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SOURCE DESCRIPTORS FOR STRUCTURE-BORNE SOUND SOURCES

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ABSTRACT

A source descriptor for structure-borne sound sources is presented which is similar to airborne sound power. It has units of power and is valid for multiple point contact and for moment as well as force excitation. The power delivered when the source is installed is a fraction of this source descriptor and is determined by the degree of mobility matching between source and receiver. Results are presented for a domestic central heating pump and centrifugal fans on various receiver structures.

INTRODUCTION

Designers, vendors and purchasers of machinery need reliable information about the 'noisiness' of machines so that they can:

(i) compare one source with another
(ii) compare sources with set limits
(iii) predict sound levels when installed
(iv) design quieter machines

Sound power (Lw) meets all of these objectives for most airborne sound sources and is widely used and standardised. In the case of structure-borne sound sources a characterisation equivalent to Lw does not exist, partly because the power delivered varies from one installation to the next, being dependent on the structure to which the source is connected (the receiver). An additional problem is that the power transfer usually occurs through a number of connections and by rotational as well as translational components of motion. The objective of this paper is to explore a structure-borne sound source characterisation achieves these objectives.

To achieve aims (i) and (ii) the source characterisation must be presented as a single figure. This does not rule out more detailed information, for example about the directivity or frequency content, but it must be possible to reduce this data to a single figure in a physically meaningful way. In the case of airborne sources this is usually achieved by the 'A' weighted sound power.

Regarding objective (iii), a machine manufacturer will not generally know how a source is to be installed. For example, the same electric motor may end up bolted to a washing machine frame or connected rigidly to a concrete slab in a plant room, and the structure-borne sound power delivered in each case would be quite different. Certain sources are always connected to a particular type of receiver, for example central heating pumps are invariably connected to pipes of nominally identical diameter and thickness. However, even here the power delivered depends on how the pipe is fixed, which is variable. Thus, to allow prediction of installed sound levels the source characterisation must be a property of the source, <u>independent</u> of the receiver.

We can now summarise the requirements for the source characterisation we are seeking if it is to achieve objectives (i)-(iv) above. It must be:

(a) characteristic of the source's ability to deliver structure-borne sound power
(b) an independent property of the source
(c) able to be expressed as a single figure.

THE SOURCE DESCRIPTOR

The source descriptor was introduced by Mondot and Petersson in 1987 [1] for a structure-borne sound source with a single point of contact. It is defined as:

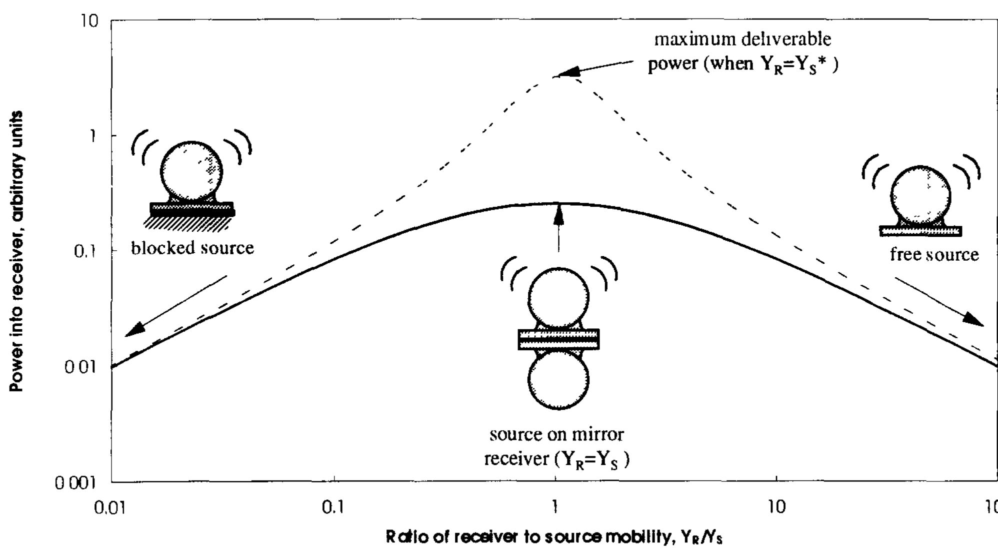
$$S = \frac{1}{2}\left|v_{fs}\right|^2 \left(Y_S\right)^{*-1} \qquad \text{Eqn (1)}$$

where v_{fs} is the free velocity of the source [2], and Y_S is the mobility of the connection point. (* denotes complex conjugate.) S is complex, has units of power, and is an independent property of the source. For practical sources this must be extended to multiple point contact and multiple component excitation (moments as well as forces). Mondot and Petersson did this by introducing the concept of 'effective mobility'. However, the resulting multi-point source descriptor is a function of the receiver mobility and so does not fulfill the criterion of independence. Thus we must extend our search.

One other possible characterisation is the free velocity which is now standardised [2]. This is an independent property and is characteristic of the vibrational 'activity' of the source. However, the free velocity is in general a vector containing both translational and rotational components which cannot be added. The free velocity cannot therefore be reduced to a single figure, and does not meet our third criterion. The 'blocked forces' (i.e. those exerted by the source when blocked with a perfectly rigid receiver) also provide an independent characterisation. However, the same problem arises as with free velocities, since the generalised force vector contains moments which cannot be combined with the forces to yield a single figure descriptor.

In order to deal with the problem of mixed excitation components, use of a descriptor based on power has often been suggested [3]. Referring to figure 1*, the free velocity and blocked forces are assymptotic cases where the source is attached to a perfectly soft and a perfectly rigid receiver respectively. In both cases no power is delivered to the receiver. However, we could also choose a point midway between these two extremes where the source and receiver are identical, that is where the receiver is a 'mirror' of the source structure (fig 1). The power delivered to such a mirror structure is characteristic of the source just as free velocity and blocked force are, but is expressed in units of power.

Figure 1 Power as a function of mobility matching



To find an expression for the 'mirror power' we first consider the power delivered to a receiver of mobility YR, which, for contact at discreet multiple points is given by:

$$Q = \frac{1}{2} \mathbf{v}_{\mathbf{fs}}^{*T} \left(\mathbf{Y_S} + \mathbf{Y_R} \right)^{*T-1} \mathbf{Y_R} \left(\mathbf{Y_S} + \mathbf{Y_R} \right)^{-1} \mathbf{v_{fs}} \qquad \text{Eqn. (2)}$$

where Q is the complex power through the interface, $\mathbf{Y_S}$, $\mathbf{Y_R}$ are the complex mobility matrices of the source and receiver respectively and $\mathbf{v_{fs}}$ is the free velocity vector. If the receiver is a mirror structure then its mobility is identically equal to that of the source, so we replace $\mathbf{Y_R}$ by $\mathbf{Y_S}$ to obtain:

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* *figure 1 applies strictly to single point contact, but can also be applied in a looser, schematic way to multiple point and area contact.*

$$Q_m = \frac{1}{8} \mathbf{v}_{\mathbf{fs}}^{*T} (\mathbf{Y_S})^{* -1} \mathbf{v}_{\mathbf{fs}}$$ Eqn. (3)

Now we define a complex source descriptor, S, as four times the power into the mirror

$$S = 4 Q_m = \frac{1}{2} \mathbf{v}_{\mathbf{fs}}^{*T} (\mathbf{Y_S})^{* -1} \mathbf{v}_{\mathbf{fs}}$$ Eqn. (4)

We notice that S collapses to Mondot and Petersson's source descriptor for single point contact and conclude that it is a generalisation of their concept to multiple point and component excitation. The source descriptor S as defined above is characteristic of the source's ability to deliver power, is an independent property of the source and is a single figure†. Thus, it fulfills all the criteria set out in the introduction. Furthermore, there is no theoretical reason why the mirror receiver approach should not be valid for contact over extended surfaces as well as at discreet points.

Further insight can be gained by noticing that the blocked force vector is related to the free velocity vector as follows

$$\mathbf{f}_{\mathbf{bl}} = (\mathbf{Y_S})^{-1} \mathbf{v}_{\mathbf{fs}}$$ Eqn. (5)

By substitution of equation 5 into equation 4, the source descriptor S is seen to equal half the dot product of the free velocity and blocked force vectors.

The idea of a mirror receiver provides a physical interpretation to the source descriptor which is conceptually helpful. It also suggests an interesting possibility for measurement, by attaching an identical passive receiver to the source and measuring the power transferred. For machines such as electric motors it may be a realistic practical possibility to mount two such sources back to back. This is particularly interesting where there is contact over an extended area since this case presents particular difficulties in measurement and analysis using conventional approaches. The main difficulty would appear to lie in measurement of the power through the interface, since direct measurement will not generally be possible and indirect measures are subject to error. This prospect will not be investigated further here, although it may form a topic for future study.

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† *the source descriptor is frequency dependent and therefore in one sense not strictly a single figure rating. However, comparison between sources, and with set limits can be achieved by applying any consistent frequency weighting. It is of course far from trivial to decide on an appropriate frequency weighting, but this topic will not be discussed further here.*

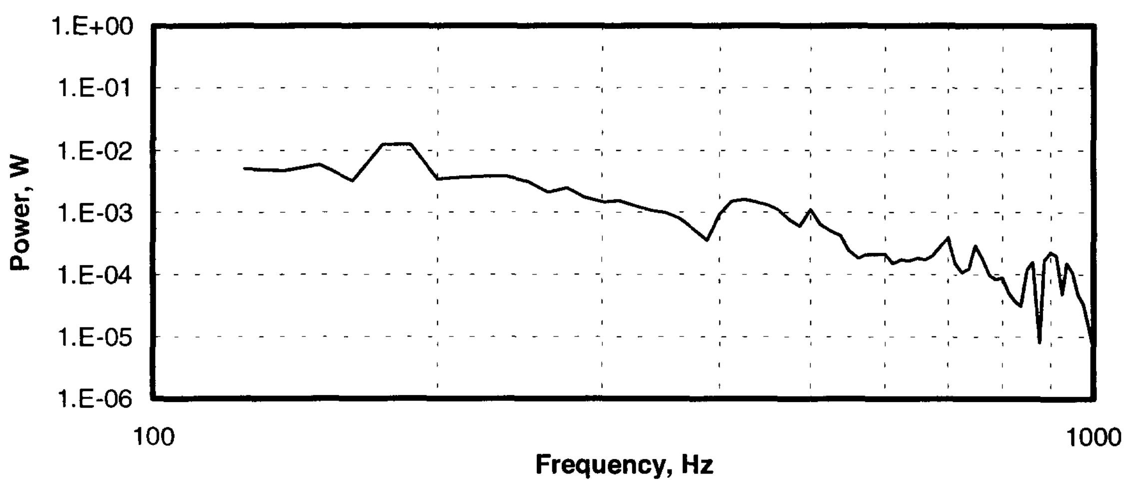
SOURCE DESCRIPTORS FOR FANS AND PUMPS

In this section source descriptors are presented for two centrifugal fans and a domestic central heating pump. These were derived from equation 4, that is by free velocity and mobility data.

Fan 1 is a 0.5kW package centrifugal fan with a base of steel angle section. 4 contact points were considered, and with 3 degrees of freedom at each (1 translation and 2 perpendicular rotations). One half of the 12x12 mobility matrix was measured (78 mobilities in all) the other half being inferred by reciprocity. Moment mobilities were measured using Petersson's moment exciter [4]. 12 free velocity measurements were made, 1 translation and 2 rotations at each point. Fan 2 was a smaller unit (0.18kW) on a 3mm steel base plate, and was described again by the 12x12 mobility matrix and 12x1 free velocity vector.

The source descriptors for these fans are shown in figs. 2 and 3. In both cases low frequency power dominates with a steady decrease to 1kHz. The airborne sound power for fan1 running under slightly different conditions was lower than the source descriptor at all frequencies (not shown). This suggests that although it would normally be considered an 'airborne' source it may have a comparable potential to transmit sound power through structural contact.

Figure 2 Source descriptor for fan 1



A practical difficulty became evident during the analysis of S in that errors in the measured mobilities resulted at some frequencies in real(S) being negative, which is unphysical. Its magnitude, |S| is less subject to such errors and has been used in figures 2-4.

Shown in figure 4 is the source descriptor for a domestic central heating pump. This is a preliminary estimate based on mobility measurements and free velocity measurements at a single point on the pump casing and without including bending moments. Nevertheless, it is thought to be of the correct order of magnitude and display the correct trends. It is seen to be of much lower magnitude than that of the fans with the highest peak of 2μW (63dB re 1pW) at about 21 and 42Hz. The pump's airborne sound power is of significantly lower magnitude than this at these frequencies, indicating that it has more potential to deliver sound power via solid connections than via the air.

Figure 3 Source descriptor for fan 2

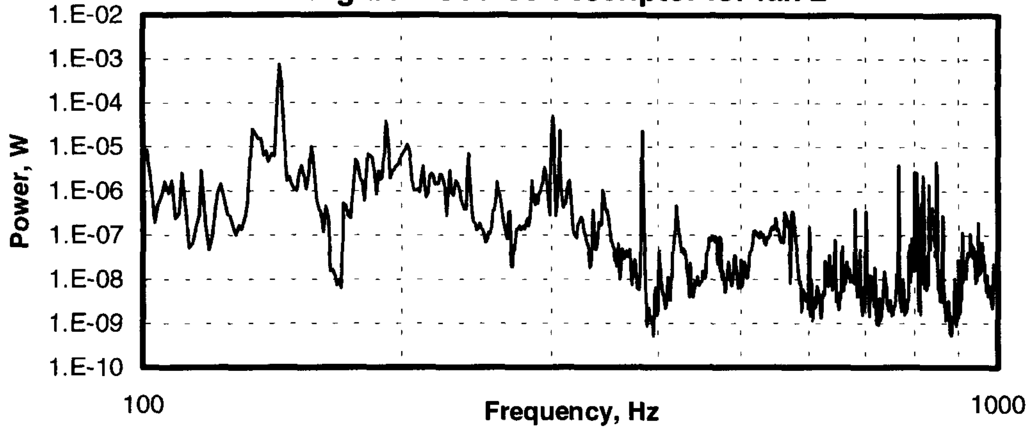
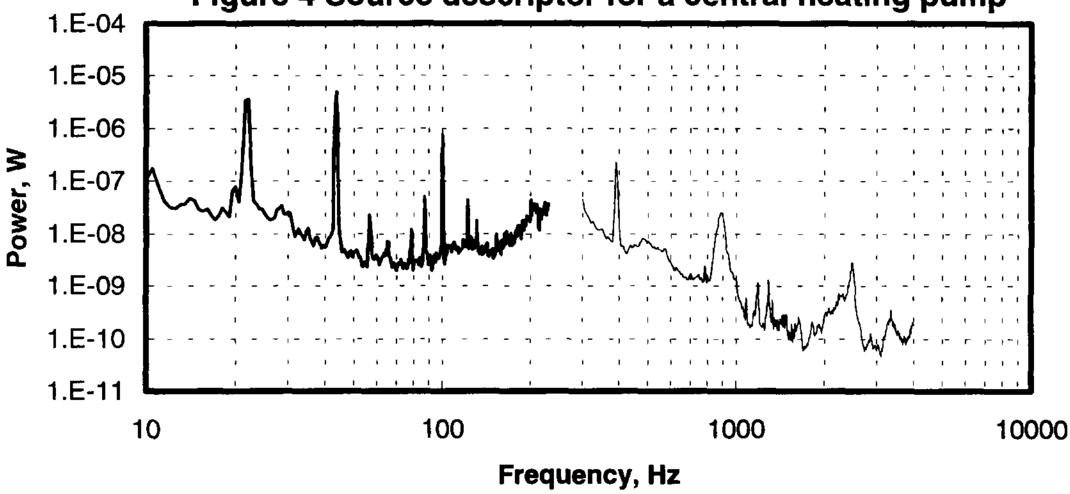


Figure 4 Source descriptor for a central heating pump



POWER DELIVERED WHEN INSTALLED

S is not in general equal to the delivered power since this depends on how well the source mobility is matched to that of the given receiver. For most receivers the delivered power will be less than S, but for a narrow range of receivers it may exceed S (see figure 1). The maximum deliverable power occurs when the receiver mobility is the complex conjugate of that of the source, that is where $\mathbf{Y_R} = \mathbf{Y_S}^*$ (fig. 1). Incidentally, this 'maximum deliverable power' is an intrinsic property of the source in the same way as S, and in many respects is a more elegant characterisation [5]. However, it has proved to be highly sensitive to errors in measured mobilities, and hence difficult to obtain reliably in practice. Thus, largely for practical reasons, S has been preferred to the 'maximum deliverable power'.

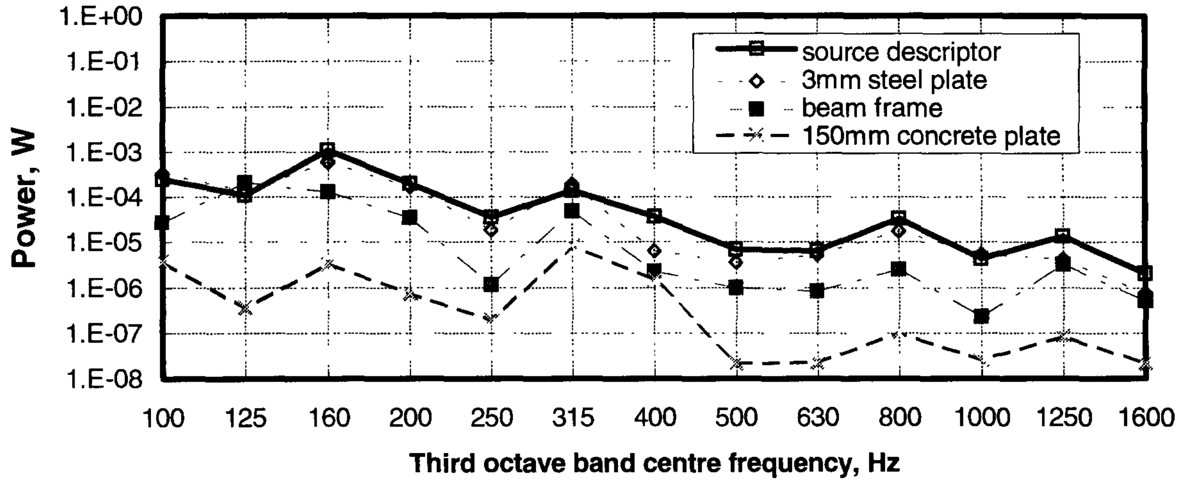
We now define the ratio C=P/|S| where P is the active power delivered to the given receiver. It is real, and a scalar for a given source-receiver combination, and is similar to Mondot's coupling function [1] in the single point case. C quantifies how much less, and exceptionally how much more power is delivered to the given receiver than to a mirror receiver. There is a loose parallel here with radiation efficiency, σ, which compares the power radiated from a given structure with that from a reference structure, (a rigid piston): C compares the power delivered <u>to</u> a given structure with that <u>to</u> a reference structure, (the mirror). Both σ and C can exceed 100% in special cases.

POWER DELIVERED BY A FAN INTO VARIOUS RECEIVERS

The power delivered from fan 2 into three different receiver structures has been calculated; an infinite 3mm steel plate, a frame of steel beams, and an infinite 150mm concrete slab. Mobilities of the beam frame were measured using the same techniques as for the source. Mobilities for the infinite plates were obtained analytically using the solution for point contact [6] which was differentiated to obtain moment and cross mobilities. A contact radius of 50mm was assumed for the point moment mobilities without which the imaginary part becomes infinite. In all cases the receiver was characterised by the full 12x12 mobility matrices.

The power delivered to each receiver is shown in third octave bands in figure 5. Power transfer to the steel plate is seen to be most efficient, which is not surprising given that this was the same thickness as the base plate of the fan and therefore well matched. The least efficient power transfer was to the concrete plate, and again this was anticipated because of the large mobility mismatch. Power transfer to the beam frame was less efficient than to the steel plate, even though the point mobilities were of similar magnitude to those of the fan over most of the frequency range.

Figure 5 Power from fan 2 into various receiver structures compared with source descriptor



Note that in no case does the delivered power significantly exceed the source descriptor |S|, even for well matched receivers. Theoretically, we can construct a complex conjugate receiver, the power into which is an absolute maximum for a given source, in general exceeding S. However, it is not obvious how such a structure could be constructed physically. Indeed, it seems marg when moment mobilities are taken into account. This may explain why the delivered power does not exceed |S|.

CONCLUDING REMARKS

A source descriptor, S, has been defined which is characteristic of the source's ability to deliver power, is an independent property of the source and is a single figure quantity. It thus fulfills all the basic requirements for a source descriptor. It is equal to 4 times the power delivered to a 'mirror' receiver, that is one which is a mirror image of the source. It is valid for multiple point contact, multiple component excitation and contact over extended areas. The power delivered when the source is installed is usually less than |S|, and for the combinations of source and receiver structures considered never significantly exceeds |S|. Thus, it may be that in practice |S| can be thought of as the 'available power' from the source. This would be a most useful concept, and further research is underway to establish whether this interpretation can be applied more generally.

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