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# MACHINE BASES AS STRUCTURE-BORNE SOUND SOURCES

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## ABSTRACT

The structure-borne sound power delivered by a vibrating machine into a supporting or connected structure is determined by both the activity of the machine and the dynamic structural characteristics at the contacts. It is a relatively simple matter to measure activity in the form of velocity at the contacts of the free source under normal operating conditions. The structural dynamics are not so easy to calculate or measure and the full mobility matrix method of prediction is time consuming. However, visual inspection of the measured mobilities of machine bases can give engineering insights on how best to treat machines as multi-point and multi-component sources. Mobility data from a range of machinery bases is described in order to confirm the generality of the relationship between point and transfer mobilities. The role of moments also is discussed and although it is much less likely that generalisations can result, the special but common case of building services machinery on concrete plantroom floors is shown to allow simplifying assumptions.

## INTRODUCTION

The recent appearance of an international standard for sources of structure-borne sound [1] has highlighted rather than solved the problem of estimating structure-borne emission from and source characterisation of vibrating machines and machine components. The standard describes procedures for measuring the vibrational velocities at machine contact points. This data is a subset of that required but it cannot give a complete source characterisation or sufficient information for structure-borne emission. The additional data required will be obtained through an as yet incomplete set of international standards for the measurement of mechanical mobility [2].

Two problems remain. The first is that the structural dynamics of the receiving structure must be known for a full description of the transmission process. The structure-borne power W, when a source s is connected to a receiver R, is given by;

$$W = \frac{1}{2} \frac{|v_{sf}|^2}{|Y_s + Y_R|^2} \mathrm{Re}[Y_R] \tag{1}$$

The free velocity $v_{sf}$ is the velocity of the contact point when the source, i.e. the machine, is isolated by soft supports or suspensions while operating under normal conditions. $Y_s$ is the mobility (velocity due to a unit force) at the contact point of the source and $Y_r$ is that of the receiver. Thus, three quantities are required to predict structure-borne power, including receiver mobility, which is seldom available since the details of all installations may not be known. Manufacturers of electric motors expect their products to be bolted to the internal frame of washing machines, the base plate of fans or form part of circulation pumps, etc., [3]. Therefore, the source must be characterised in terms of source parameters only.

Structure-borne sound sources can be characterised, on a power basis, using free velocity and source mobility. This has been demonstrated by Mondot and Petersson [4] where equation (1) is rewritten as;

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

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 descriptor S is a quantity which solely involves data related to the source. It has units of power but is not the power delivered. It is, in fact, an expression of the ability of the source to deliver power [5]. The actual power is obtained by including the coupling function which contains the receiver mobility. The engineer may find that this characterisation is sufficient when comparing the vibrational noisiness of a machine with those of competitors or before and after noise control treatment.

The second problem, which is of interest in this paper, concerns the complexity of the structure-borne transmission process and its representation. Machines are connected through several contacts, with up to six components of excitation (three translations and three rotations) at each contact. The contact can be point-like (with respect to the governing wavelength), a line or an area. Each component of the response at a contact depends on all the components of the forces and moments at all contacts and the total power from a machine depends on the coupling between components and contacts. The full expression for the power is;

$$W = \mathbf{v}_{sf}^{*T} \left[\mathbf{Y_R} + \mathbf{Y_S}\right]^{*T^{-1}} \mathrm{Re}(\mathbf{Y_R}) \left[\mathbf{Y_R} + \mathbf{Y_S}\right]^{-1} \mathbf{v}_{sf} \qquad (5)$$

where $\mathbf{v_{sf}}$ is the free velocity vector, and $\mathbf{Y_R}$ and $\mathbf{Y_S}$ are the mobility matrices of the source and receiver, respectively. For M components of vibration and N contacts, there are MxN complex free velocity spectra required. The source and receiver mobility matrices are of size MxN by MxN requiring, for example, 576 complex spectra each, for the case of four contact points and six components of motion. Reciprocity can be invoked to reduce the number to 348 but the problem remains intractable. Seldom can this amount of data be assembled for a complete description of power or source characterisation and design engineers and consultants are forced to refer to simple representations which are often unphysical or they avoid the issue altogether.

The special but common case of resiliently mounted machines on concrete floors allows some simplification since the source mobility matrix is replaced by MxN dynamic stiffnesses of the resilient mounts [6]. Further, whilst the receiver mobilities are still required, floors are often simpler constructions than machine bases with simple relationships, particularly between the transfer and point mobility terms [7,8].

In this paper the mobilities of typical source structures are examined as a prelude to simplification of structure-borne power estimates from rigidly mounted multi-point-multi-component sources. It is assumed that free velocity data is available but can be reduced according to the simplified representations proposed.

In addition, the special but common case of machines installed on thick concrete floors is discussed with reference to the role of moments and forces in structure-borne sound transmission in buildings.

## SOURCE MOBILITY

In equation 5 the source mobility matrix $\mathbf{Y_S}$ comprises point, transfer, cross-point and cross-transfer mobility elements. Consider a contact point 1 (indicated by an arrow in Figure 3). There are six point mobilities, representing three rotational and three translational components of excitation and response. Thus $Y_{Fz1}^{vz1}$ is the point mobility for a force and response velocity in the z (vertical) direction. In addition, there are transfer and cross terms; $Y_{Fz1}^{vz2}$ is the transfer mobility for a force at point 1 and component velocity at point 2, $Y_{fz1}^{wx1}$ is the cross-point mobility for a force at point 1 and a rotational velocity about the x-axis at point 1, and so on.

Can any element of the mobility matrix be neglected? The physical implication of neglecting terms is that some components of excitation do not contribute to the total power. An extreme example is when all off diagonal terms are zero; the power at each point and through each component is determined only by the component force or moment at that point and the resultant velocity in the same direction. The length of the diagonal reduces with reduced number of components of vibration to be considered.

The approach therefore is to first consider the diagonal terms and to calculate the least important components of power transmission to determine if they can be neglected. Then to inspect off diagonal terms with respect to the point mobility terms on the diagonal and again determine if such terms can be neglected.

## IN-PLANE TRANSMISSION

In Figure 1 is shown the free velocities at a mount point of a thin base plate of an electric motor, operating without load. Little can be inferred as to the important components in the transmission process. The rotational velocities $w1_{x,y,z}$ are not comparable with the translational velocities. Even when dealing with comparable components such as the three translational velocities $v1_{x,y,z}$ the highest overall value may not represent the most important component of excitation in the installed condition. For instance, the solid line in Figure 1 corresponds to vertical translation $v1_z$, conventionally assumed to be the most important component of vibration [9].

In Figure 2 are shown the corresponding source descriptors, from equation 3, for five components of excitation. Three components, $S_{fz}$, $S_{mx}$ and $S_{my}$ were obtained from measured mobilities and free velocities; $S_{fx}$ and $S_{fy}$ were obtained from measured free velocities and calculated mobilities where the inplane mobility is assumed to be mass controlled [10]. The components are now comparable on a power basis and the importance of vertical translation at low frequencies is demonstrated more clearly and now appears to support the common assumption that vertical forces need only be considered at low frequencies.

However, the hierarchy still may not correspond to that of the transmission in the installed condition. If the inplane mobility of the floor also is assumed to be mass controlled in the frequency range of interest, then the value will be pure imaginary and there will be no power, according to equation 1 and inplane power can be neglected.

Therefore, for the case of machines on thick floors, the assumption is that three components, translation vertical to the floor and rotations about axes in the plane of the floor contribute only to transmission and the mobility matrix reduces in size to 3N x 3N. This assumption is expressed with caution since the contact point of excitation is not at the neutral axis of the thick plate and cross mobility terms will be non zero i.e. a horizontal force at the surface of the floor will generate a rotational velocity about an axis perpendicular to the force and in the plane of the plate. Also, inplane motion in a floor may convert into bending motion in supporting walls.

It remains to inspect the relationship between the remaining point mobility terms on the leading diagonal and the associated transfer and cross-transfer terms.

## POINT MOBILITIES

A limited measurement survey has been conducted of machine bases, categorised as follows (see Figure 3): compact source, plate base, flange and frame. The list is not exhaustive and machine bases will fall outside or between categories. In Figure 4 are shown typical measured point force mobilities for each type.

For the compact source (Figure 4(a)), there is a rigid body (RB) motion up to 400 Hz., a stiffness controlled (SC) region up to 2 kHz. and above this, a resonance controlled (RC) region. For the plate base measured (Figure 4(b)), the RB region is below 80 Hz, the SC region is between 80 Hz and 200 Hz and the RC region is above 200 Hz. The trends are clearly seen for a flange (Figure 4(c)) but less so for frame bases (Figure 4(d)). The curves are similar for an apparently disparate set of machine bases but differ in overall magnitudes (the thinner structures, with lighter machines, give higher mobilities) and they are shifted in frequency relative to each other. A compact source would be expected to display RB characteristics to a higher frequency than a large area plate but interestingly, for the case shown (Figure 4(a)), the SC region also extends over a wide frequency range and this region will be seen to be of particular interest.

It is straightforward to measure force mobility or predict it from material constants and geometry [11], but of immediate concern is the relationship between the point mobilities and the transfer mobilities which constitute some the off diagonal elements of the mobility matrix.

## TRANSFER MOBILITIES

In Figure 5 are shown the level difference between transfer mobilities and point force mobilities for a compact source, plate base and flange. As would be expected, the ratio is about unity in the RB region (up to 400 Hz. for the compact source) and fluctuates about unity in the RC region (above 2 kHz. for the same source).

In the SC region, the ratio gives a level difference of 10 to 20 dB. and the transfer mobilities can be neglected [12]. The transfer mobilities can be neglected between 200Hz. and 1kHz. for the flange (Figure 5(c)) which is most of the SC region. Results for the plate a similar (Figure 5(b)) and also show a clear drop but for a small range 100 - 200 Hz., again corresponding to the SC region.

So far, vertical force only has been considered. In order to consider moments, the associated mobilities must be measured. They were obtained directly using a moment actuator [5], constructed to a design by Petersson [13]. In Figure 6 are shown the level difference between transfer and point moment mobility for a compact source. The trends are similar to those for force mobility but with a more pronounced decrease in the SC region.

The case of cross mobility is problematical since it cannot be compared with either moment of force mobilities. However, some data reduction is possible be comparing the cross-transfer terms with the point cross terms. In Figure 7 is shown the level difference for the compact source and in Figure 8 for a small plate base with a SC region in the frequency range 100 - 500 Hz. Again, the transfer terms can be neglected in the stiffness controlled region.

To summarise; the density of the mobility matrix is determined by the controlling mechanisms of the mobility terms. They include RB, SC and RC motions which are indicated from point force mobility which is relatively easy to measure or calculate. The matrix is least dense in the stiffness controlled region and each contact and component can be considered in isolation. This region can form an important part of the excitation spectrum, particularly for compact sources. The mass and resonance controlled regions yield denser matrices where the off diagonal elements are of the same order of magnitude as the diagonal elements, the main difference between them being in the phase relationships.

It is not possible to generalise completely this statement since the mobility terms are only indicators of the effect of forces at other points on the contact point under consideration. If a force at point 2 is 20 dB greater than that at point 1 then it will still have influence even if the transfer mobility is 20 dB less than the point mobilities. However, theoretical [12] and experimental work [14] has shown that the forces at multiple contacts do not deviate more than +/- 10 dB at low frequencies and converge with increased frequency.

## RECEIVING STRUCTURES

A similar inspection of predicted or measured point force mobility of supporting structures can simplify calculation of the power when the machine is installed (see equation 5). Take as an example, the compact source previously described, now attached to the large plate base which now acts as a receiving structure. Between 80 Hz. and 200 Hz. the source mobility is RB (see Figure 4(a)) and the receiver mobility (see Figure 4(b)) is SC. Between 300 Hz. and 2 kHz. the source is SC and the receiver is RC.

The mobilities have been described without reference to relative magnitude and the potential for matching. For a full discussion of this phenomenon, see [15,4]. It will be appreciated however, that a large thick plate may give a similar mobility signature as a small thin plate but the former will have overall a lower magnitude than the latter.

## MOMENTS AND CROSS MOBILITY TERMS

A description of the role of moments and forces requires knowledge of both the source and receiving structures [16-18]. The conventional view that moments contribute to the total transmission only at high frequencies is challenged in a series of theoretical and experimental studies by Petersson[19] where an idealised lever source is employed so that a simple relationship between an applied force and an accompanying moment can be established. It is demonstrated that moments can be significant at low frequencies when the source is close to structural discontinuity.

This has been confirmed by measurements of real machine bases on concrete floors [20]. It was not possible to register the forces and moments directly at the contact points between a machine and a floor. Therefore, they were measured indirectly, using reciprocal transfer mobility measurement of velocity at the contact points and forces at far -field points on the floor.

In Figure 9 is shown the power from forces and moments through one contact at a central location. The force $F_z$ predominates over the frequency range of interest and needs only to be considered in estimating the total power; the source and receiver mobility matrices now reduce to NxN each where N is the number of contacts. This is not the case when the same source is relocated near to a floor edge (Figure 10) and moments must be included in estimates of power.

## CONCLUDING REMARKS

Measurement or estimates of point force mobility allow machine bases to be characterised in terms of rigid body, stiffness controlled and resonance controlled regions.

In the stiffness controlled region, transfer and cross-transfer terms can be neglected and the mobility matrices simplified.

For machines on thick concrete floors, inplane excitation can be neglected and vertical forces dominate for installations away from floor edges.

This is not the case near to an edge but, for practical purposes, a distance of $\lambda/6$ is sufficient to allow moments to be neglected. An example of a 120 mm concrete floor gives a minimum distance of 0.5 m at 100 Hz.

## ACKNOWLEDGEMENTS

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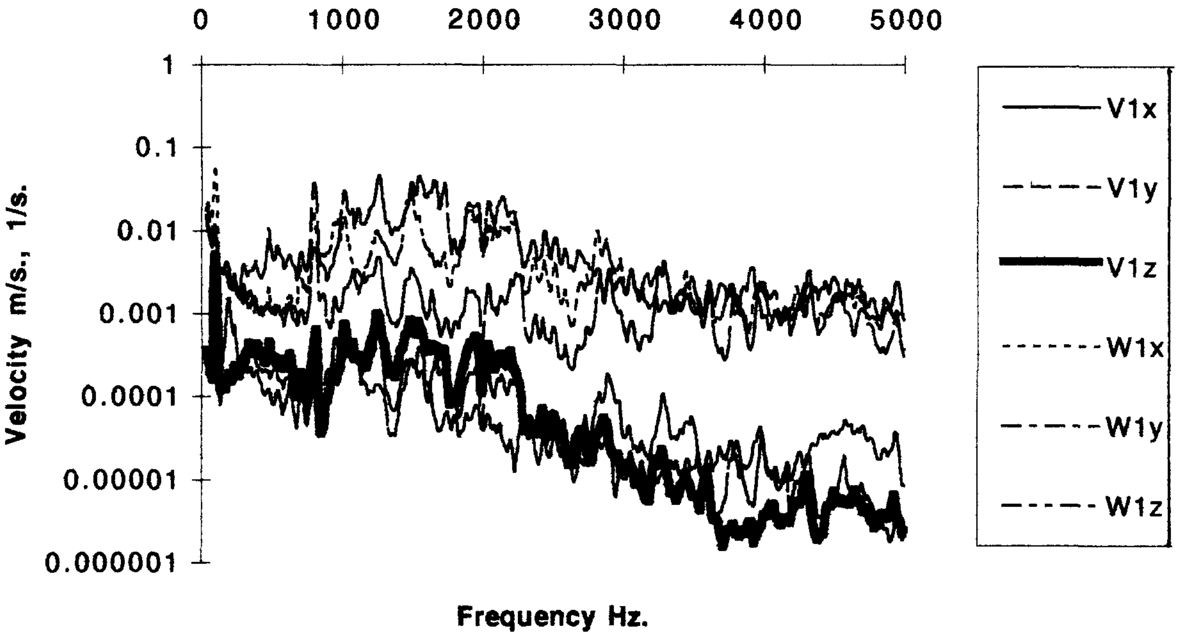
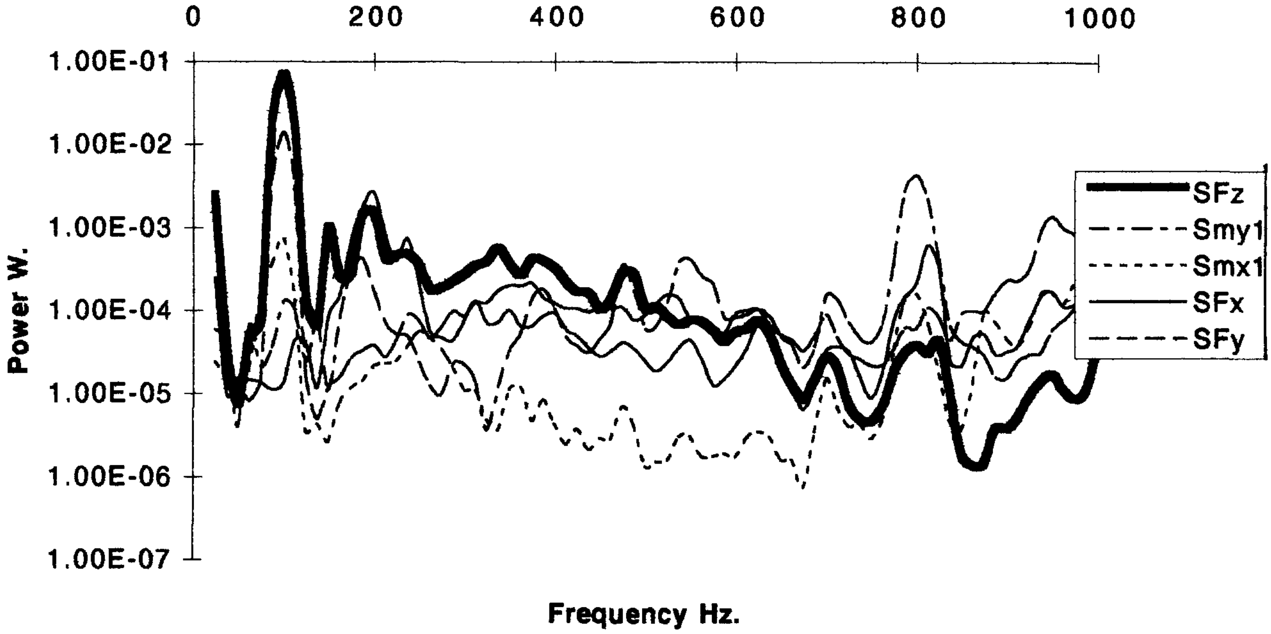
## Figure 1. Free velocities on a plate base.



## Figure 2. Source descriptors on a plate base.



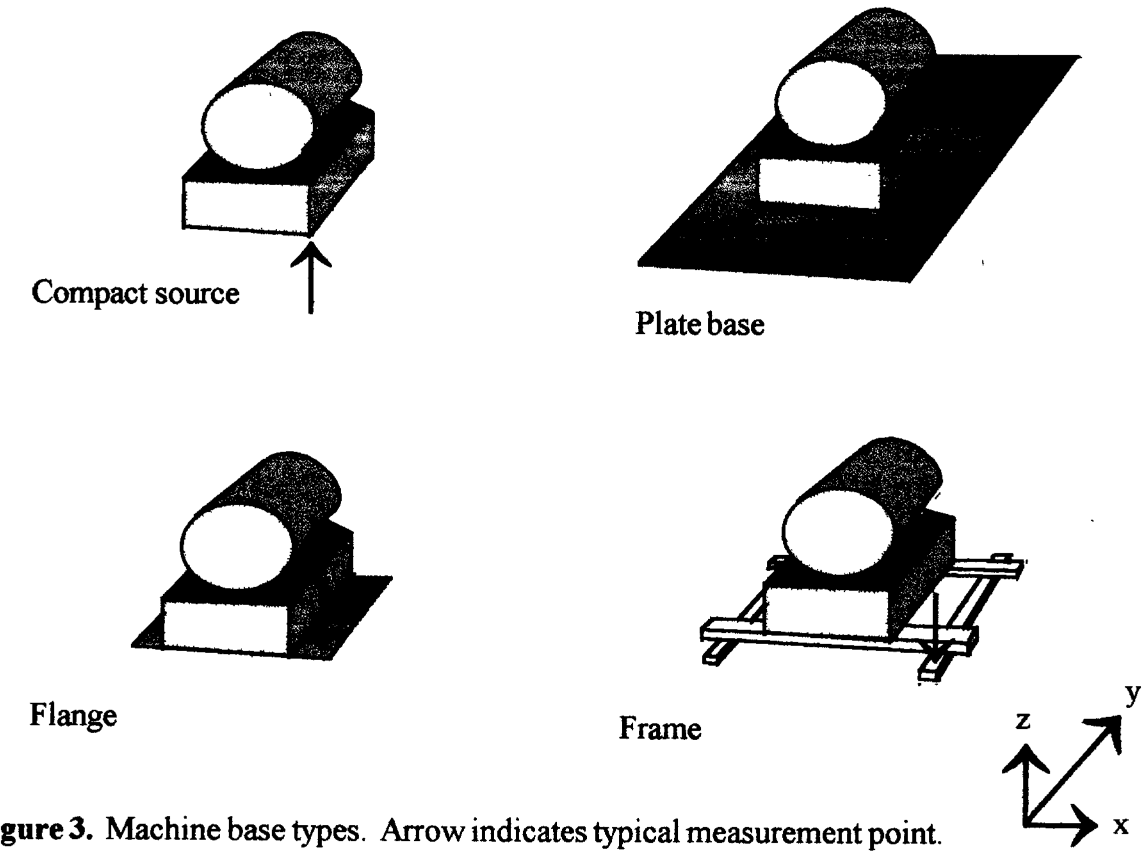
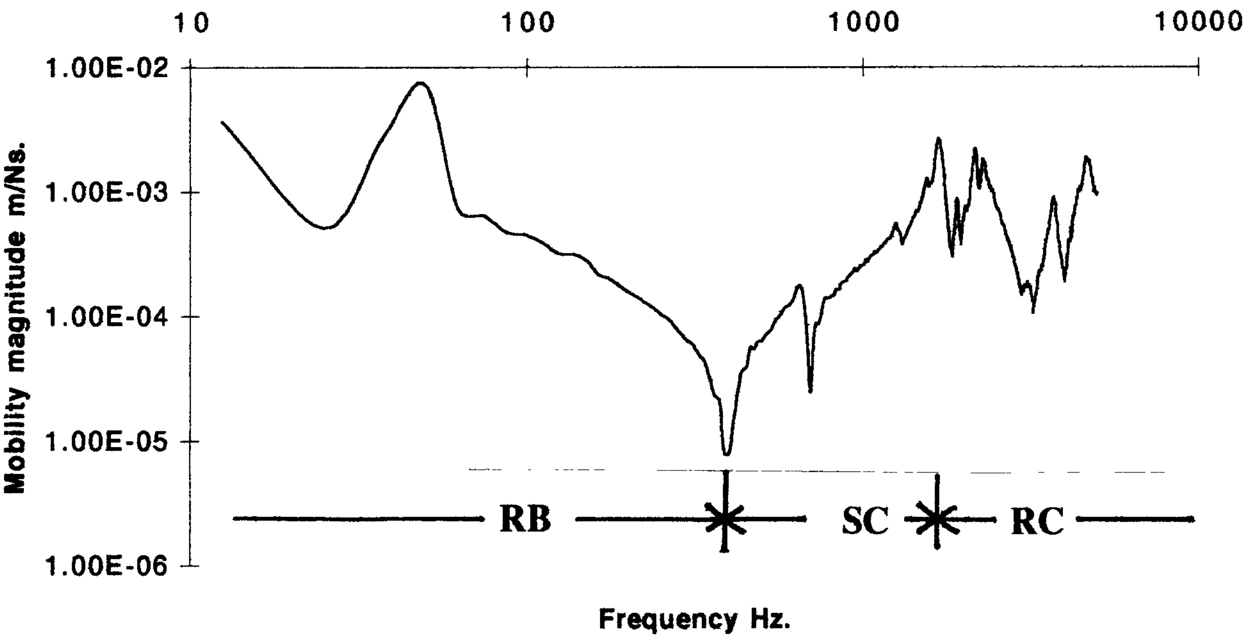


**Figure 3.** Machine base types. Arrow indicates typical measurement point.

**Figure 4(a). Force mobility of a compact source.**



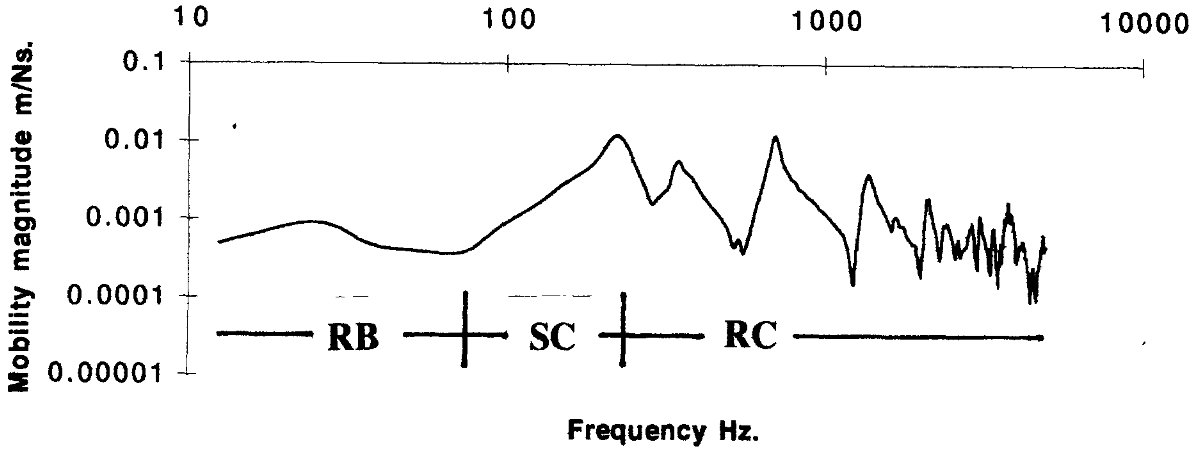


Figure 4(b). Force mobility of a plate base.

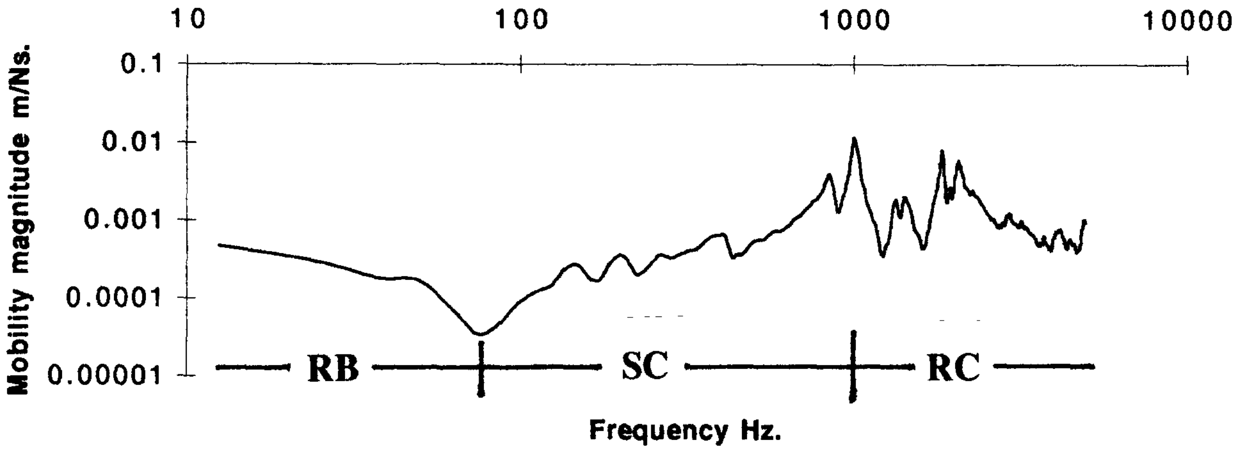


Figure 4(c). Force mobility of a flange

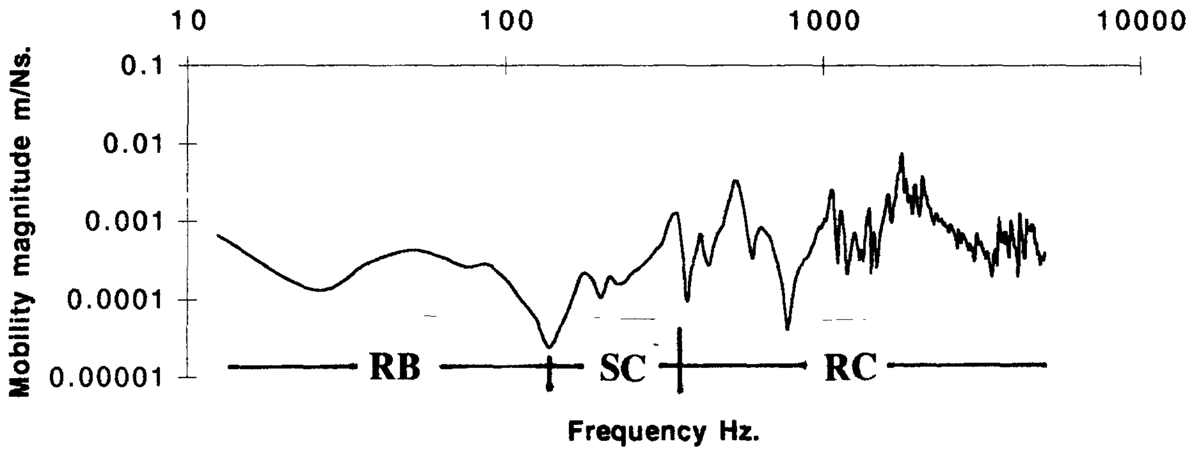


Figure 4(d). Force mobility of a frame.

Figure 5(a). Level difference between transfer and point force mobilities for a compact source.

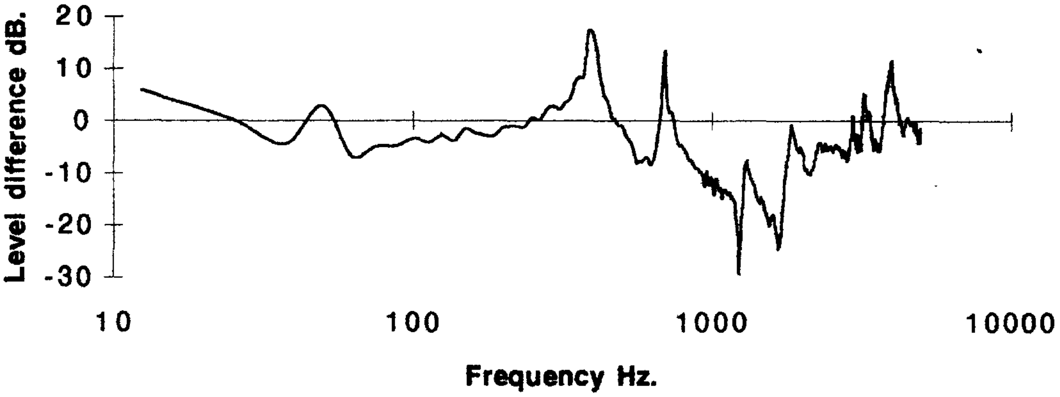


Figure 5(b). Level difference for a plate base.

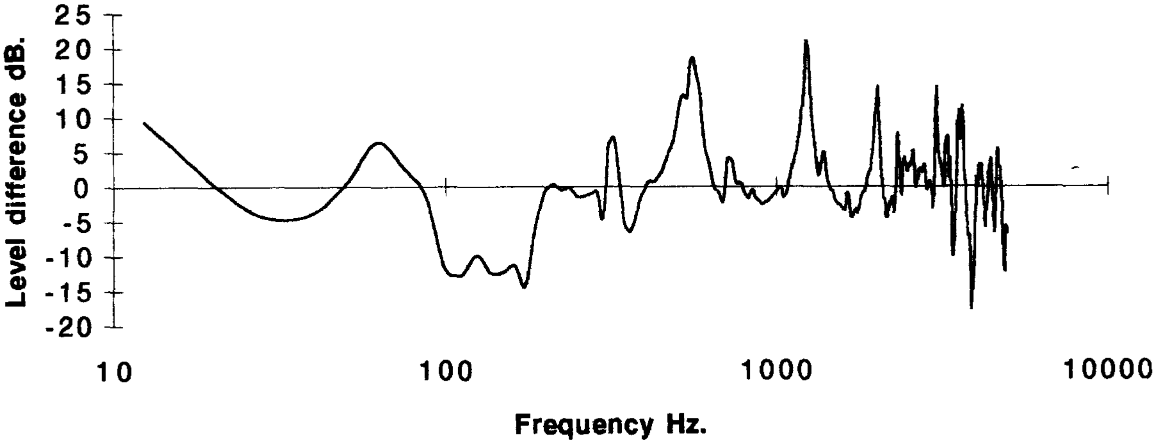


Figure 5(c). Level difference for a flange.

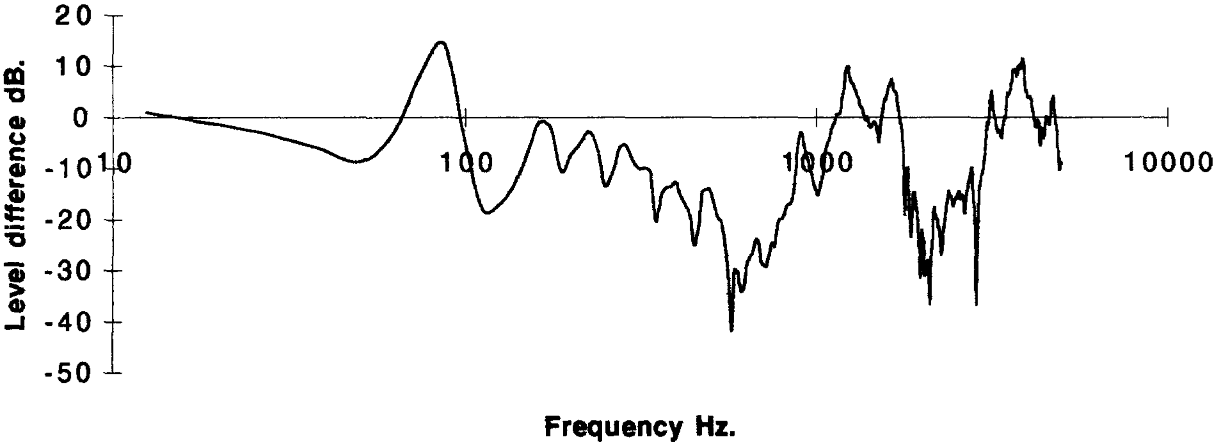


Figure 6. Level difference between transfer and point moment mobilities for a compact source.

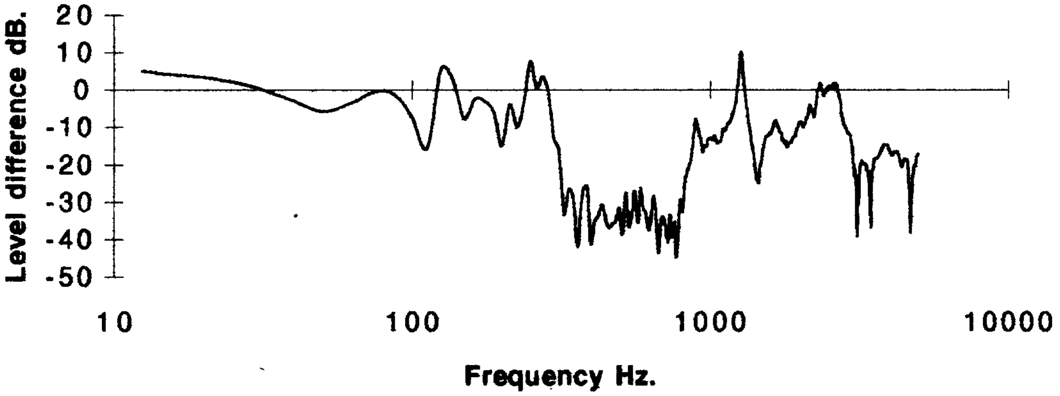


Figure 7. Level difference between cross-transfer and cross mobility for a compact source.

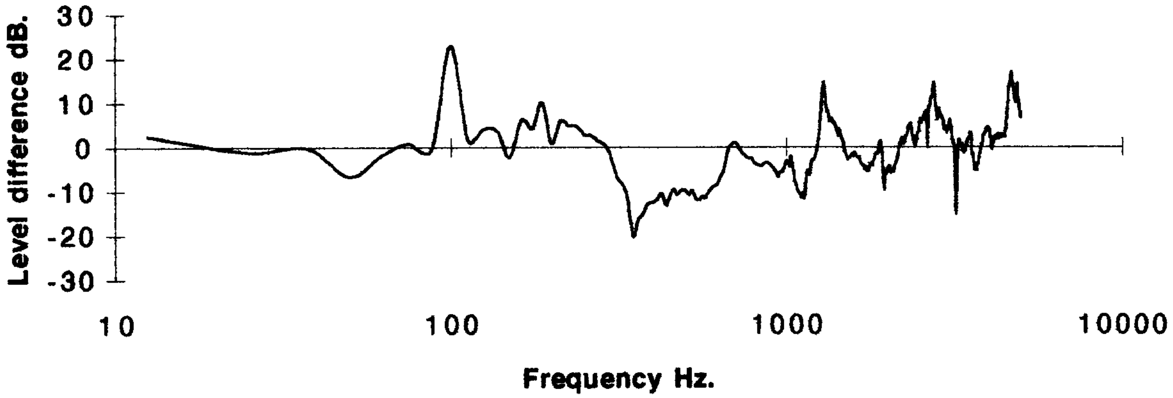
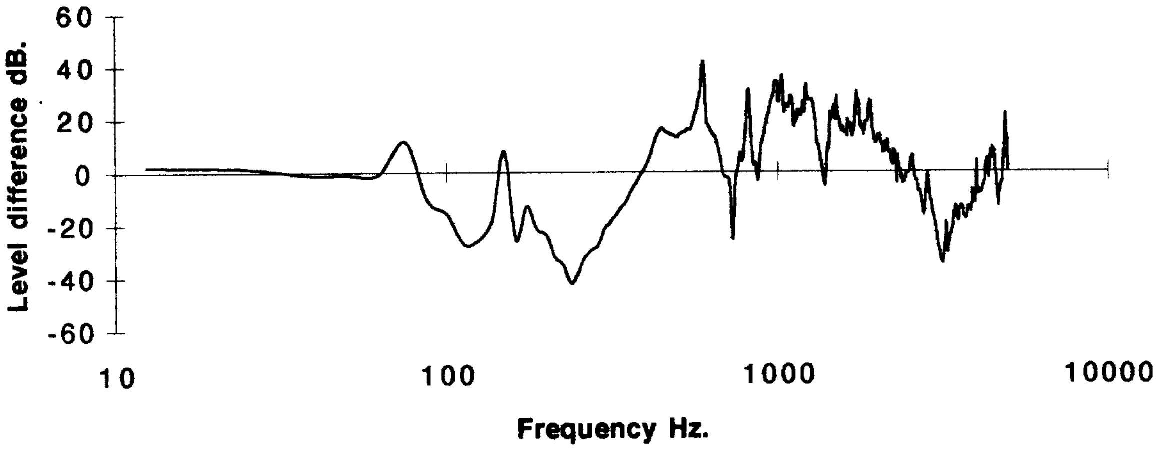


Figure 8. Level difference for a small plate base.



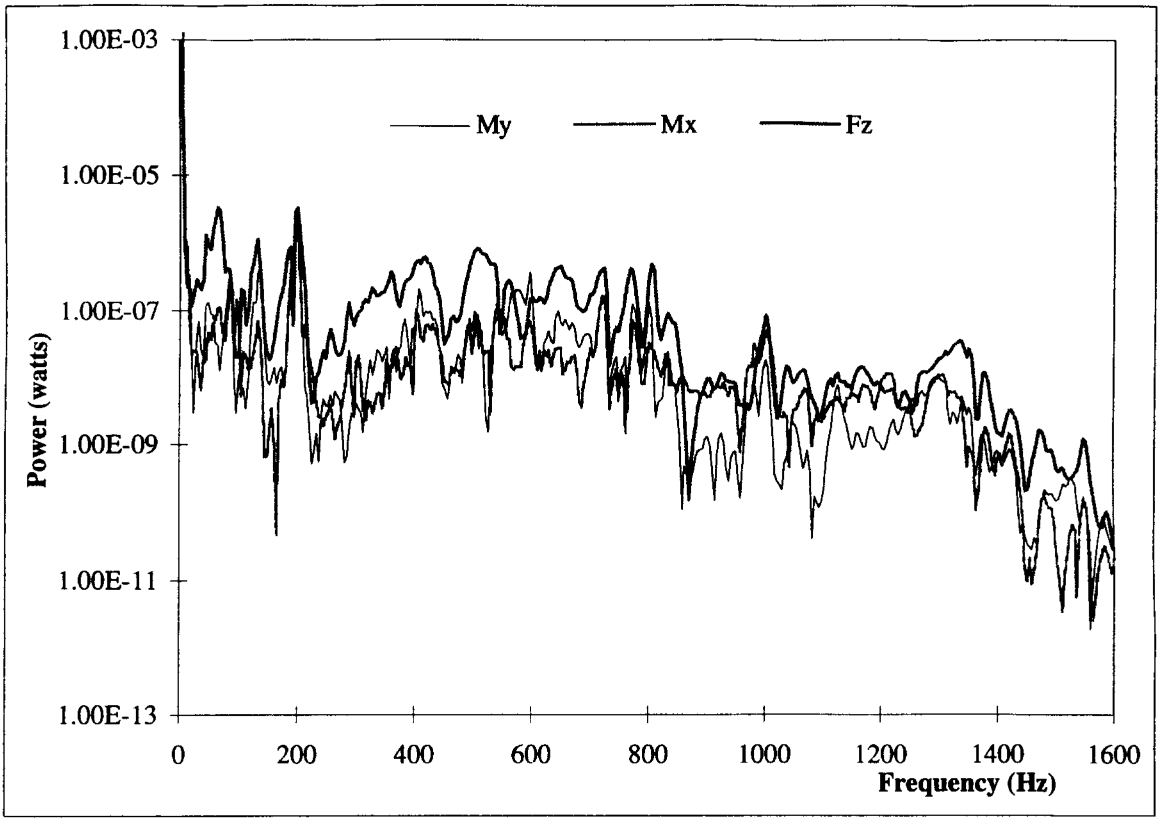


Figure 9. Power near central location

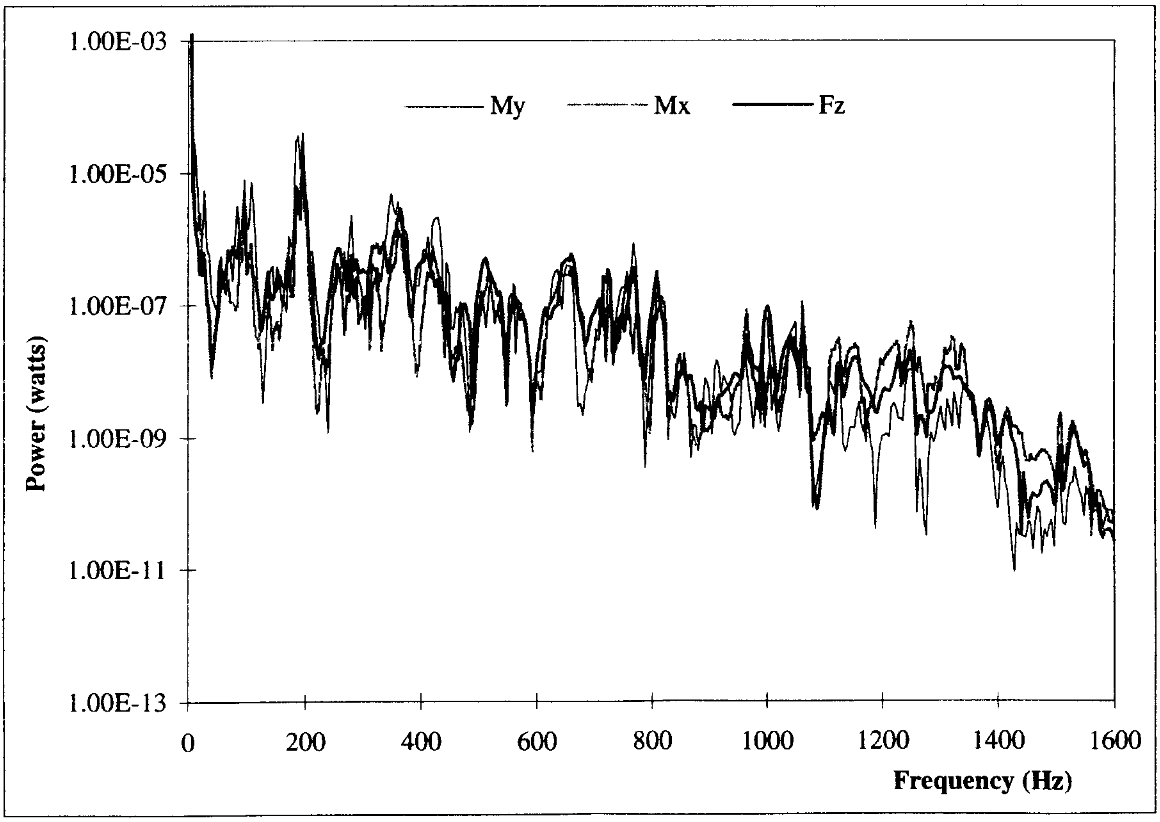


Figure 10. Power near an edge