CONFORTO NO AMBIENTE CONSTRUIDO
III ENCONTRO NACIONAL
I ENCONTRO LATINO-AMERICANO
Gramado, RS, 4 a 7 de julho de 1995

Structure-borne sound: The unheard acoustics

B M Gibbs

Acoustics Research Unit
Liverpool University School of Architecture and Building Engineering
PO Box 147, L69 3BX, UK.

ABSTRACT

It is more difficult to solve structure-borne noise problems than airborne noise problems. One reason for this is that there is not an agreed approach to it; in particular, on how to describe machines as vibrational sources. A review is given of proposed approaches to the characterisation of machines,as structure-borne sound sources. It is demonstrated that both a machine's activity and its dynamic characteristics are needed to properly describe its ability to emit structure-borne sound. It is also demonstrated that emission and source characterisation are distinctly different. In addition, at present,. there does not appear to be a compromise possible between a proper characterisation and methods which are simple and practical and it is argued that present attempts to produce standards are premature. In the short term, a measure of source activity such as free velocity may be acceptable. A source descriptor is described which is a proper characterisation but requires the acquisition and processing of much data. It would appear worthy of development but the challenge remains to present product data in a simple and practical way.

1. INTRODUCTION

Recently, a University installed a large V-type gas compressor, driven by a 225 kW electric motor, as part of its combined heating and power scheme. It is normal practice to bolt this type of compressor to a concrete floor but this machine was to be installed close to a laboratory which contained vibrationally sensitive electron microscopes. It was decided to install the compressor on anti-vibration mounts but the resultant increased machine motion caused fractures of several components including gauges and gas pipes and the operation of the compressor now must be carefully monitored for such failures. Subsequent detailed calculations showed that stiffer mounts would have restricted machine motion and component failure while still preventing excessive vibrations in the microscope laboratory [1]. A simple well proven procedure for such calculation, accompanied by appropriate manufacturers' information, could have been employed at an early stage to assess isolation requirements, thereby eliminating the need of costly field trials or excessive isolation.

The Acoustics Consultant or Noise Control Engineer is often asked to address noise problems at the design stage where there is a need to estimate the effect of numerous sound transmission paths before re-design or modification. All paths must be considered to achieve a solution, but there are not available equally good methods of analysis and prediction and appropriate data for each. This is particularly true for structure-borne noise. Although there are excellent texts dealing with the theory [2] and approaches to control [3], the methods and data available to the practitioner are not freely available or in a usable form. As a result, structure-borne noise control is often ignored (or unheard of, as in the title), even when important.

2. SOURCE-PATH-RECEIVER APPROACH

There are accepted methods for representing airborne (and duct borne) sound problems. They involve a **source-path-receiver** approach (see Figure 1) where each component can be considered separately.

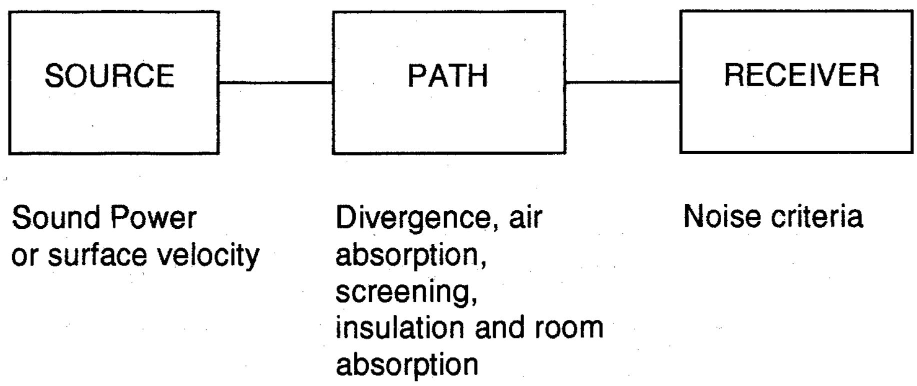

Figure 1. Schematic for airborne sound.

In reverse order; the receiver can be characterised by design criteria and the success of the design depends on whether the predicted or measured sound pressure level in the room of concern falls below the criteria set [4].

The path can be viewed as a succession of attenuations (and sometimes amplifications) between source and receiver which result from distance and room effects, air and surface absorption, insulation at intervening walls and partitions and screening and enclosure. All can be quantified, many by standard methods [5].

The source characterisation is comparatively straightforward. The source impedance is very large and the 'constant velocity' source is unaffected by the surrounding air. The surface velocity and the impedance of the air yields the acoustic power [6]. Power is usually 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 [7].

Therefore, airborne sound power is an acceptable source characterisation. A vacuum cleaner will have the same sound power, whether in a reverberant bathroom or an absorbent living room. The resultant sound pressure levels do of course, vary with location, but they are easily obtained by including the distance and room effects as part of the path.

3. APPROACH TO STRUCTURE-BORNE SOUND

The representation for structure-borne sound appears similar to that for airborne sound (Figure 2) but there are important differences.

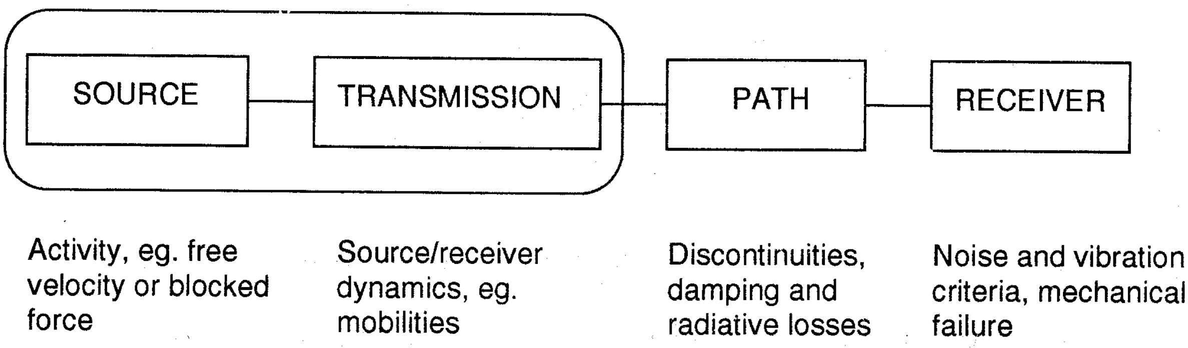

Figure 2. Schematic for structure-borne sound.

Again, in reverse order; if the noise produced is in the audio frequency range then the normal criteria apply. Whilst there are standards [8] and recommendations described in [9] for human response to vibration and low frequency sound, they are less well developed and detailed. This is understandable; we are in the region of human perception which is not strictly concerned with hearing or with vibrational response, but with a combination of the two.

Even if appropriate criteria exist, it is not at present possible to predict whether they will be satisfied. Structure-borne sound propagation through structures such as buildings involves a multitude of reflections and wave conversions from, for instance, longitudinal to bending vibrations [2] and the analysis and prediction becomes intractable for all but the simplest of structures. Even if prediction of the effect of path was possible, the use of structural isolation and vibration damping remote from the source would not normally be practical.

A practical solution requires control at source but a fundamental problem is now exposed in how to characterise machines as sources i.e.. 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? Similar questions are asked by design engineers concerned with producing quiet machinery. Which are the noisiest vibrating components in a washing machine, say, and what are their contributions to the overall acoustic emission of it? In short, how can these components be characterised as structure-borne sources? From Figure 2, two terms have been introduced; the vibrational activity of the machine and the vibrational energy transmission which results when it is connected to a structure such as a floor. The latter depends not only on the former but on the degree of dynamic matching of the source and receiving structures. These and other terms are now described and a description is given of proposed methods of measurement.

4. POWER vs. FORCE or VELOCITY

There is an abundance of one form of information on the transmission process; that on the performance of anti-vibration mounts. Also, standards are being developed for the measurement of transfer properties of resilient elements [10]. Common expressions of performance are force and displacement transmissibility. The first is the ratio of the force transferred to the floor through the mount to that generated by the machine. The second is the ratio of the machine displacement to that of the structure supporting the machine. Both are attenuations or amplifications which do not give absolute values of the vibrational levels achieved. It remains the case that the selection of an anti-vibration mount usually requires knowledge of similar installations; e.g.. the transmissibility of a resiliently supported compressor above a conference room should be 0.05 since this has been found to provide adequate isolation in similar situations [9]. To this extent, the selection process remains a matter of experience rather than calculation.

Even if the force produced at the support points could 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 well 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 since it is the energy flowing into the floor which will eventually radiate as sound in another part of the building after suffering some propagation losses [12].

It is possible to represent the process analogously to simple electric circuits (see Figure 3). For example, a battery of voltage V and internal impedance z_i is equivalent to a vibrational source with free velocity v_{sf}

and source mobility Y_S, respectively. Mobility is the ratio of the response velocity to force at a point; it is the inverse of mechanical impedance. It represents the ability of a structure to be moved dynamically. The load impedance z_e is equivalent to the receiver (i.e.. floor) mobility Y_r and the resultant current i is equivalent to the force at the contact point F_{SR}. The free velocity v_{Sf} is the velocity at the contact point when the source, i.e. the machine, is suspended by soft supports or suspensions and is operating under normal conditions.

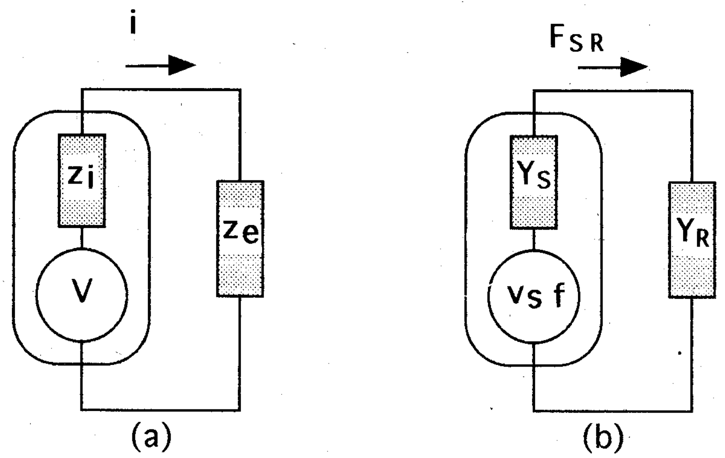

Figure 3. Equivalent circuits for structure-borne sound sources. (a) electric circuit, (b) for a vibrational source.

Simple linear circuit theory can be employed in calculating the active power W from the source to the receiver.
From Figure 3b;

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

Three quantities are required to predict structure-borne power and neglect of either source or receiver mobility will result in errors. An illustrative example is shown in Figure 4 where a floor has been excited by the same source at two locations; one away from a floor edge and the other over a supporting wall. The ratio of the structure-borne emissions was calculated from that of the radiated sound in the enclosed space [13].

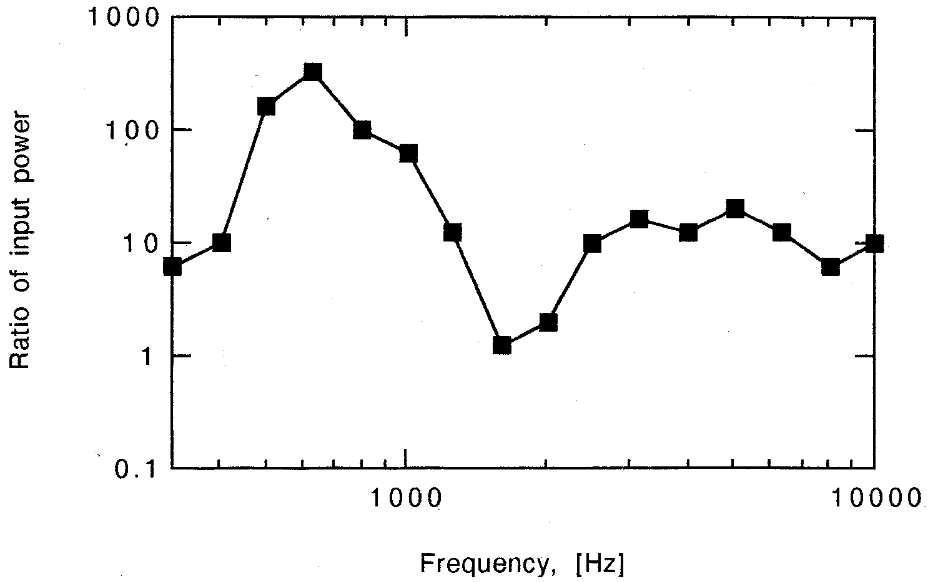

Figure 4. Ratio of structure-borne sound power emission for a source at two locations on a floor; after Petersson [13].

The ratio is highly variable and is due to the variation of the receiver mobility between locations. However, the free velocity and source mobility is unaltered and it should therefore be possible to characterise the source on a power basis, using these two quantities.

5. DEFINITIONS AND REDEFINITIONS

The general field of structure-borne acoustics is complicated by the large number of terms used when engineers and acousticians are discussing machines as vibrational sources. A term such as source strength often confuses rather than clarifies. The following, shown schematically in Figure 5, may help the reader to identify the mechanisms involved and how they can be measured.

Activity is the process where internal dynamical forces in a machine produce the vibrations at the external surface of the machine or at the proposed contact points. It is not practical to measure these internal forces directly but the activity can be represented by the velocity at the contact points when the machine is operating. If the machine is resiliently suspended or supported then the velocity measured will not be influenced by contact with other structures and is thus a function of source

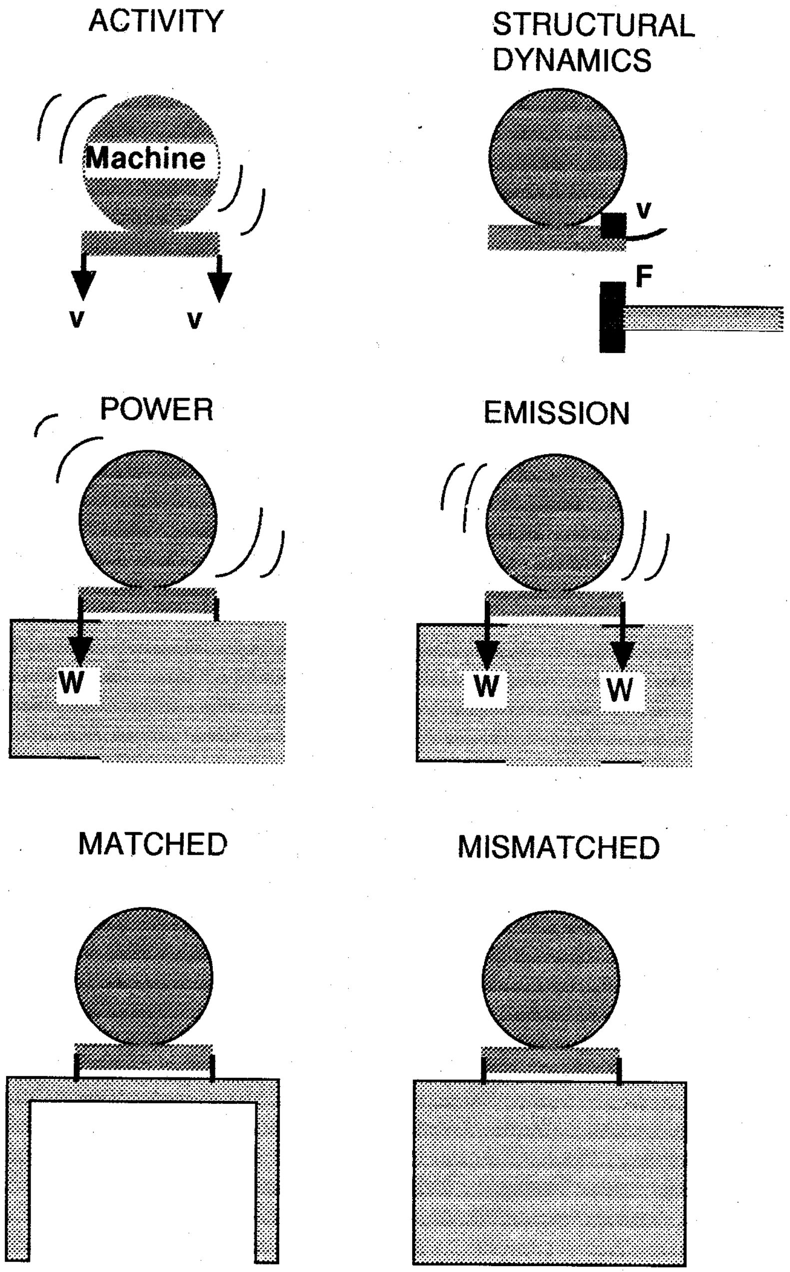

Figure 5. Terminology

properties only. This velocity is therefore known as the free source velocity. It may be more convenient in some situations to measure forces at the contact points when the machine is attached to a large inert (blocked impedance) structure. Therefore, either free velocity or blocked force is a suitable measure of activity.

Source structural dynamics is the additional quantity required of a machine as a structure-borne sound source. It is measured as the mechanical impedance or the inverse, mobility, at the proposed contact points of the machine when the machine is freely suspended and not in operation..

Matching is the indication of how efficiently vibrations, which are a result of the machine's activity, will transfer to a connected structure. It is, however purely a function of the structural dynamics of the source and receiver. It can be expressed as a ratio of the mechanical impedances or mobilities or some other function such as the coupling function.

Power is the vibrational energy flow through the contact point into the connected structure. It is product of the velocity and force at the contact point when the machine is connected to the structure and results from both the activity and the matching. It is possible to obtain negative power (i.e.. from the floor to the machine) through one mount at some frequencies provided the total through all mounts is positive at all frequencies.

Emission can be defined as the total power from the machine, through all mounts. It is the vibrational energy which propagates through the building, and eventually radiates in rooms removed from the machine after propagation losses. Therefore, according to this and the previous definition, if a machine has only one contact point through which a force only applies, then the power at the contact is the emission of the machine. For real machines, with many contact points and components of vibration, this is not the case. Emission only occurs because of contact with the receiver structure.

Activity, in the form of free velocity, for example, is likely to be increasingly used since it is relatively easy to measure. Emission is ultimately the required quantity but is difficult to measure or predict. A proper **source characterisation** should form a link between the two. It should indicate the ability of a machine to emit structure-borne sound and be a characteristic of machine properties only, but the data produced should be combinable with receiver characteristics to give the emission.

6. CHARACTERISATION vs. EMISSION

Despite the general complexity of the problem, attempts continue to represent machines as structure-borne sources in a practical way. Present approaches, known to the author, are now described and it will be seen that most, although apparently simple practically, are not generally applicable and will yield data of use for special cases only. Ideally, any standard method of test of machines as sources of structure-borne sound should allow the following [14];

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

A standardised test and the data which results should achieve these four requirements directly or indirectly after some transformation and they should be confined to the source rather than the source connected to a 'typical' supporting floor or other structure.

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 [14]. Its aims are those listed above. Working groups also have been set up to consider specific machine types such as circulation pumps [15]. Standards exists for measurement of vibration levels of machines, such as for large fans [16], but these are measures of source activity rather than emission.

There has been concomitant work on small air movement devices by an INCE technical group [17]. 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 [18]. Sometimes known as the free velocity method, it involves measurements of vibrational velocity at contact points of resiliently installed or suspended machinery (Figure 6).

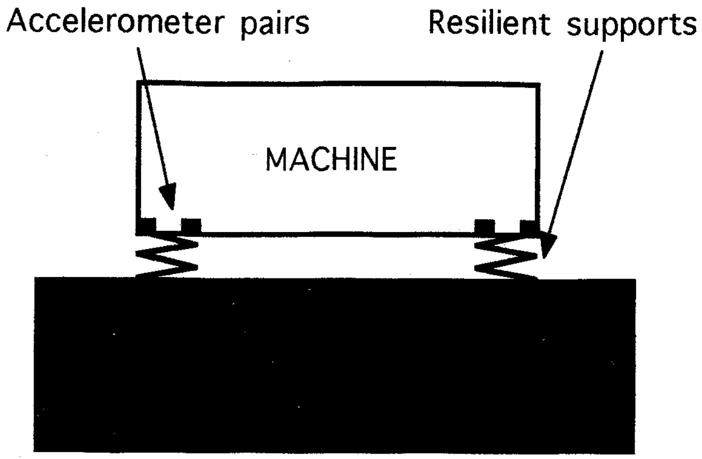

Figure 6. Free velocity method.

However, it is not a full characterisation. Two sources of the same velocity will give different sound levels even when installed at the same location in a building. 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.

An example of the second category is the **reception plate** method, which is at early draft standard stage [18]. A thin plate is attached to the source and its spatially averaged acceleration measured [19] (Figure 7). Again, two sources could give the same value but different sound levels when installed at the same location in a building. 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 [17]. It has relevance only if a 'typical' installation is assumed which is truly representative of the range of installations likely.

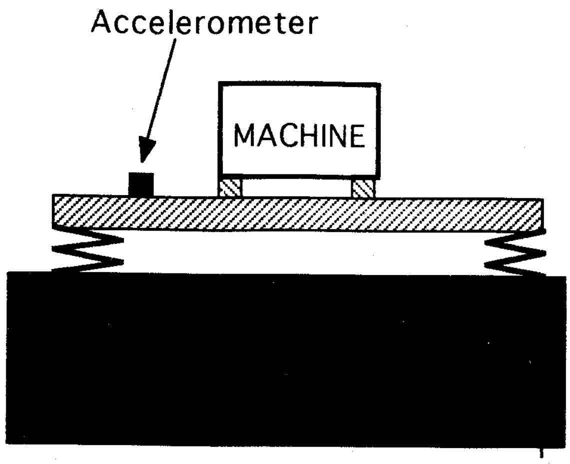

Figure 7. Reception plate method.

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 (see Figure 8). 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 [14]. 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. In the extreme case; if the machine imparted power only through a pure moment then it cannot be represented by a single vertical force. As in the other methods described, the data produced will not describe the machine's noise emission in other installations.

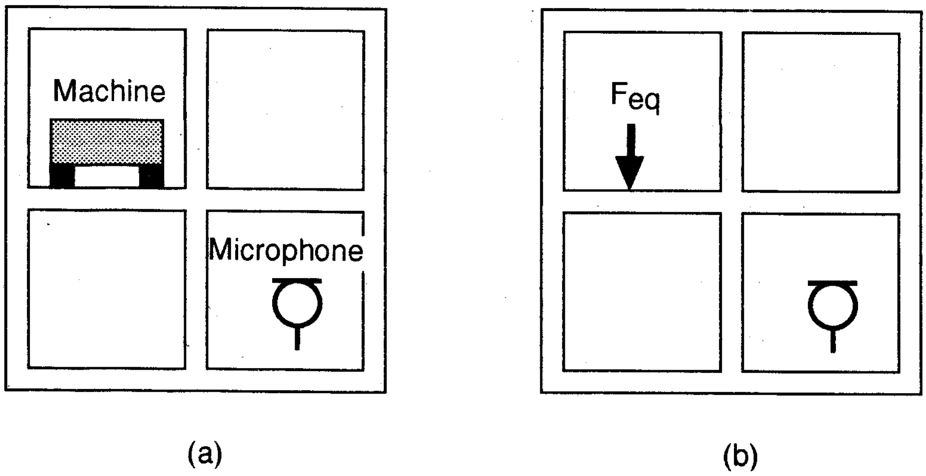

Figure 8. Equivalent force; (a) machine in place, (b) equivalent force.

7. ABILITY TO EMIT STRUCTURE-BORNE SOUND

The four requirements of a standard would be satisfied by the structure-borne power but this requires knowledge of both source and receiver characteristics. It has been shown that it should be possible to characterise the source, on a power basis, using free velocity and source mobility. This has been demonstrated by Mondot and Petersson [20] where equation (1) for emission can be rewritten as;

$$W = Re[SC_f] \tag{2}$$

where S is the source descriptor, given by;

$$S = |v_{Sf}|^2 / (2Y_S^*) \tag{3}$$

and C_f is the coupling function, given by;

$$C_f = Y_S^* Y_R / |Y_S+Y_R|^2 \tag{4}$$

The source descriptor is a quantity which solely involves data related to the source. It has units of power but is not the emission [21]. It is, in fact, the ability of the machine to deliver power. The emission is obtained by including the coupling function which is high for connected structures with a high degree of matching and low for a low degree of matching.

Again, because its units are those of power, it allows a proper 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 since they are dimensionally incompatible, but by applying the source descriptor, the source's ability to yield power through those components of vibration can be compared.

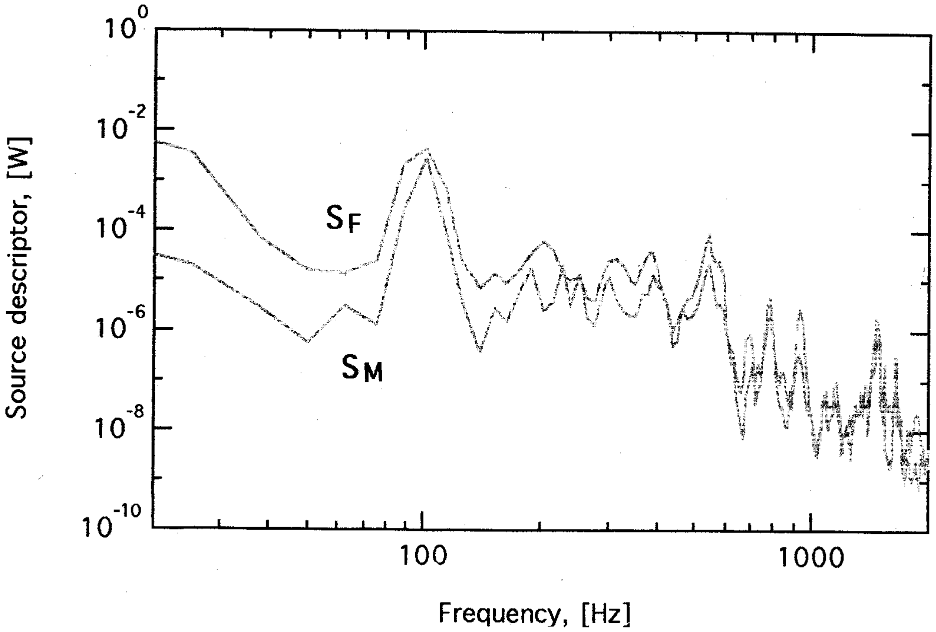

Figure 9. Moment source descriptor S_M and force source descriptor S_F for a mount of a medium size fan unit; after [22].

In Figure 9, the force source descriptor is predominant at low frequencies but the moment source descriptor becomes equal to or larger at mid to high frequencies [22]. In this case, none of the components of vibration considered can be neglected when considering the total emission.

To summarise; any true source characterisation, involving source terms only, cannot give the emission when the machine is installed. Conversely, the emission is strongly dependent on the dynamic characteristics of both the machine and receiving structure and therefore cannot be used as a source characterisation. With this proviso, the source descriptor would appear to be a logical source characterisation worthy of development.

8. PRACTICALITIES OF MEASUREMENT

There is a programme of work at Liverpool University concerned with the practicalities of the source descriptor concept [22]. Measurements have been undertaken on small and medium sized centrifugal fans, compressors and electric motors. The free velocities at each of typically four mount points were measured with the machines operating normally but while suspended by means of elastic strips. Matched accelerometer pairs gave signal sums proportional to translational acceleration and signal differences proportional to rotational acceleration. Measurements included vertical translational velocity and rotational velocities.

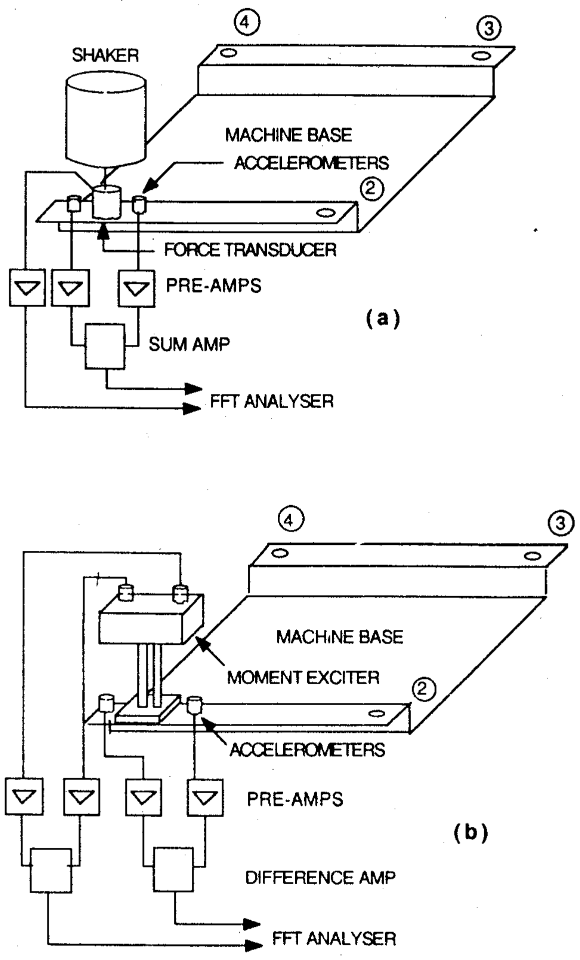

Figure 10. Measurement of (a) force mobility and (b) moment mobility.

Mobilities were measured at the same support points by means of force and moment actuators which were mounted as indicated in Figure 10, again with the machines elastically suspended. Force mobility was measured by means of electrodynamic shakers and force transducers. A novel moment actuator was constructed to a design by Petersson [23] for the measurement of moment mobility. The source descriptor was calculated according to equation (4) at all mount points and for typically three components of vibration; vertical translation and two rotations. In Figure 11 are shown the force source descriptors for four mount positions. In Figure 12 are the moment source descriptors for the same mounts. The variation between mounts is of the order of 5-10 dB and this suggests a possible simplification of data presentation by taking averages.

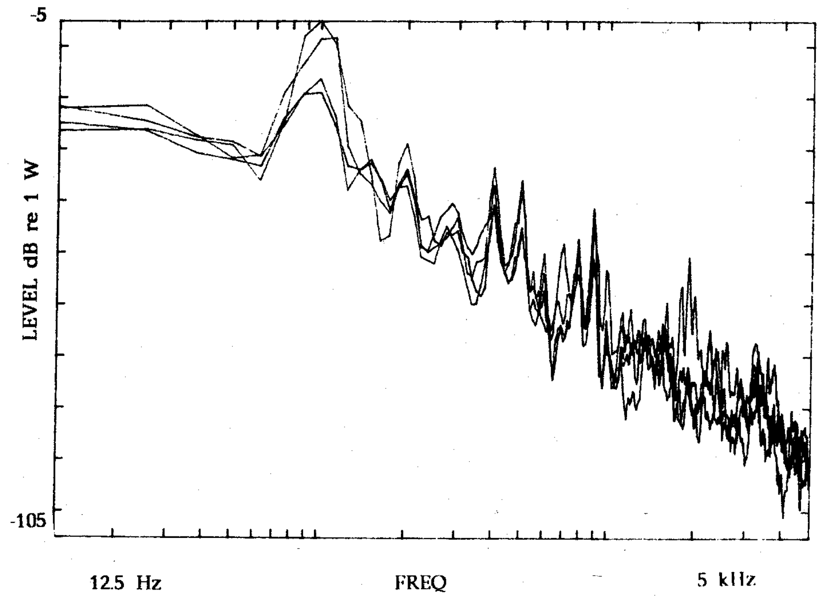

Figure 11. Force source descriptors at four mount points.

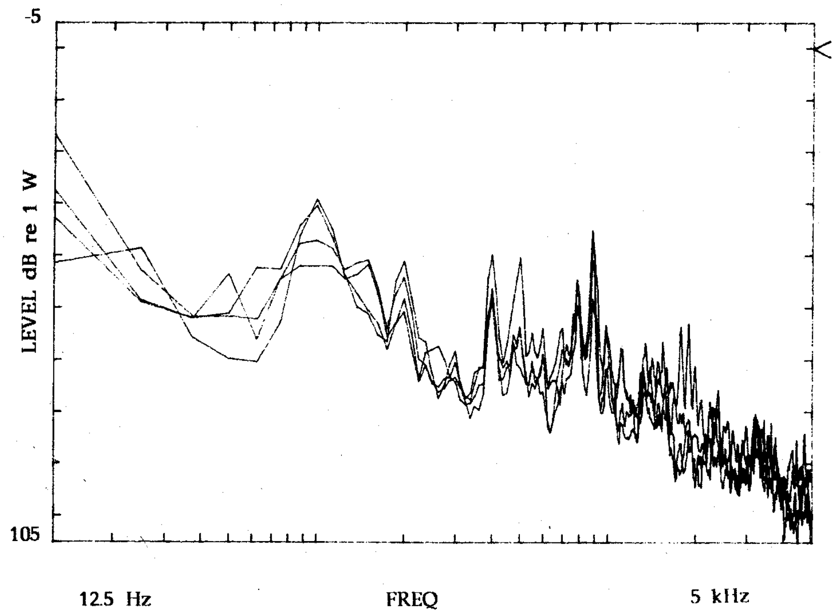

Figure 12. Moment source descriptors at four mount points.

Measurement of source descriptor, or indeed any of the proposed rating methods described, is not a problem in a well resourced laboratory. The challenge is in presenting the data obtained in a practical and usable form for the design engineer, manufacturer and user.

9. 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 equations 1 and 2 can be preserved, however, by substituting effective mobilities for the source and receiver for the point mobilities [24]. The effective mobility of a point is the velocity at a point due to the force at that point plus the forces at all other points. The advantage of the effective mobility is twofold. Firstly, the simplicity of the single point formulation can be retained and secondly, simplifying approximations are more easily introduced, allowing engineering insight.

Work continues on developing representations for multi-point and multi-component sources. The effective mobility depends not only on the transfer and cross mobilities but also on the distribution of the forces between the mount points. Again, these are obtained only when the machine is attached to the floor. Fulford is considering simplifying assumptions for force distribution, using deterministic and statistical analyses [25].

Moorhouse has shown that all mobility terms can be incorporated into a representation which provides the convenience of a single figure rating [26]. The solution to these problems are not imminent but it is becoming clear that it should be possible to represent a complex process in a practical way without loss of essential detail.

10. CONCLUDING REMARKS

It has been demonstrated that both a machine's activity and its dynamic characteristics are needed to properly describe its ability to emit structure-borne sound. It has also been demonstrated that structure-borne sound emission and source characterisation are distinctly different. Any true source characterisation (i.e.. involving source terms only) cannot yield emission in the installed condition. Conversely, the emission of a machine is strongly dependent on the dynamic characteristics of both the source and receiving structures and cannot be used as a basis for source characterisation unless all proposed installations are the same.

The source descriptor would appear to be a logical source characterisation but its development requires consideration of multiple point interaction, multiple component interaction, including phase information.

It can be argued that, based on present knowledge, attempts to produce a proper standard 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 will involve data reduction, including single value rating and the investigation of the relationship between such ratings and annoyance.

Many of the issues on source characterisation addressed have yet to be resolved. A solution would be an important step in the development of a methodology and associated data for structure-borne sound control.

ACKNOWLEDGEMENTS

Much of the author's contribution to this field has been in collaboration with Professor Bjorn Petersson, now of Loughborough University and Dr. Andrew Moorhouse of Liverpool University. Their work, referred to in this paper, is gratefully acknowledged, likewise the many stimulating discussions with them on the subject.

REFERENCES

1. A. T. Moorhouse and B. M. Gibbs, 1990, *Field measurement of structure-borne emission of ventilation fans and compressors,* Proc. Inter-noise 90, vol.1, 205-208.
2. L. Cremer, M. Heckl and E. Ungar, 1973, *Structure-borne sound,* Springer Verlag, Berlin.
3. R. H. Lyon, 1987, *Machinery noise and diagnostics,* Publ. Butterworths.
4. L. L. Beranek, 1989, *Criteria for controlling noise and vibration,* Proc. Inter-noise 89, vol. 1, 5-42.
5. ISO 140:1978, *Measurement of Sound Insulation in Buildings.*
6. A. D. Pierce, 1989, *Acoustics: An Introduction to its Physical Principles and Applications,* Publ. Acoustical Society of America.
7. ISO 3741-7, *Sound power levels of noise sources.*
8. BS 6472:1992, *Evaluation of Human Exposure to Vibration in Buildings (1 Hz to 80 Hz).*
9. A. Fry, 1988, *Noise Control in Building Services,* Publ. Pergamon Press.
10. ISO/CD 10846-1 1994, *Acoustics-Laboratory measurement of the vibro-acoustic transfer properties of resilient elements.*
11. A. T. Moorhouse and B. M. Gibbs, 1987, *Vibrational power flow from machines into structures,* Proc. Institute of Acoustics, Spring Meeting.
12. H. G. D. Goyder and R. G. White, 1980 ,*Vibrational power flow from machines into built-up structures,* J. Sound Vib. 68(1), 97-117.
13. B. A. T. Petersson, J.Sound and Vibration 91, 219-238,1982.
14. T. ten Wolde and G. R. Gadefelt, 1989, *Development of standard measurement methods for structure-borne sound sources,* Noise Control Engineering J. 28 (1) 5-14.
15. CEN/TC 197/SC 4/WG1, 1994, *Circulation pumps for heating and water services installations.*
16. BSI 848: *Fans for general purposes, Part 6.*
17. L. E Wittig and H. Hsieh, 1990, *A test fixture for measuring small fan vibration levels,* Proc Noise-Con 90, 49-54.
18. ISO/DIS 9611.2, 1993, *Acoustics - Characterisation of sources of structure-borne sound with respect to the airborne sound radiation of connected structures - Measurement of velocity at the contact points of machinery when resiliently mounted.*
19. ISO draft, 1993, *Measurement of the average vibration velocity of a thin reception plate to which the source is connected.*

20. J.M. Mondot and B.A.T. Petersson, 1987, *Characterisation of structure-borne sound sources: The source descriptor and coupling function,* J. Sound Vib.114 (3), 507-518.
21. B. A. T. Petersson and B. M. Gibbs, 1994, *Aspects of structure-borne sound source characterisation and emission,* Proc. Inter-noise 94, vol. 1, 621-626.
22. B. M. Gibbs. B. A. T. Petersson and Qiu Shuye, 1991, *The characterisation of structure-borne emission of building services machinery using the source descriptor concept,* Noise Control Engineering J. 37(2), 53-61.
23. B. A. T. Petersson, *The use of giant magnetostrictive devices for moment excitation,* J. Sound Vib. 116, 191-193.
24. B. A. T. Petersson and J. Plunt, 1982, *On effective mobilities in the prediction of structure-borne sound transmission between a source and a receiver structure,* J. Sound Vib. 82 (4), 517-529.
25. R. A. Fulford and B. M. Gibbs, 1994, *Structure-borne sound power in multiple point connected systems using the effective mobility concept,* Proc. Third International Congres on air- and structure-borne sound and vibration, vol. 1, 209-216.
26. J. Su and A. T. Moorhouse, 1995, *Towards a practical characterisation for structure-borne sound sources*, accepted for J. Sound Vib.