Proceedings of the Institute of Acoustics

RATING OF MACHINES AS STRUCTURE-BORNE SOUND SOURCES

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1. INTRODUCTION

The Acoustics Consultant or Noise Control Engineer is often required to address noise problems at the design stage where there may be a need to estimate the effect of several sound transmission paths. All paths must be considered in order to achieve a solution, but the engineer does not have at his disposal equally good methods of analysis and prediction and appropriate data for each transmission path. This is particularly true for structure-borne noise. The methods and data available are the result of experience and are not well developed or freely available. As a result, structure-borne noise control remains somewhat of a black art. It is often ignored, even when important, giving rise to over-compensation in design.

A practical solution requires control at source. However a fundamental problem is now exposed in how to characterise machines as sources of structure-borne sound ie. how much vibrational energy will flow into a building when a machine is installed? What information do we require of the machine and of the building in order to make such a prediction? The same questions are asked by the design engineer. What is the contribution of a vibrationally active component to the overall acoustic emission of a machine? How can this component be characterised?

2. SOUND SOURCE CHARACTERISATION

Ideally, a standard test of machines or components as sources of structure-borne sound should allow the following [1];

i) comparison of machines,
ii) comparison with set limits,
iii) data useful for prediction and acoustic planning,
iv) data useful for the design of quieter machines.

At the very least, it should be possible to indicate improvement in design by a measurable reduction in source activity. A standardised test and the data which results should achieve these four requirements directly or at least be compatible after some transformation. Ultimately, the data should be expressible as a single-value rating which relates to human perception.

3. WHY AIRBORNE SOURCE CHARACTERISATION WORKS

Characterisation is comparatively straightforward for the case of airborne sources. The source impedance is very large and the 'constant velocity' source is unaffected by the surrounding air. The source strength is a function of surface velocity and knowledge of the air impedance yields the acoustic power. Power is often given as the fundamental quantity and the implicit assumption is made that the air impedance is insensitive to location. Indirect measurements of sound power, conducted in reverberant or anechoic environments or by means of intensimetry, should yield the same quantity and be applicable to most other environments. The general acceptance of the principle is seen by the existence of standard methods of measurement and the data bases which have resulted [2,3].

The source data, the airborne sound power, is used in the source-path-receiver approach to prediction. The path is characterised as a combination of attenuations (and sometimes amplifications) which, again, can be obtained by standard methods [4]. The receiver is characterised by design criteria and the success of the design depends on whether the sound pressure level in the room of concern falls below the criteria set [5].

Such a representation is not possible for structure-borne sources. The source impedance may not be appreciably different from that of the receiver and indeed may match it. The impedances are complex functions of frequency and depend on the position of the contact points on the machine and floor. Despite the general complexity of the problem, work continues in an attempt to represent machines as structure-borne sources in a meaningful and practical way.

4. PROPOSED METHODS

There are several national and international working groups concerned with the formation of standards for characterisation of structure-borne sound sources since there are no standards presently available.
An ISO working group was established in 1984 to consider the generic problem [1]. Its aims are those listed above. Working groups also have been set up to consider specific machine types such as circulation pumps [6]. Standards exists for measurement of vibration levels of machines, such as for large fans [7], but these are measures of source activity rather than strength.

There has been concomitant work on small air movement devices by an INCE technical group [8]. The aims are similar to those of the ISO working group but are less ambitious since the method is to apply to one family of machines only; fans and blowers used in computers and other business machinery.

Many methods have been considered (the ISO working group originally considered seven), but it is possible to identify two main approaches; measurement of machine 'activity' when isolated from connecting structures and measurement of the response of connected structures.

One proposal, in the first category, is at final draft stage [9]. Sometimes known as the free velocity method, it involves measurements of vibrational velocity at contact points of resiliently installed or suspended machinery. However, it is not a full characterisation. Two sources of the same velocity will yield different sound levels even when installed at the same location. They are equivalent only when the source impedances are the same. The data obtained is therefore useful but is only a subset of that required.

For example, the noise level from an installed circulation pump cannot yet be predicted from the measured free velocity spectrum. However, it is reasonable to assume that a modification of design which results in a reduced free velocity will be generally beneficial. The problem remains however, in using free velocity only in comparison of machines and with set limits.

An example of the second category is the reception plate method [10]. A thin plate is attached to the source and its spatially averaged acceleration measured. Again, two sources could give the same value but different sound levels when installed in buildings. The INCE technical group are adopting a similar method which involves the use of a damped plate which has an impedance similar to that of an ensemble average of computer-like structures [8]. It has relevance only if a 'typical' installation is assumed which is truly representative of the range of installations likely.

Another example of the second category gives as source data an equivalent force. The sound pressure in a remote room due to the installed machine is recorded. The machine is then replaced by a point force which gives the same sound pressure level. A reciprocal method is also proposed where the machine does not need to be removed [1]. Although simple, the approach is unphysical. A machine excites the supporting structure by moments as well as forces, through several contact points or areas of contact and these cannot be represented by a single point force in a meaningful way. As in the other methods described, the data produced will not be transferable for other installations.

5. POWER vs FORCE or VELOCITY

Even if the force produced at a support point can be predicted, the result may be misleading. If the floor were rigid then even a large force would not cause vibration of the building. Velocity of the floor may be a better indicator but the highest response levels may occur at distance from the machine [11].

There is a growing consensus that vibrational power, which is the product of force and response velocity at the contacts, is the appropriate variable [12]. The vibrational power (or emission) through a contact point between a machine and a floor is given by;

$$W = \frac{1}{2} \frac{|V_S|^2}{|Y_S + Y_R|^2} \mathrm{Re}[Y_R] \qquad (1)$$

v_{Sf} is the velocity at the contact point of the free source before it is attached to the supporting (receiving) structure, and Y_S and Y_R are the source and receiver mobilities, respectively. Mobility is the inverse of mechanical impedance. From this expression it can be seen that three quantities are required to predict structure-borne power and that neglect of any will result in errors. An illustrative example is shown in Figure 1 where a floor is excited by the same source at two locations and the emission is assessed from the radiated noise [13].

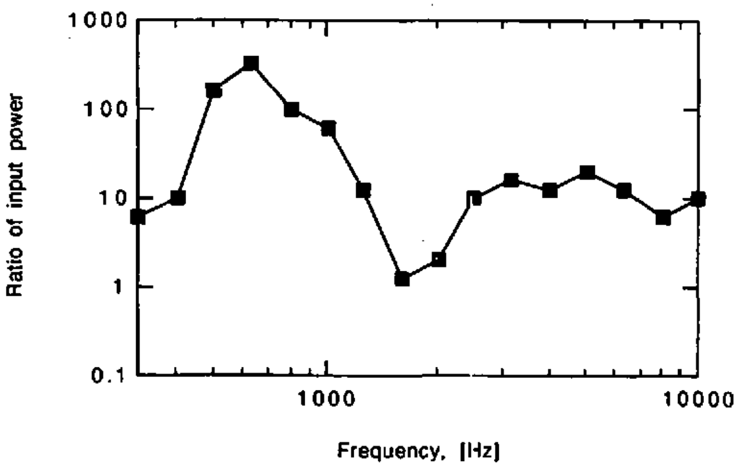

Figure 1. Ratio of structure-borne sound power emission for a source at two locations on a floor.

The free velocity and source mobility is unaltered between locations; the receiver mobility however has changed. It should therefore be possible to characterise the source on a power basis, using the first two quantities.

6. SOURCE CHARACTERISATION vs EMISSION

Equation 1 for emission can be rewritten as;

$$W = \mathrm{Re}[SC_f] \quad (2)$$

where S is the source descriptor $S = |v_{Sf}|^2 / (2Y_S^*)$ and C_f is the coupling function $C_f = Y_S^* Y_R / |Y_S+Y_R|^2$. The source descriptor is a quantity which solely involves data related to the source but which is not the emission [14]. However the emission can be retrieved by including the coupling function. The source descriptor has units of power and allows comparison of the effect of different components of vibration. For example, we cannot assess the relative importance of translational and rotational components of vibration by measurement of free velocities alone, but by applying the source descriptor, the source's ability to yield power through those components of vibration can be compared.

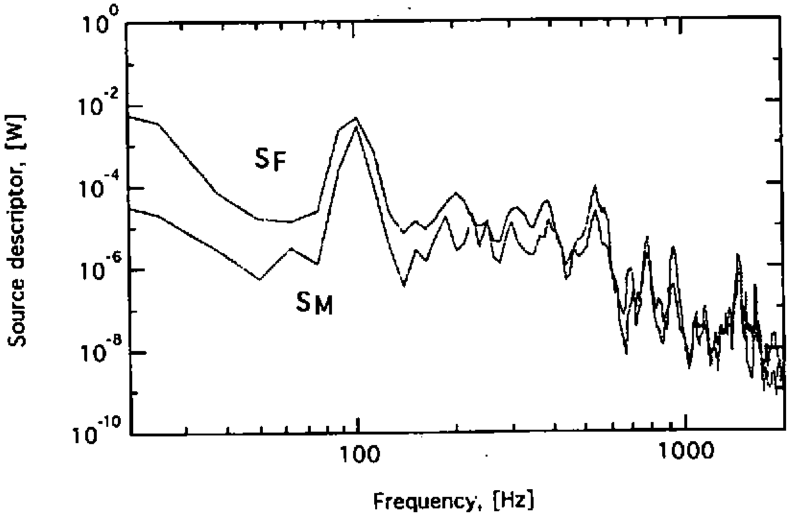

Figure 2. Comparison of moment source descriptor S_M and force source descriptor S_F for a footing of a medium size fan unit.

In Figure 2, the force source descriptor is predominant at low frequencies but the moment source descriptor becomes equal to or larger at mid to high frequencies [15]. In this case, none of the components considered can be neglected when considering the total emission.

To summarise; any true source characterisation (ie. involving source terms only) cannot yield emission (ie. in the installed condition).

Conversely, the emission for a given source is strongly dependent on the dynamic characteristics of both the source and receiving structures and therefore cannot be used as a source characterisation.
This is contrary to the often implicit assumption concerning airborne sound in that the source strength and emission are equivalent.
With this provisor, the source descriptor would appear to be a logical source characterisation worthy of development.

7. FUTURE DEVELOPMENTS

At present, there does not appear to be a compromise possible between a proper characterisation and methods which are simple and practical. The source descriptor is a proper characterisation but requires the acquisition and processing of much data. Machine motion at contact points involves up to six components of motion and excitation where forces and moments contribute to the total emission. The response at one contact point is the result of forces and moments at all points and it is necessary to consider transfer and cross mobilities in addition to point mobilities.

The simple single point expression in equation 2 can be preserved, however, by substituting the effective mobilities of source and receiver for the point mobilities [16]. Work continues on developing simplifying representations for multi-point and multi-component sources [17] and in data reduction in presenting information on machine vibration [18].

8. CONCLUDING REMARKS

It has been demonstrated that both the source's activity and its dynamic characteristics need be specified in order to satisfy the four criteria required for a standard, described earlier.

It has also been demonstrated that structure-borne sound emission and source characterisation are distinctly different [19]. Any true source characterisation (ie. involving source terms only) cannot yield emission (ie. in the installed condition). Conversely, the emission for a given source is strongly dependent on the dynamic characteristics of both the source and receiving structures and cannot be used as a basis for source characterisation.

It can be argued that, based on present knowledge, attempts to standardise to the previously stated aims are premature.

In the short term, a measure of source activity such as free velocity may be acceptable.

In the long term, it is anticipated that a source characterisation will be available to manufacturers involving free velocity data combined with the dynamic characteristics of the source structure. The latter may be obtained by analytical and numerical methods rather than measurement. The challenge of presenting the product information in a simple and practical away can then be addressed. This is likely to involve data reduction, including single value rating and the investigation of the relationship between such ratings and annoyance .

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