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CHARACTERISATION OF SOURCES INJECTING A MOMENT POWER WITH THE TWO-STAGE-METHOD

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Building services equipment in residential and office buildings can be disturbing for the occupant if it produces noise. In this case structure-borne sound induced by of these sources has to be investigated. To avoid noise, a prediction and calculation is required and the behaviour of the source has to be known. Source characterisation can be done with the Two-Stage-Method (TSM). The source-specific parameters source mobility, free velocity and blocked force characterise sources and can be used for the prediction of structure-borne sound in buildings, as measurements show for different source types. The characterisation method itself is based upon the reception plate method determining the power injected into the receiver. Nevertheless, a remaining question is how moments, acting at the source connection points, affect the reception plate power. In this paper the injected moment power measured by the reception plate method is compared with the calculated moment power. The aim of the investigation is to achieve a more reliable source characterisation with TSM.

1. Introduction

For the use of the structure-borne sound source characterisation method *two-stage-method* [1] it is assumed that the injected force and moment power due to the source can be measured by the surface activity of a thin reception plate. In presence of only perpendicular forces the injected force-power can be estimated by measuring the reception-plate power and TSM, as well as sound pressure prediction in rooms [8, 8] gives good results. In the following paper it will be discussed how injected moment-power can be treated by reception plate power and how such sources with mainly moment power injection can be characterised. Therefore a moment source has to be used which injects a defined and calculable moment power which is not too low compared to the induced force power. In the present work a twin-shaker system is used.

2. Twin-Shaker – moment source

The twin-shaker source consists of two synchronized electrodynamic shakers, which were connected to the reception plate in different distances. The phase of the signals going into the source amplifier of the shakers and the corresponding forces were: identical – 0° phase shift, forces act synchronously; phase shifted by 180° and randomly phase shifted. The type of signal was white noise. The distances of the two shakers were 3.5, 7.0, 14 and 28 cm. For 180° phase shift and little distance between the injection points, it is assumed that the resulting injected force into the plate is very low and mainly moment power is transmitted.

Besides using a twin-shaker system there are other also methods to generate moments and moment power. According to [11], synchronized hammers or a moment actuator are possible as well.

However, in the present work a twin-shaker system was used because it can be connected to the used reception plates rigidly by screws going through the plates. In general, having a rigid and solid connection is important for good structure-borne sound measurements.

2.1 Estimation of the moment power injected into reception plates

According to [5] moment excitation in the center of a plate only has to be taken into account if the Helmholtz number *kx* is higher than 10. *k* is the wavenumber of the receiver and *x* is the characteristic length. For the low frequency range the force power is the dominant part injected into the plate. In the high frequency range moments can play a major role. In the present investigation it will be discussed how straight acting moments affect the reception plate power and if they can be characterised by TSM.

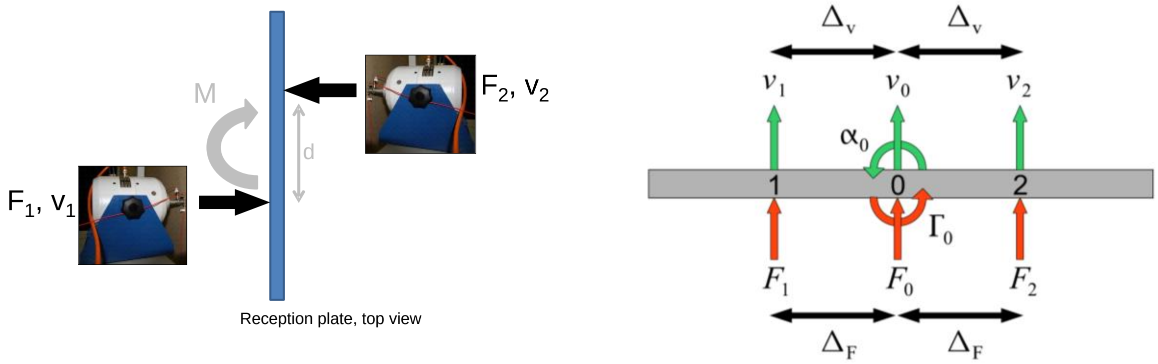

Figure 1: Twin-shaker measurement setup (left); values measured at the setup (right) according to [3].

Figure 1 shows the twin-shaker setup and a sketch of the measured values (the method is described in detail in [1], [5] or [3]). The distance between the shaker connection points 1 and 2 is two times the distance Δ_v to the point of interest 0. At point 0 the moment M_0 ($=\Gamma_0$) is calculated. At the contact points 1 and 2 of the shakers the force and acceleration magnitudes were measured by two impedance heads (the final values were the mean of 20 second measurements). In the present work a simple estimation of the injected moment power was done. Therefore, the magnitudes of the measured values were used and the phases between v_1/F_2, v_2/F_1, v_1/F_1 and v_2/F_2 are assumed with 0°.

The assumption of a 0° phase for v_1/F_1 and v_2/F_2 is valid if the point mobility is real, what is correct using thin, infinite plates with respect to the wavelength. Additional to that the phase between v_1/F_2, v_2/F_1 can only set to zero, if the distance Δ_{F1-F2} is small compared to the wavelength. The phase measurements between all values confirm the phase assumptions for most part of the frequency range of interest within this investigation.

The moment power P_M can be calculated with equation ((1) and the real part of the moment power is calculated with equation ((2). The moment M_0 acting at point 0 can be calculated with equation ((3) and the angular velocity α_0 at point 0 with equation ((4), using the velocity magnitudes measured by the two impedance heads.

$$P_M = M^2 \cdot \bar{Y}^{B}_{Mx,y(\infty plate)} \quad (1) \qquad \mathrm{Re}\{P_M\} = |M_0|^2 \cdot \mathrm{Re}\{\bar{Y}^{B}_{Mx,y(\infty plate)}\} \quad (2)$$

$$M_0 = \frac{\alpha_0}{Y_{\alpha/M}} \quad (3) \qquad \alpha_0 \approx \frac{1}{2\Delta_v}(v_2 - v_1) \quad (4)$$

P_M – moment power in W
M_0 – moment at point 0 Nm
$\bar{Y}^{B}_{Mx,y(\infty plate)}$ – moment mobility of the thin, infinite plate x- or y-direction in s/(m² kg)

α_0	– angular velocity at point 0, calculation with the rotation at point 0 in rad/s
$Y_{\alpha/M}$	– moment mobility, measured at point 0 in s/(m² kg)
v	– velocity at point 1/2 in m/s
Δ_v	– distance of the velocity measurement point to point 0
Δ_F	– distance of the force measurement point to point 0

The theoretical moment mobility for an infinite plate according to [1] can be calculated with equation ((5). The measured moment mobility at point 0 is calculated by equation ((6).

$$\bar{Y}^{B}_{Mx,y(\infty plate)} = \frac{3\omega \cdot (1-\mu)}{2G \cdot h^3} \cdot \left[\frac{1}{4} + j \frac{\ln\left(\frac{2}{k_B \cdot a}\right)}{\pi} \right] \quad (5)$$

$$Y_{\alpha/M} = \frac{\left(\left(\frac{v_1}{F_1}\right) - \left(\frac{v_2}{F_1}\right) - \left(\frac{v_1}{F_2}\right) + \left(\frac{v_2}{F_2}\right)\right)}{4\Delta_F \Delta_v} \quad (6)$$

Δ_F and Δ_v are the distances between the shaker connection (measurement points for force and velocity) and the point 0, where the moment is determined. For the calculation of the moment mobilities the magnitudes of force and velocity were used. The phase shifts between forces and velocities were assumed with 0°.

2.2 Criteria for the assumption of a small moment injection area

For the calculation of the moment mobilities according to [1] the criteria for a small area, on which the moment is acting, has to be valid. The injecting area is small if $k_B \cdot a << 1$. a is the distance between the shaker connection point to point 0 where the moment is calculated, or the radius of the moment injection area. k_B is the wave number of the free bending wave. Much more smaller „<<“ is here if the left part of the inequation is smaller than 1/10. Then, $k_B \cdot a < 0{,}1$.

Figure 2 shows the criteria calculated for the reception plates used. According to this figure, the strong criteria of the smallness $k_B \cdot a << 1$ is not fulfilled for the plates in the whole frequency range. Therefore, it is assumed, that a criteria of a simple smallness $k_B \cdot a < 1$ is sufficient for the described moment mobility calculation above.

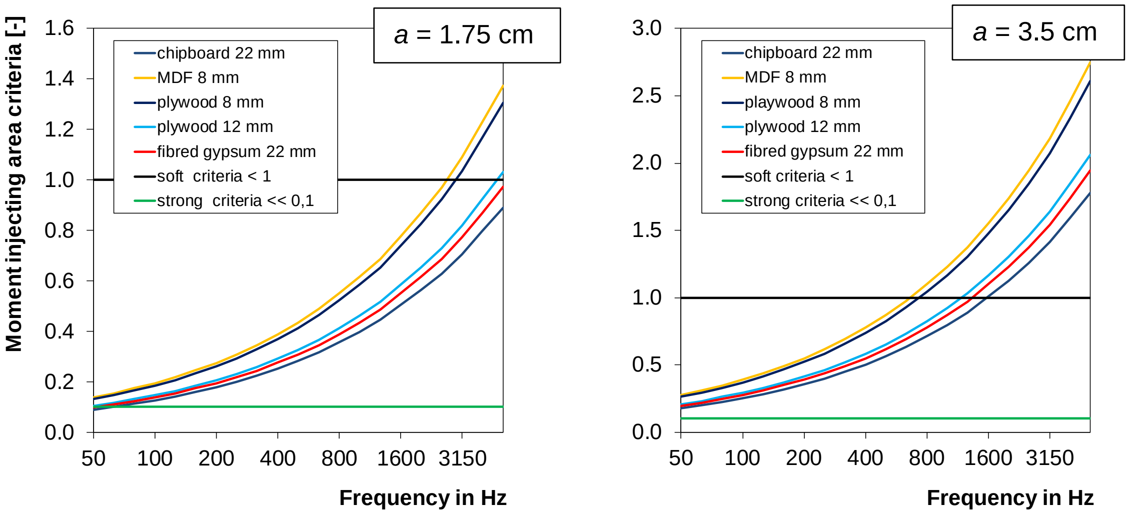

Figure 2: Criteria for small moment injection areas according to [1] for the estimation of moment mobilities.

2.3 Measured and theoretical moment mobilities

Figure 3 compares the theoretical (5) with the measured values (6) of the moment mobility. The values are magnitudes; however, the distance of the force injection points only affects the imaginary part of the mobility.

If the radius of the moment injection area is small (a = 1.75 cm and 3.5 cm) the measured and calculated moment mobilities are very similar in most parts of the frequency range. In the middle frequency range the graphs are nearly parallel.

The correlation between measurement and calculation for thin plates is better than for thick plates. This can be due to the force connection points which do not act in the resulting neutral axis, but a little outside. This effect is stronger if thick plates are used. If the injection area radius used is shifted for the calculation about 1 - 2 cm (depending on the plate material and thickness) the curves would fit best. This is due to the bigger injection area, especially regarding thick plates, as it is assumed with the shaker distance of the twin-shaker setup. With increasing shaker distances, the moment mobilities do not fit as well as for smaller distances (lowest diagram row). Then, the criteria according to [1] is not valid any more for larger moment injection areas.

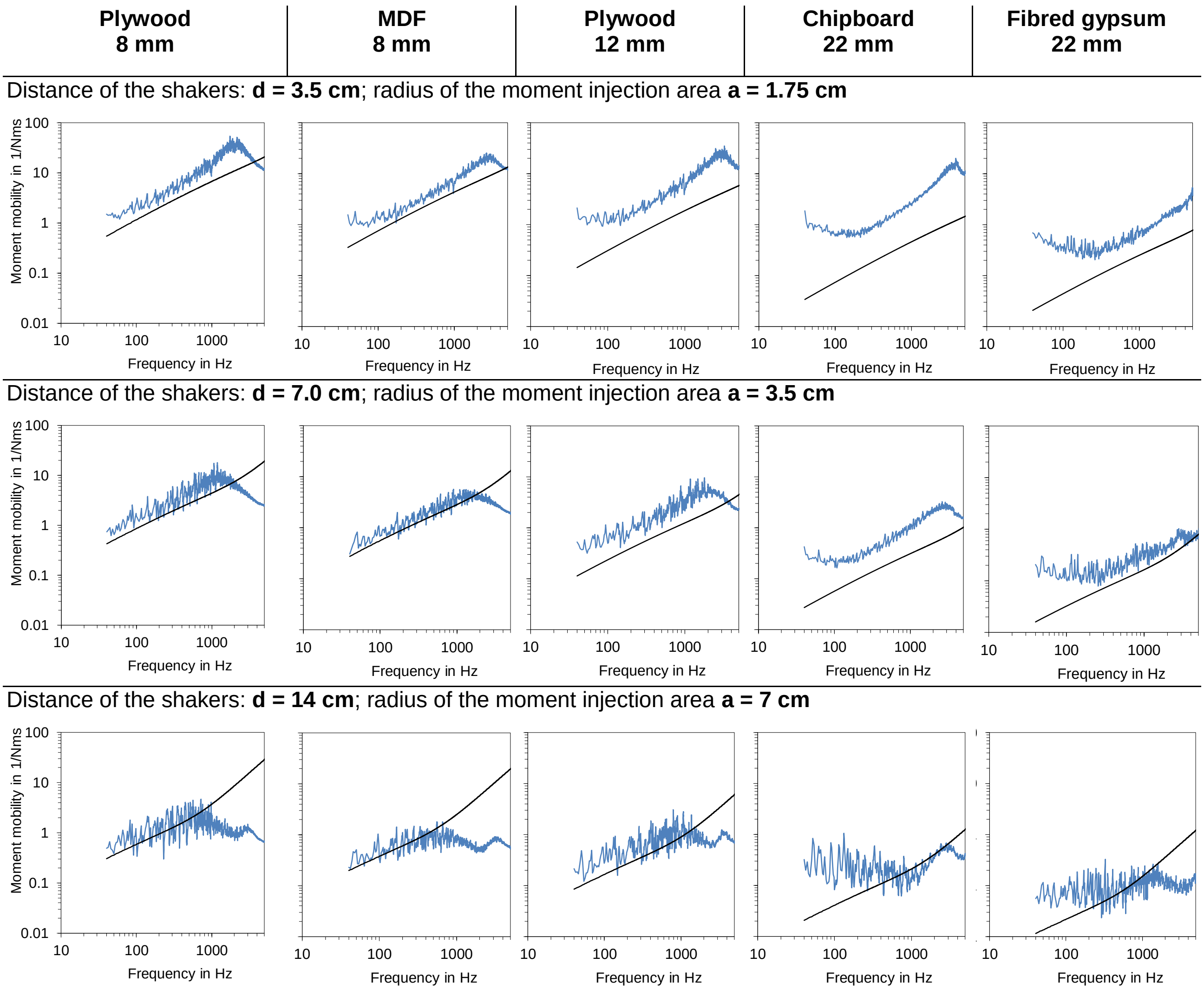

Figure 3: Measured and calculated moment mobilities of the used reception plates; distances of the shakers: 3.5; 7.0; 14 cm.

In general, further discrepancies can be caused by imprecise material parameters. The origin of these values was provided by the producer. In case of unknown values, typical values for the given material were estimated.

2.4 Comparison of moment power and reception plate power

In the following part the injected power into the plates due to moments is measured. Therefore a twin-shaker setup was used. At the same time, the reception plate power was measured by 12 acceleration meters [4]. The question was if injected moment power is also measureable as reception plate power. However, the reception plate power is the sum of all injected powers due to forces and moments.

In the special cases of a small distance of the forces compared to the wavelength and a force phase shift, the force power can be estimated with equation (7). In the case of two synchronously acting forces the force power can be calculated according to equation (8).

Force power – phase shift 180°

$$P_{\text{force},180°} = \left(|F_1| - |F_2|\right) \cdot \left(\frac{|v_1| - |v_2|}{2}\right) \quad (7)$$

Force power – phase shift 0°

$$P_{\text{force},0°} = \left(|F_1| + |F_2|\right) \cdot \left(\frac{|v_1| + |v_2|}{2}\right) \quad (8)$$

$$P_{CP1+CP2} = \text{Re}\{F_1 v_1\} + \text{Re}\{F_2 v_2\} \quad (9)$$

Sum of power at the shaker connection points 1 and 2 (CP1 + CP2)

These equations using only magnitudes are valid, because the measured phases between v_1 / v_2 and F_1 / F_2 were 180° respectively 0° in most parts of the frequency range. The phases between v_1 / F_1 and v_2 / F_2 are nearly 0° in both acting cases.

In Figure 4 and Figure 5, the determined powers using 5 different reception plates are shown. With respect to the acting mode of the twin-shaker setup (forces acting synchronously or with 180° phase shift), different moment activity can be observed at the plate.

In Figure 4 right the twin-shaker was connected to a chipboard plate with synchronously acting forces. Then, the sum of force power (blue curve) at each connecting point is nearly the same as the reception plate power (black curve). The estimated moment power (red curve) is much lower. This behavior was measured for every plate and every shaker distance.

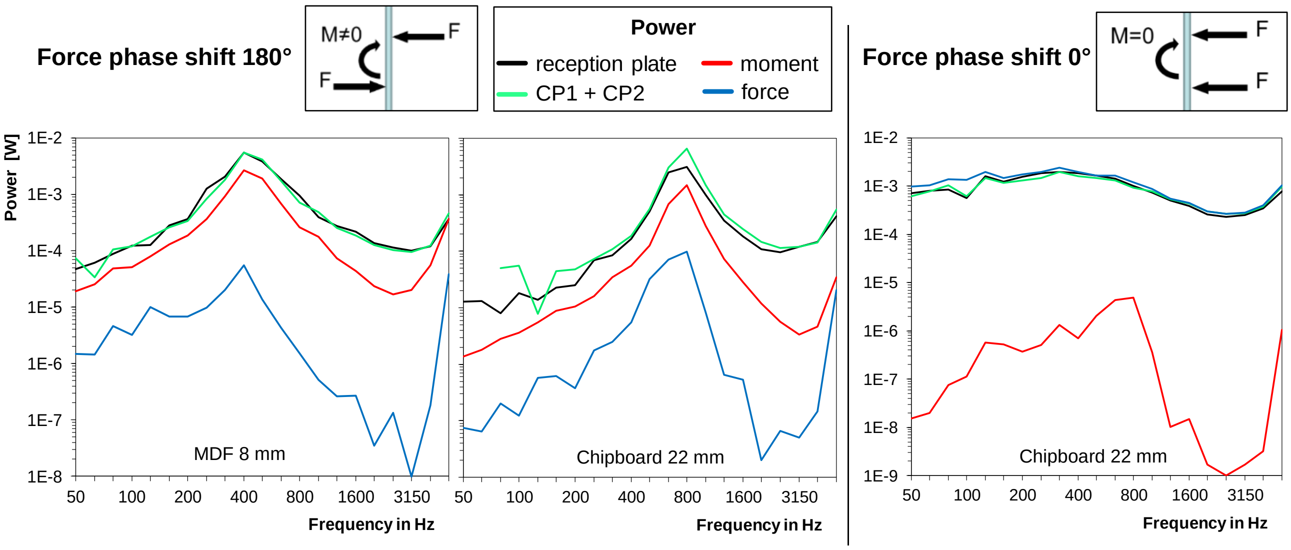

Figure 4: Comparison of measured powers due to: forces - blue; moment - red; sum of power on connection points 1 + 2 - green; reception plate power - black; radius of the moment injection area ***a* = 1.75 cm**; third-octave bands.

Figure 4 (left and middle diagram) shows the results for acting forces with 180° phase shift and a distance of the injected forces of 3.5 cm. The reception plates were a lightweight plate MDF 8 mm and a chipboard plate 22 mm, which is a heavier plate. Both plates show a similar behaviour: the sum of estimated moment power (red curves) and force power (blue curves) is measurable as reception plate power (black curves). In both cases the force power estimated according to equation 7 is much lower than moment power. Furthermore, even in the moment acting mode the sum of the powers at the impedance heads measured synchronized (green curve; equation 9) is nearly the same as the reception plate power and the moment power as well. This can be explained by the relation of a pair of forces and its substitution by a moment. In the case of a small distance and 180 ° phase shift between the forces, both moment power at point 0 and sum of the force powers at the connecting points 1 and 2 are the fairly the same.

The systematical parallel shift between the reception plate power and the moment power can be attributed to an unclear injection area. If the area is set little further, the moment and reception plate powers fits best (not shown in the paper).

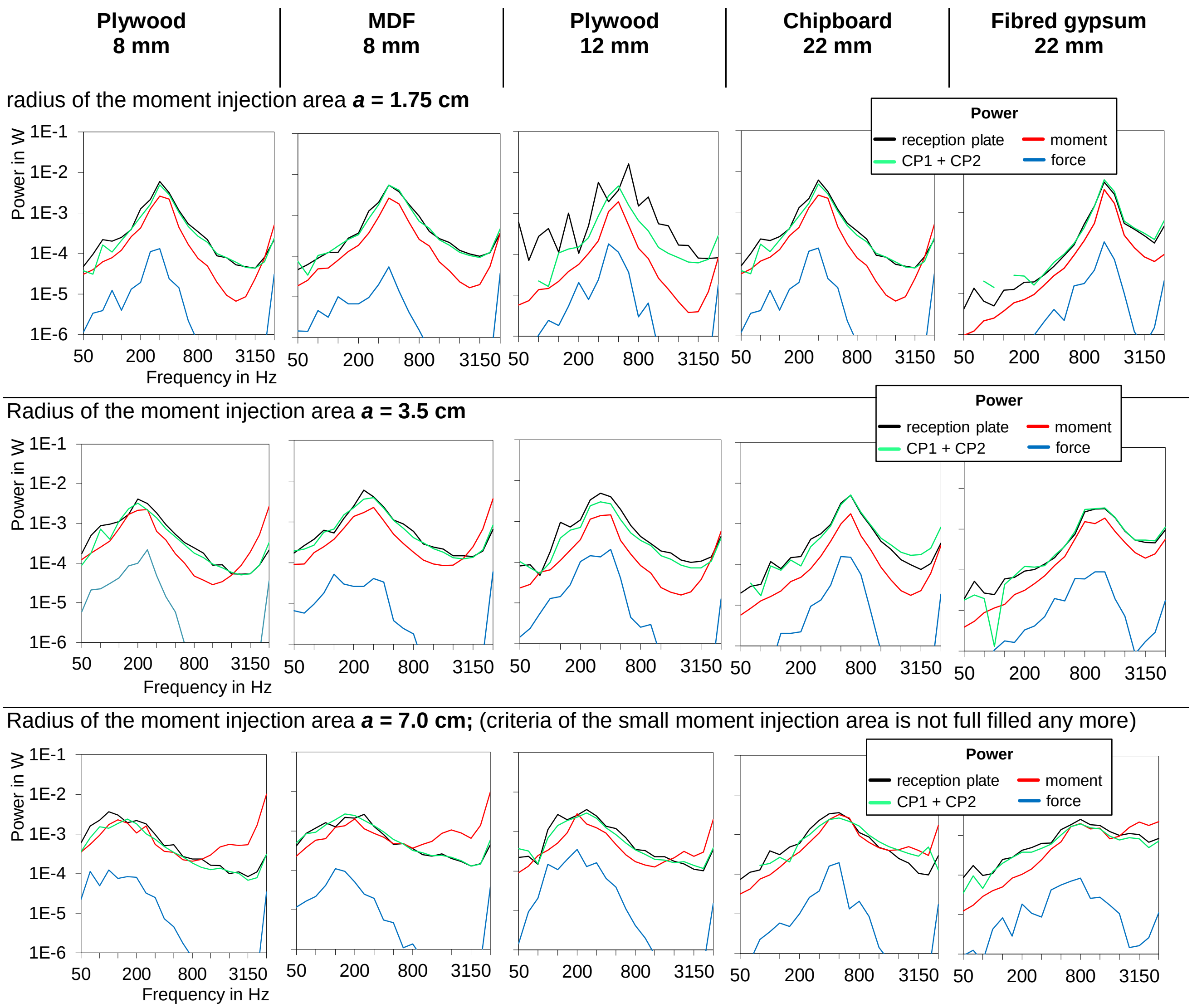

Figure 5: Measured moment power, force power, sum of powers on at the connection points 1+2 and reception plate power using a twin-shaker as source; force signal is 180° phase shifted; third-octave bands.

3. Source characterisation of the twin-shaker setup using TSM

In this chapter it will be investigated if a moment source can be characterised by the two-stage method. The activity of a source, even of a moment source, is measurable as reception plate power. This is obviously true regarding the examination above. Then, the blocked force was measured with a heavy plate (22 mm double leafed gypsum fibre plate) and the free velocity of the source with a light weight reception plate (plywood 8 mm). Afterwards, the power prediction is compared to measurements. Figure 6 shows the power level differences between predicted and measured power on the plate.

In general, if the phase shift of the twin-shaker setup is random or 0°, the source can be characterised well with TSM, because the power prediction in a plate shaped receiver is rather good (power discrepancies fairly ±3 dB). This is independent of the moment injection or the shaker distance. For the pure moment source (phase shift 180°, a = 1.75 and 3.0 cm) higher power discrepancies occur in the frequency range where the highest moment power is injected into the plate (black and red curve, middle diagram row). There, the power differences can be 10 to 15 dB.

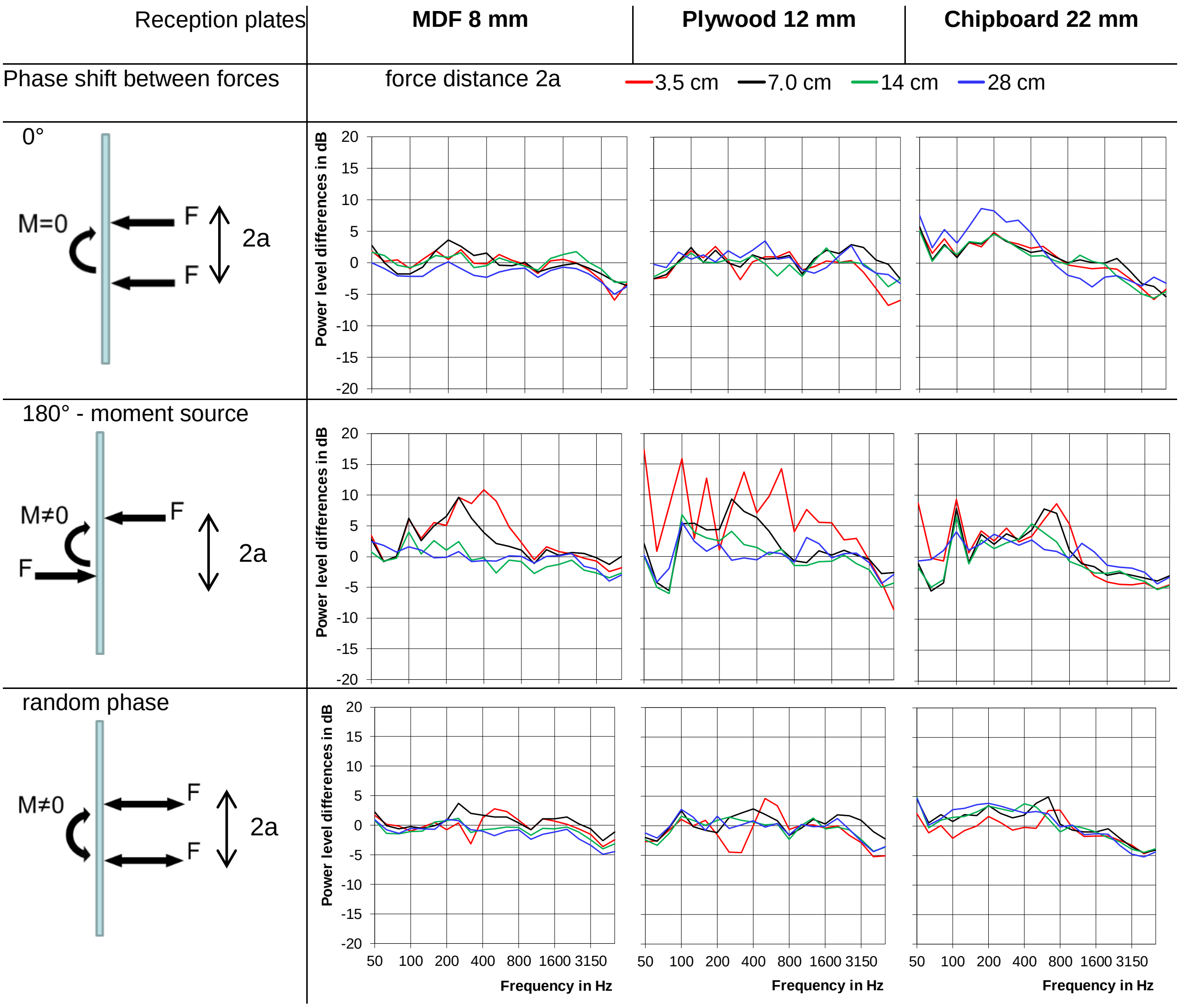

Figure 6: Power level differences between measured and predicted power ($P_{measure} - P_{predict}$) on reception plates using a twin-shaker setup as source moment source [4]; third-octave bands.

4. Conclusion

The characterisation of a structure-borne sound source can be done with the two-stage-method (TSM). In the present investigation the role of moment power with respect to the characterisation method was investigated. First, it was investigated if the influence of moment power can be measured by the reception plate power. Therefore, a moment source, in this case a twin-shaker setup, was used. The results show a good agreement between the measured moment power at the contact point and the power on the plate, even if the moment power part predominates. With the adjustment of the injection area, the powers fit better.

If the twin-shaker does not act as a pure moment source, the force power part predominates. If the twin-shaker acts as pure moment source, the estimated moment power is nearly equal to the reception plate power and the sum of the powers at the injection points. In this special case the moment is replaceable by a force pair and its power sum.

The second part of this work was an investigation if a moment source can be characterised by TSM. Therefore the plate power on reception plates was predicted with the characterised source parameters and compared with the measured reception plate power. If the pure moment source is used, power differences of 10 to 15 dB can occur using shaker distances of 3.5 and 7 cm. This special case is probably not the common behaviour of a structure-borne sound source. If the twin-shaker acts with random phase shift a good characterisation and power prediction is possible, independent of the shaker distance. If the shakers act synchronously, characterisation and prediction work very well, as was expected. However, even sources with considerable moment power parts can be characterised with TSM, but with less accuracy. A simple criteria for the use of TSM can be the following: If a force phase shift of 180° between two source connection points with a distance of 2*a* is expected, TSM can be used without any further examination when $k_{\mathrm{B}} \cdot a > 1.5$. Then, the acting forces are sufficient far away from each other and the force power component is determinative of the reception power.

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