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CHARACTERISATION OF MACHINES AS SOURCES OF STRUCTURE-BORNE SOUND EMISSION - PROGRESS OF ISO/TC43/SC1 WG 22

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1. INTRODUCTION

Machine induced noise problems in buildings and other structures result when excessive sound power is generated into the surrounding air, through points of contact and along pipework and ductwork. The problem for the noise control engineer is often made more difficult since the noise can result from a combination of these transmission mechanisms.

The analysis and control of airborne noise is reasonably straightforward. A source-path-receiver approach is possible since the source often can be described by the sound power. In situations where the machine is predominantly a structure-borne source the engineer is confronted with a difficulty which results from the lack of a recognised method of characterising vibrationally noisy machines.

In an attempt to rectify this omission the International Organisation for Standardisation (ISO) established the working group ISO/TC 43/SC 1/WG 22 which has concerned itself since 1984 with methods of characterising the structure-borne emission of sources. The aim of the working group was to produce standards on structure-borne sound emission which would allow the following:

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.

Ideally an approach and the data which results should achieve these four requirements directly or at least be compatible after some transformation and it should be confined to the source rather than the source in a 'typical' environment.

The task is not easy when seen in comparison with airborne emission where the source strength is a function of surface velocity and knowledge of the fluid (air) impedance yields the power delivered. Here, the source impedance is assumed large and such a 'constant velocity' source is unaffected by its surroundings. Airborne sound power is often given as the fundamental quantity. Indirect measurement of airborne power in reverberant or anechoic environments or by means of energy intensity methods should yield the same value and be applicable to most other environments. The general acceptance of the principal is seen in the existence of ISO standards [1] and the data bases which have resulted (eg. [2]).

Can a similar approach be adopted for structure-borne sources where transmission is via solid links? The problem seems intractable on first inspection.The impedances (or conventionally, the mobilities) of a source, such as a small axial fan and a receiver, such as computer enclosure, may not be greatly different and there is the danger of matching with resultant increased vibrational power [3]. Machine motion at the mount points involves up to six degree of freedom where forces and moments contribute to the total emission. The response under one mount is the result of forces and moments at all mount points and it is necessary to consider transfer and cross mobilities in addition to point mobility.

2. METHODS PROPOSED

By 1985 seven methods had been proposed for consideration [4] which were:

M1. Measurement of velocities or accelerations on the feet (and other contact points) of resiliently mounted machinery.
M2. Measurement of a set of equivalent forces and torques by means of a resiliently mounted block.
M3. Measurement of the equivalent force on the structure close to the machine.
M4. Measurement of free velocities and local mobilities of the machine's feet by means of different mechanical loadings.
M5. Measurement of the acceleration on a reception plate.
M6. Measurement of sound pressure in a reception enclosure.
M7. Measurement of velocities on the machine housing.

On initial inspection it appears possible to identify two main approaches; an attempt to characterise the machine from measurements of the machine and an attempt to characterise the machine by consideration of the response of a passive system attached to it. Closer scrutiny of all the methods in the context of the four previously stated requirements leads to the following comments, disregarding for the present the measurement techniques involved.

M1 gives a velocity vector (v_i^k) which approximates the velocity vector of the free source if the machine is resiliently mounted. The required power is given by,

$$W_{in} = 0.5 \frac{|v_{FS}|^2 \ \mathrm{Re}[Y_R]}{|Y_S + Y_R|^2} \qquad (1)$$

Therefore the velocity data is a subset of that required since, ignoring the requirement for receiver mobility, source mobility Y_S is lacking.

M2 yields a so-called equivalent force vector ie. the net (Newtonian) forces and moments exerted by the source on a rigid block, $\{F_N\}$. These forces approximate those of the blocked source and in analogy with equation (1),

$$W_{in} = 0.5 \frac{|F_{BS}|^2 \, Re[Z_R]}{|Z_S + Z_R|^2} \qquad (2)$$

Again the passive characteristics of the source, Z_S is required.

M3 gives as source data an equivalent force, derived from the power injected to a test environment and as such no expression can be developed for arbitrary receivers since the equivalent force is unphysical. However, the power transmitted can formally be stated as,

$$W_{in} = 0.5 \, W_{B,in} \frac{Re[Y_R]}{Re[Y_B]} \qquad (3)$$

where Y_B and Y_R is the laboratory (bench) mobility and actual receiver mobility, respectively and do not relate to the source.

M4 yields the velocity vector of the free source and the point and cross mobilities for each point whereas all transfer and cross-transfer elements are neglected. The data which results remains a sub-set of that required.

M5 yields the spatially averaged acceleration, $\langle a^2 \rangle_p$ of a reception plate attached to the source. Again it is not possible to derive the power transmitted to an arbitrary receiver from this data.

M6 yields the spatially averaged sound pressure inside an enclosure, $\langle p^2 \rangle_{cav.}$ and suffers from the same limitation as M5.

M7 refers to a spatially averaged velocity $\langle v^2 \rangle_S$ of the surface of the source structure when attached to some receiver. It relates directly to the source but not to the contact point(s) and is not independent of the test (receiver) facility.

It is clear that none of the methods originally proposed by the working group unambiguously fulfils the four requirements. The methods either provide a subset of the data required, depend on the installation or are unphysical.

Despite this, the working group has concentrated on methods which are simple to implement and three of the original seven methods are being actively considered:

M1, the measurement of velocity at the mount and contact points of resiliently mounted machines, has been presented as a proposed ISO standard [5].

M3, the measurement of the equivalent force by substitution or reciprocal methods, has been the subject of some field trials but its development is in general not so advanced as that of M1.

M5, the reception plate method, is at the same stage of development as M3.

To summarise, of the seven methods proposed for the characterisation of machines as sources of structure-borne sound proposed in 1985, three have been the subjects of further investigation and one of these, M1, the measurement of velocities on the feet of resiliently mounted machinery, is at ISO draft stage. It is worth repeating however that none of the methods proposed unambiguously fulfils the requirements for source data which can be used to estimate input power, given a specific installation.

There has been concomitant work on fan vibration by the International Noise Control Engineering (INCE) Technical Group on Computer and Business Equipment (TG/CBE), based in the USA. Since 1987 a sub-committee has been concerned with the structure-borne component of sound emission from air movement devices. The requirements of a method or methods are similar to those identified by WG22 and, again, the intention is to produce a standard. The aims of the group are less ambitious than those of WG22 since the method is to apply to one family of machines only; fans and blowers used in computers and other business machinery.

The method being adopted involves the use of a damped plate which has a mobility similar to that of an ensemble average of computer-like structures [3] but again the method cannot be described as a true source characterisation since a 'typical' installation is required or assumed.

3. REFORMULATION OF THE PROBLEM

It has been established from the discussion so far that the four requirements are simultaneously satisfied by knowledge of the structure-borne power. Moreover, the power is obtained from knowledge of both source and receiver characteristics. At best, therefore a source can only be characterised in terms of its ability to yield power.

Mondot and Petersson [6] define a source descriptor $\underline{S}$ in terms of free velocity $\underline{v}_s$ and source mobility $\underline{Y}_s$ where,

$$\underline{S} = v_s^2 / \underline{Y}_s^* \qquad (4)$$

The product of the descriptor and a coupling function $\underline{C}$ yields the complex power at the contact point, where,

$$\underline{C} = \underline{Y}_s^* \underline{Y}_r / | \underline{Y}_s + \underline{Y}_r |^2 \qquad (5)$$

$\underline{Y}_r$ is the receiver (floor) mobility. It has the dimension of power and offers the possibility of comparisons of machines. The source mobility required for the descriptor is also used in combination with receiver mobility to calculate the coupling function and thence the structure-borne emission for any component at the point of contact between machine and floor.

4. SOURCE DESCRIPTOR FOR FANS

Present work at Liverpool University is concerned with the application of the source descriptor concept and results are presented for small and medium sized centrifugal fans. Consideration is given to more than one degree of freedom of motion and for multiple supports. Simplifications in data presentation are suggested which might ensure ease of comparison of machines and a useful data base.

The free velocities at each of typically four mount points were measured when the fans were operating normally but while suspended by means of elastic strips. Matched accelerometer pairs, at a spacing of 40mm about the mount points, gave signal sums proportional to translational acceleration and signal differences proportional to rotational acceleration for frequencies below 2 kHz which was the bandwidth of measurement. The survey included measurement of vertical translational velocity v_z and rotational velocities w_x and w_y

Mobilities were measured at the same support points by means of force and moment actuators which were mounted as indicated in Figure 1 with the fans elastically suspended. Force mobility was measured by means of electrodynamic shakers and force transducers and where, again, increased discrimination was obtained by use of accelerometer pairs.

The source descriptor was calculated according to equation (4) for each fan, at all mount points and for three degrees of freedom. In Figure 2 are shown the force source descriptors for four mount positions. The difference in level between mount positions is of the order of 5-10 dB. and this suggests a possible simplification by presenting results as spatial averages. In Figure 3 such average source descriptors associated with the force and two moments are shown for two fans. The expectation that the vertical, translatory force dominates at low frequencies is confirmed but there is evidence of convergence at mid and high frequencies which suggests an equipartition of vibratory energy associated with rotation and translation which, in turn, may form a basis for substantial simplifications with respect to the high frequency transmission.

5. CONCLUDING REMARKS

The progress of the working group ISO/TC 43/SC 1/WG 22 has been reported. Included is the concomitant work of the sub-committee of INCE TG/CBE. Both have set as their aim the formation of a standard or standards for the characterisation of structure-borne sound sources. From consideration of basic principles it has been shown that none of the methods proposed can satisfy the four primary requirements stated. It can be argued that, based on present knowledge, any attempts to standardise are premature.

A reformulation of the problem yields a source descriptor and coupling function which, when combined, gives the required structure-borne emission. The source descriptor is calculated from source characteristics only and will allow the manufacturer to provide unambiguous data. Results obtained so far for real machines under normal operation show that the approach remains practical for multi-point and multi-component sources. However it must be emphasised that this offers an approach rather than a proposed standard and the opinions which have been presented are those of the authors.

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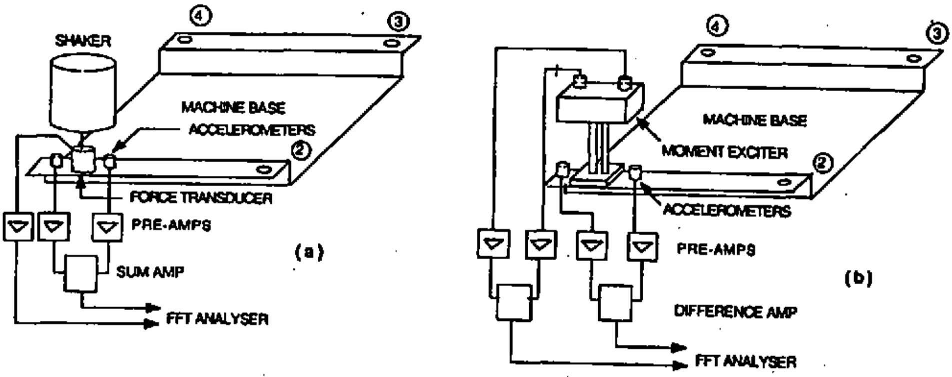

Figure 1. Measurement arrangement for (a) force and (b) moment mobility.

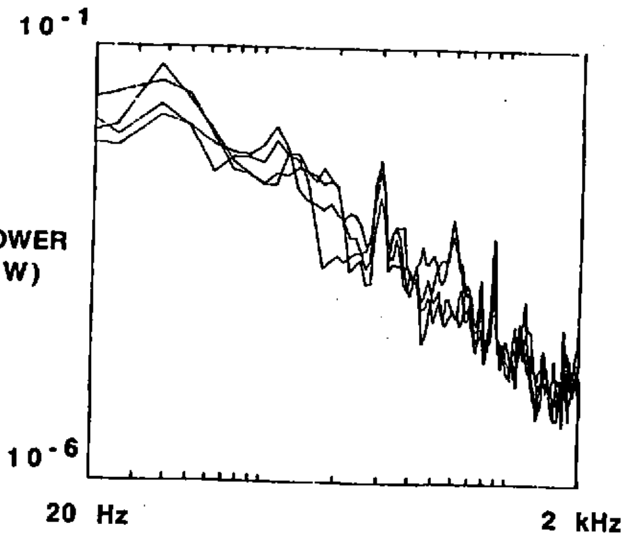

Figure 2. Source descriptors for vertical force at four mount points of a fan.

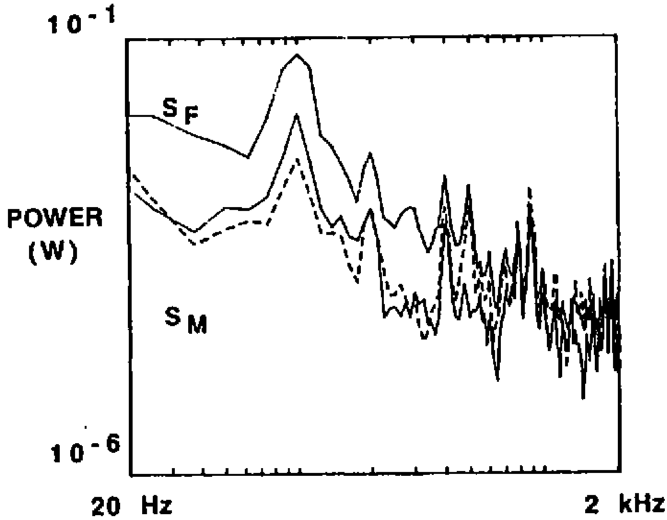

Figure 3. Average force and moment source descriptors for two fans.