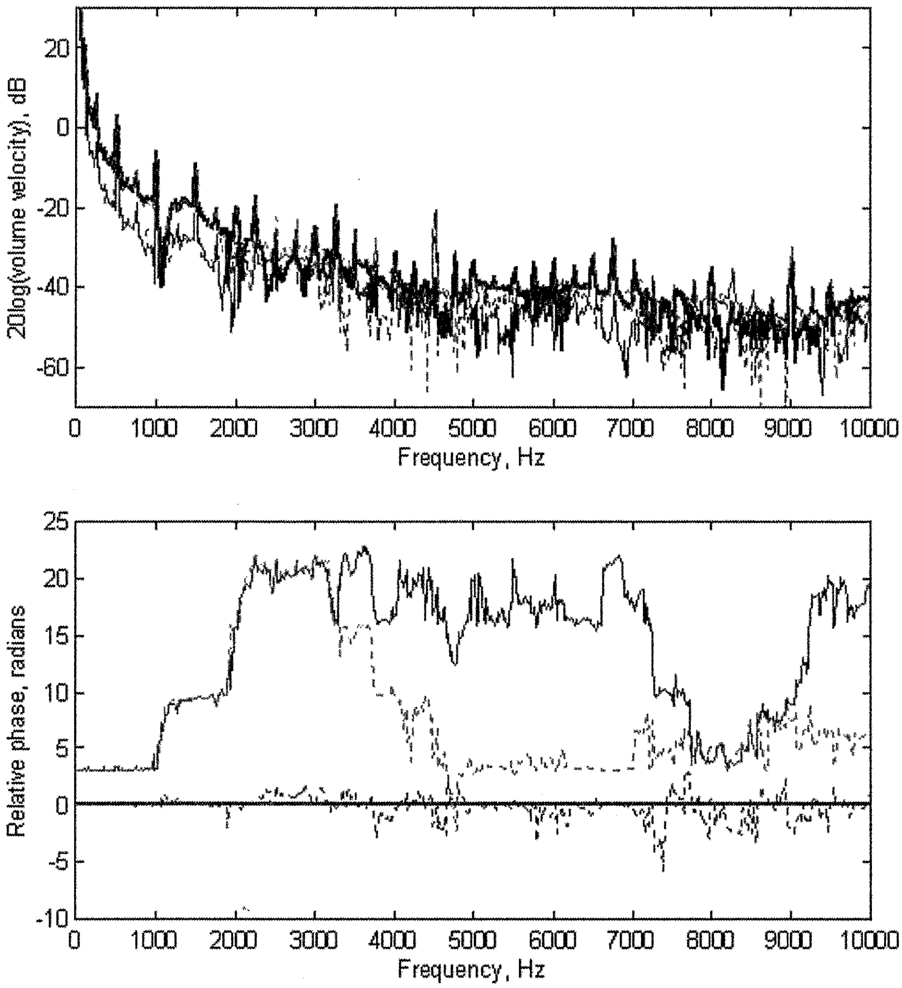

Fig 2 Volume velocity of monopoles in equivalent sources, top: magnitude, bottom: phase relative to source a

3. CHARACTERISATION OF THE FRAME

The previous section described characterisation of the motor. The next step is characterisation of the machine frame. Reception positions around the machine were selected at which sound pressure is to be evaluated. These positions were the same as those specified in ISO3744 for measurement of sound power. To measure the required transfer functions by a conventional

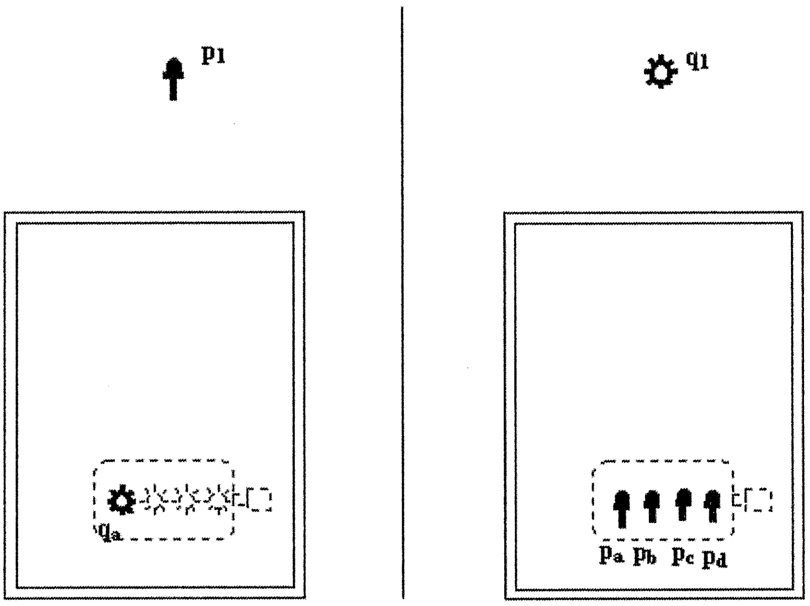

Fig 3 Conventional (left) and reciprocal (right) measurement of transfer functions

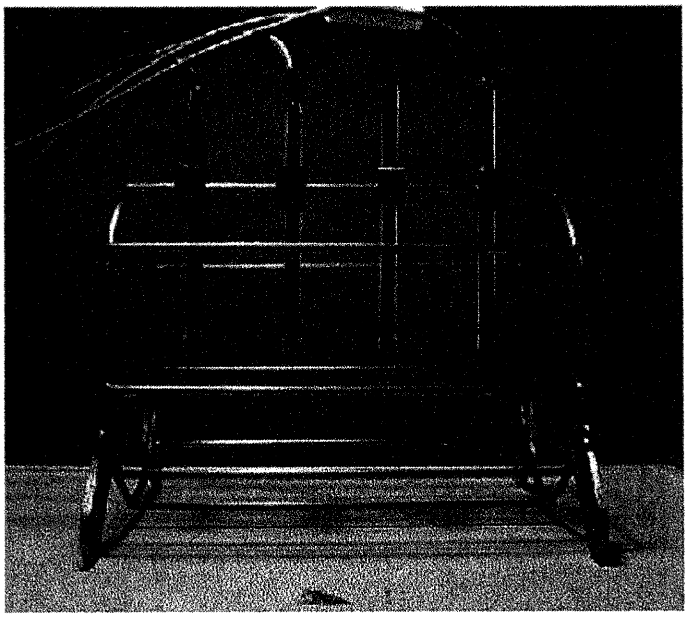

Fig 4 Cage for positioning microphones on motor centre line.

method would require placing a monopole source at each of the positions of the equivalent sources inside the frame (a-d) and measuring the sound pressure response at the external positions (1-6) as shown in fig 3. This is impracticable due to the limited space inside the frame, and the difficulty of precisely positioning the source. As a more practical alternative, the reciprocity principle has been invoked, which by now has been well established for such measurements [1-3].

3.1 Reciprocal measurement of transfer functions

In the reciprocal measurements, the positions of source and receiver are interchanged so that an omnidirectional source of known volume velocity is required at each external position, and four microphones are placed inside the frame on the axis of the motor (the motor is removed). The test arrangement is illustrated schematically in figure 3(b).

The required transfer functions are the ratios of external pressure due a unit strength internal monopole. By reciprocity, this is equal to the internal pressure due to a unit strength external monopole:

$$h(R_1 \mid S_a) = p_1 / q_a = p_a' / q_1'$$

where h is the element of the transfer function matrix **H**, p_1, q_a are the pressure and volume velocity for the forward measurement, and p_a', q_1' are the internal pressure and external volume velocity in the reciprocal experiment. The prime is to distinguish a reciprocal measurement from a forward measurement. To take the measurements, the external source is moved from position 1 to 6, and at each the pressure at microphones a-d is recorded simultaneously.

A dodecahedron loudspeaker was used as a noise source. This is omnidirectional up to 3kHz, but since measurements were required up to 10kHz, it proved necessary to rotate it on turntable to achieve a sufficiently uniform sound field around it.

Reproducibility of the results is important since it is then possible to quantify small changes in frame performance. It was therefore necessary that the microphones could be removed and repositioned in the same place. A cage in the form of a dummy motor (fig 4) was therefore constructed allowing precise positioning on the motor axis. The microphones can be placed, and repositioned inside this cage to an accuracy of about 1mm.

3.2 Measured transfer functions

In total, a 6x4 matrix of transfer function spectra was measured, a small sample of which are shown in figure 5. Also shown is the calculated result that would be obtained in free field (dotted line). The difference between the measured and calculated curves is therefore related to the insertion loss of the frame.

4.

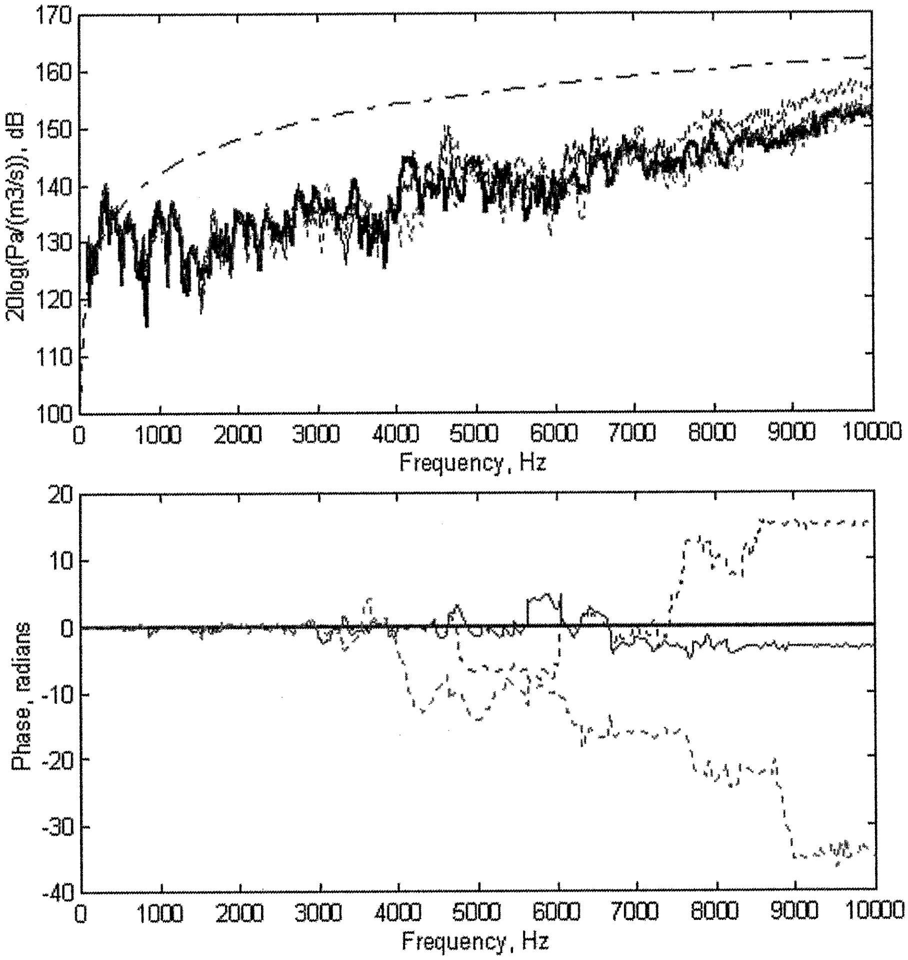

Fig 5 Transfer functions for machine frame, top: magnitude (dotted line is the caluculated free-field transfer function) and bottom: phase relative to source a.

PREDICTION OF SOUND FROM ASSEMBLED MACHINE

All the ingredients are now available to predict sound output from the assembled machine. The measured transfer function matrix **H** from section 3 was combined with the vector of monopole source strengths, **q**, from section 2 in equation 1. The calculation is a straightforward matrix multiplication requiring no special techniques, and results in a predicted sound pressure spectrum for each of the 6 external points.

To provide independent validation the motor was physically mounted inside the frame, but hung by string from its supports in order to eliminate structural transmission. Sound pressure was measured at the six external positions.

A spatial average sound pressure was calculated for both measured and predicted cases, and the results are shown in figure 6. The agreement is mostly good, and it is thought that many of the discrepancies between the two curves are due to differences in the operating conditions of the motor. It had proved difficult to obtain repeatable results from the motor even when taking two sets of measurements one immediately after the other in the anechoic chamber. In fact, the motor characterisation and validation tests were carried out on different days and there are clearly differences in operating conditions, for example the running speed was slightly different as evidenced by the different frequencies of the peaks at around 9kHz.

Shown in figure 6 are third octave band spectra, reconstructed from the narrow band results. Agreement is within 5dB for each band. The overall values were 51.1dB measured and 51.1dB predicted.

Also shown on this plot is the result of a simplified prediction based on only the zero order singular mode. This can be thought of as all four monopoles acting together rather like a single large monopole, and accounts for the sound power of the motor, but ignores its directivity. There is a discrepancy of 10dB in the 800Hz third octave, but elsewhere the agreement is as good or better than for the full prediction. This is interesting because it suggests that the motor directivity is not important in determining overall sound output from the assembly. It is also potentially significant from a practical point of view, because the 'zero order' source strengths can be obtained from any conventional sound power measurement.

5. CONCLUDING REMARKS

The electric motor, as the active component in a machine has been characterised as an equivalent source consisting of four monopoles along its axis. The source strength is quantified as the magnitude and phase of the volume velocity of these monopoles. Note that sound power output of the motor could be affected by being tightly enclosed, and so conventional sound power would not be a suitable source characterisation. On the other hand, the equivalent volume velocity should not be affected by enclosure and so is properly independent of the frame. This does not mean that the characteristics of the enclosing cavity are ignored, simply that they are included as part of the frame in the measured frame transfer function.

As well as the predicted spectra, it has also proved possible to perform an inverse FFT. The resulting time histories can be auralised, so that one can listen to an assembly of a motor and frame which has never been physically assembled. Such 'virtual machines' could have far reaching benefits to machine designers: equipped with appropriate data bases of sources and frames they could investigate the effect of interchanging different designs of motor and frames, predict the sound power output, and even carry out sound quality assessments without the need to assemble physical prototypes.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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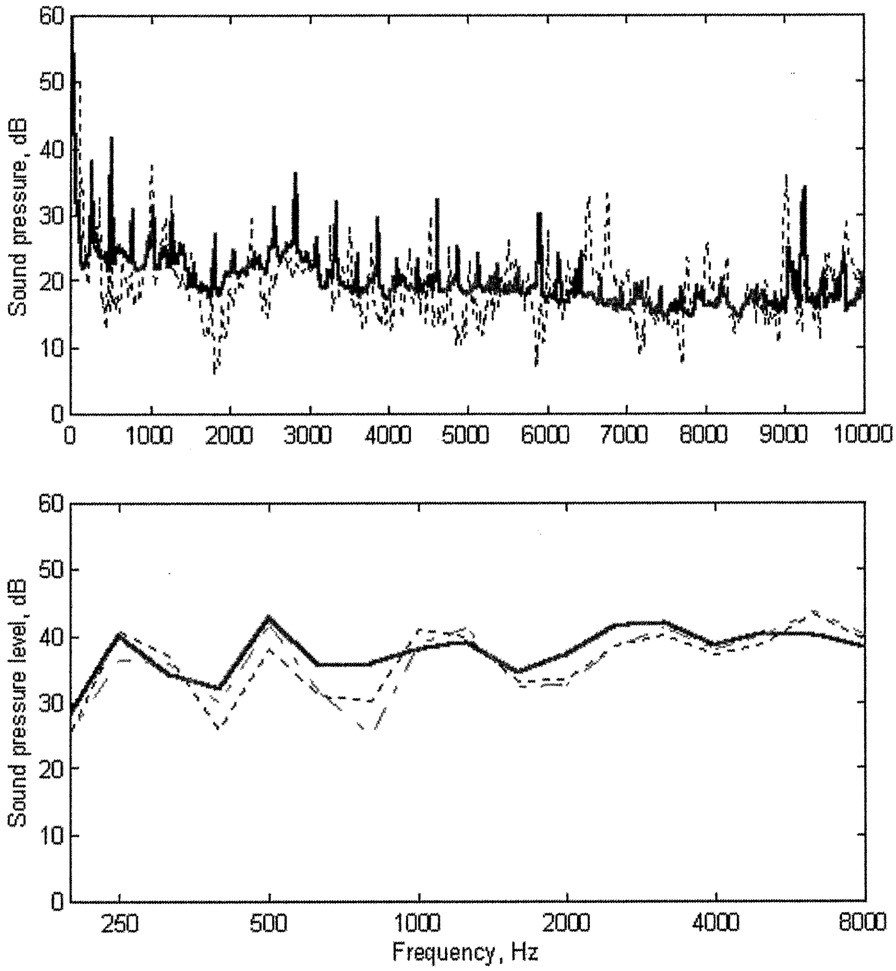

Fig 6 Measured (solid line), and predicted (dotted line) sound pressure in narrow and third octave bands. The simplified prediction is the dash dot line in the lower figure.