THE RECIPROCAL SUBSTITUTION METHOD FOR MEASURING THE TRANSMISSION OF STRUCTURE BORNE SOUND

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1. INTRODUCTION

In connection with much noise-producing equipment, such as domestic appliances, structure-borne sound transmission is more important than air-borne sound transmission. Methods for describing or measuring sound emission and transmission, however, only deal with air-borne sound. This may be due to the more complicated way in which the structure is excited and vibrations are transmitted.
In [1] results of research to find an appropriate description of the structure-borne sound strength are presented. It was concluded that the (A-weighted) equivalent force proved to be a suitable source description.
Knowing the source strength of the equipment, the sound pressure level in a receiving room can be calculated, if the transmission is known. This paper will deal with the measurement of the structure-borne sound transmission, and in particular with the use of the reciprocal substitution method.

2. EQUIVALENT FORCE

The excitation of the building structure by vibrating equipment can consist of many locations and directions of forces and torques. Using the equivalent force concept all energy from forces and torques from all excitation points is attributed to a single excitation mode, at a single point. This can be a force or torque. The equivalent force is defined according to the substitution method; the source strength is the source strength of a substitution force, which gives the same response, i.e. the same receiving sound pressure level, as the actual source. So an accurate determination of the transmission according to the substitution method is not only important for calculating the appliance level, but also for the determination of the equivalent force from the measurement of the receiving level.
The pre-conditions for the application of the equivalent force concept are that the force does not depend on the receiving structure (low impedance of the appliance compared to the structure), and a sufficient modal density.

3. STRUCTURE-BORNE SOUND SENSITIVITY

The relationship between the equivalent force level L_F and the sound pressure level L_p is described by the structure-borne sound sensitivity for vertical forces L_{SF}:

$$L_{SF} = L_p - L_F \qquad (1)$$

where $L_p = 10 \log p^2/p_o{}^2$ with $p_o = 2 \cdot 10^{-5}$ Pa
$L_F = 20 \log F/F_o$ with $F_o = 1 \cdot 10^{-6}$ N

p and F are evaluated as time-averaged (RMS) values in third octave bands.
The structure-borne sensitivity for moments is defined in the same way:

$$L_{SM} = L_p - L_M \qquad (2)$$

where $L_M = 20 \log M/M_o$ with $M_o = 1 \cdot 10^{-6}$ Nm

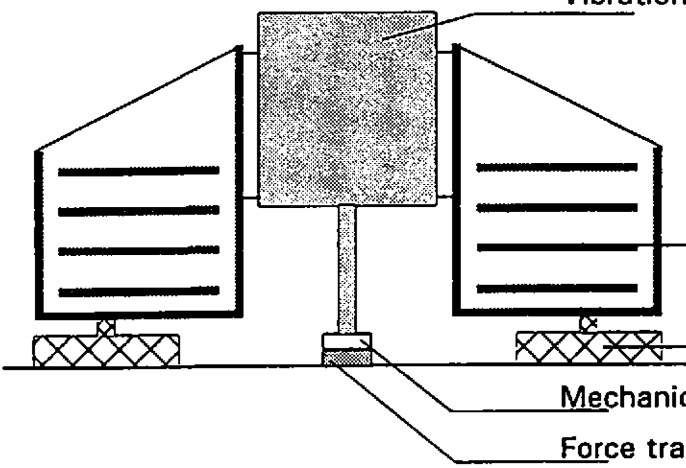
For low frequences with relatively large wavelenths the torque M is equal to two forces operating in opposite directions, multiplied by the distance D.
The sensitivity can be calculated if the input impedance of the structure, the transmission through connections of building elements, damping and radiation are known or can be estimated.
The sensitivity can be measured by means of the substitution method.

4. DIRECT SUBSTITUTION METHOD

In the direct substitution method, the appliance is replaced with a structure-borne noise generator with a known force. Structure-borne sources suitable for use as a substitution source are the standardised tapping machine, a hammer, or an exciter. When using a hammer or an exciter, the actual force has to be measured with a force transducer.
For this study, a structure-borne noise generator was developed (see figure 1). The exciter is hung in a resiliently-mounted steel frame. Extra mass is added to the frame to obtain a low resonance frequency of approx. 7 Hz. A vertical force is applied to the structure and measured by a force tranducer.
Torques were also applied to the structure by using two of these exciters with identical amplitudes but opposite phases. The distance between the excitation points was 0,5 m. The exciters were carefully selected to give identical amplitudes and opposite phases for all relevant frequencies.
The disadvantages of the direct substitution method as compared with the reciprocal substitution method (chapter 5) are the need for this special noise generator, the low receiving level and, in some cases, the difficulty of positioning a structure-borne noise source. There

fore an (improved) reciprocal method was developed. The results are compared to the direct method with the source in figure 1.

Figure 1. Structure-borne noise generator



5. RECIPROCAL SUBSTITUTION METHOD

5.1 Electrical and acoustical method

Reciprocity means that, if a force applied at point A will result in an acceleration at point B, the same acceleration will occur at point A when the force is applied at point B. The acceleration and force at point B can be translated to other systems. This has been done in [2] in electrical terms for a loudspeaker system and in [3] in acoustical terms. The latter is deduced with the help of an imaginary mass in the wall of the receiving room ([1],[3]). Comparison of the results of this acoustical method with the direct method, however, showed systematic differences. Therefore, some improvements concerning this method were made, as described in section 5.2.
The advantage of the electrical method over the acoustical method is that a diffuse receiving room is not required, which is especially advantageous for the lower frequencies. This method is preferable for determining source strength. It does however not provide the sound sensitivity. Therefore, for the determination of the transmission of structure-borne sound, the acoustical method is to be preferred.

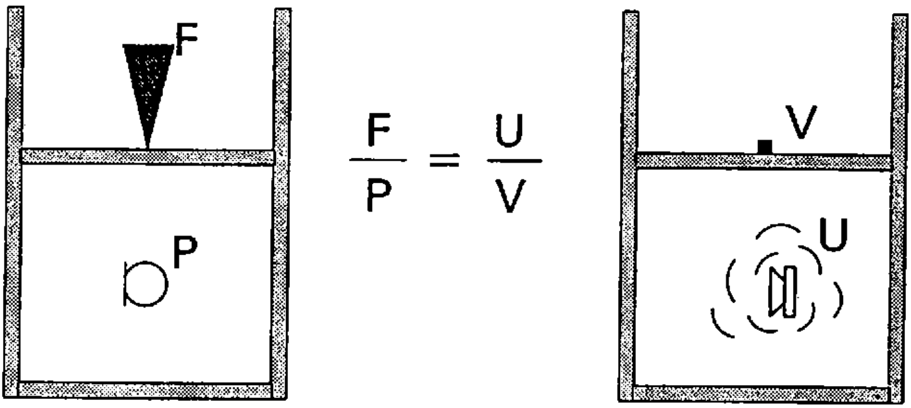
5.2 Improved acoustical method

In figure 2, a situation is given with a receiving room directly below the floor on which a force F is exercised by an appliance. The reciprocity relation is directly formulated as (see also [4]):

$$\frac{F}{p} = \frac{U}{v} \qquad (3)$$

where p = sound pressure in receiving room [Pa]
U = volume velocity of an airborne sound source in the receiving room during the reciprocal measurement [m^3/s]
v = velocity at the position of the appliance, due to the sound source in the receiving room [m/s]

Figure 2. Reciprocity relations for the acoustical method



This relationship is only valid if the directional characteristics of F and v and of p and U are equal.
If the loudspeaker radiates as a monopole, the sound power of the loudspeaker can be described by:

$$W = \frac{\rho c}{4\pi} \cdot \frac{\omega^2}{c^2} \cdot U^2 \qquad (4)$$

RECIPROCAL SUBSTITUTION METHOD

where ω = angular frequency [rad/s]
c = velocity of sound [m/s]
ρ = density of air [kg/m^3]
The acoustical impedance ρc is for a point source in a free space.

From (1), (3) and (4), transferring velocity into acceleration, the sound sensitivity can be shown to be:

$$L_{SF} = L_a - L_w + 10\log \frac{\rho . F_0^2 . a_0^2}{4\pi c . p_0^2 . W_0} \qquad (5)$$

where L_a = acceleration level (= 20 log a/a_0)
a_0 = reference acceleration (= 1 . 10^{-6} m/s^2)
L_W = sound power level (= 10 log W/W_0)
W_0 = reference sound power (= 1 . 10^{-12} W)

Filling in all constants will give:

$$L_{SF} = L_a - L_W - 61,5 \text{ dB}$$

The structure-borne sound sensitivity for torques (2) can be deduced in the same way:

$$L_{SM} = L_{\Delta a} - L_w - 20 \log d + 10 \log \frac{\rho . F_0^2 . a_0^2}{4\pi c . p_0^2 . W_0} \qquad (6)$$

where $L_{\Delta a}$ = the difference in acceleration of the two mounting positions at distance d, caused by the sound source in the receiving room

When using a fixed distance of 0,5 m (as in this study) (6) can be written as:

$$L_{SM} = L_{\Delta a} - L_W - 55,5$$

Special attention has to be paid to the selection of accelerometers to ensure that they have the same response and phase characteristics for the frequencies involved.

6. CALIBRATION OF SOUND SOURCE

It turned out that for the accuracy of the results, the directional characteristics of the sound source and the assumptions made in

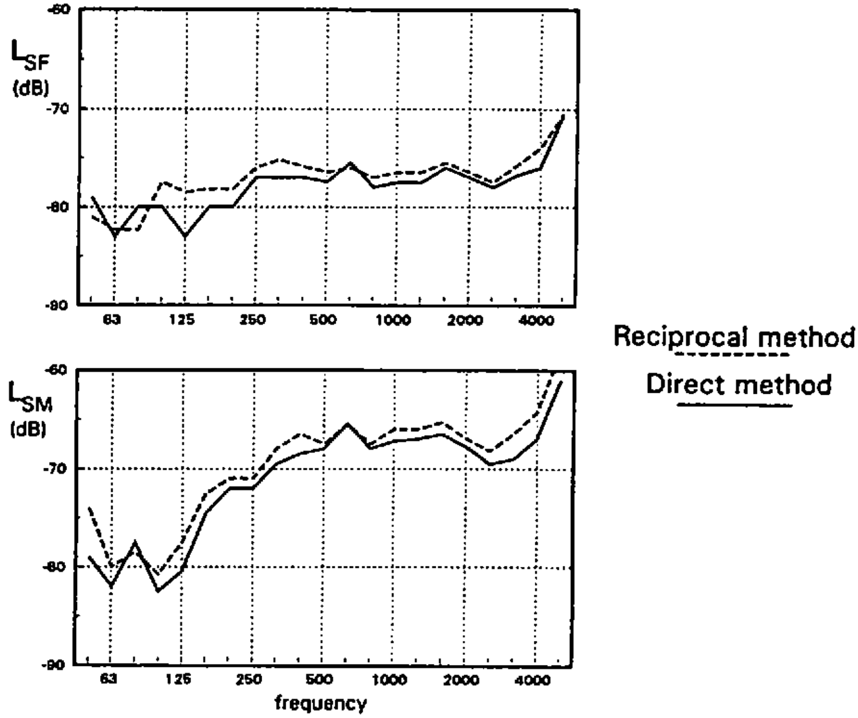
formula (4) were essential.
The sound power L_W of the sound source used in the reciprocity measurements was not measured in the field because measurement conditions are usually very poor (small rooms, no diffuse sound field). The source was calibrated in the laboratory, in a reverberation room of about 200 m3. An omnidirectional sound source was used to achieve a monopole. Contrary to standard methods, the source was placed in the middle of the room at a height of approx. 2m, to ensure the smallest possible acoustical impedance, approaching the free field situation. Apart from the positioning of the loudspeaker, the measurement was conducted according to ISO 3741, including waterhouse correction which improved the accuracy.
It should be noted that the L_W in the laboratory can be different from the value in the field. This is not a problem, because the volume velocity will (and should) be the same.

During reciprocal measurement, the position of the loudspeaker should be equal to the position of the microphone during the direct measurement. If using a rotating microphone, the loudspeaker should also be rotating. This is a practical problem which was solved by using 4 loudspeaker positions at different heights, corresponding with the positions of the orbit of the microphone. The differences were negligible.

7. MEASUREMENTS

Comparisons were made of the direct method and the reciprocal method. Results in the laboratory are shown in figure 3. The results correspond quite well. There seems to be a small systematic difference of approx. 1 dB, both for the force and torque sensitivity. Figures 4 and 5 show the results in two field situations, both dwellings with concrete floors. The living room is directly below the mounting position, and the bedroom is on the same floor.
Two mounting positions are used; in the middle of the floor and at the edge.
The correspondence between direct and reciprocal methods is still good. No systematic differences are found. For individual third-octave bands the differences can be up to 5 dB.

Figure 3. Comparison of direct and reciprocal method in the laboratory



8. CONCLUSIONS

This paper shows that the structure-borne sound sensitivity can be measured with the reciprocal substitution method. Good correspondence was obtained with the direct substitution method, both for forces and for torques.

9. REFERENCES

[1] M.L.S. VERCAMMEN & P.H. HERINGA, 'Characterising Structure-borne Sound from Domestic Appliances', *Applied Acoustics*, 28 (1989) 105-117
[2] T. TEN WOLDE, 'Reciprocity experiments on transmission of sound in ships', PhD thesis, *Delft University of Technology*, 1973
[3] K.J. BÜHLERT & J. FELDMANN, 'Ein Messverfahren zur Bestimmung von Körperschallerregung und Übertragung, *Acustica*, 42 (1979) 108-113
[4] L. CREMER, M. HECKL, E. UNGAR, 'Structure-borne sound', *Springer Verlag*, Berlin, 1973

Figure 4. Direct and reciprocal measurements in two field situations for forces

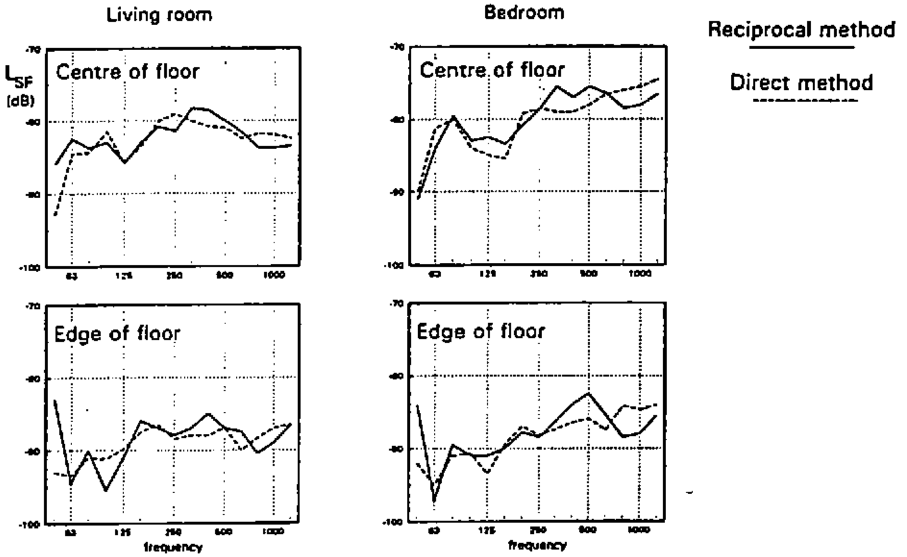


Figure 5. Direct and reciprocal measurements in two field situations for torques