Reciprocity as an Analysing Technique in Building Acoustics
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A reciprocity relation between the sound radiation of a structure and its vibration response to diffuse sound field excitation is regarded in connection with floating floors. A double wall was built in the laboratory as approximation of an ideal floating floor. The effect of a single sound bridge was examined through connection of the two leaves by a steel bar. After all, structural defects like sound bridges greatly diminish the assets of floating floors. The reciprocity relation between the radiation and the response of a structure was experimentally verified and afterwards applied for detection of the sound bridge. From the above reciprocity relation another remarkable equivalence can be derived, stating the sum of the air-borne sound insulation and the standardized impact noise level to be only dependent of frequency and independent of all structural properties. This relation was used in a case study as an indicator for leakage and flanking transmission.

1 Introduction

The theorem of reciprocity exists in many forms and is therefore applied in a wide range of scientific fields. Reciprocity relations often yield the simplification of experimental set-ups. For this reason, Maruyama, Aoki and Furuyama [1] used acoustic reciprocity to measure transfer functions, as one way of dealing with noise pollution coming from road traffic is controlling the transfer function from the noise source to the human ear. Zheng, Fahy and Anderton [2] made use of a vibro-acoustic reciprocity technique for the experimental prediction of the complicated sound field radiated by an internal-combustion engine. According to Fahy, vibro-acoustic reciprocity can also be applied to determine the optimal attachment positions of vibrating machinery as to minimize radiated sound pressure levels by the structure. In [3] and [4], Fahy gives an entire series of application examples for the principles of vibro-acoustic reciprocity. In building acoustics the reciprocity relation between the sound radiation and the vibrational response of a structure is most frequently referred to. Fisher and Focke [5] used this relation to measure the performance of building structures with respect to the radiation of structure-borne sound due to the connection of a waste water installation.

The present work regards the relation between the radiation and the response of a structure in connection with floating floors. Nowadays, the application of floating floors is advised for adequate impact sound insulation and an air-borne sound insulation improvement. It is however a precondition that the construction is build up skillfully. Defects like sound bridges or leakage will cause a decrease in sound insulation performance. A double wall, built in laboratory conditions, was used to analyse bridge-effects between stony materials. For this purpose the two leaves were point-connected by a steel bar bridge.

Reciprocity was used as a tool for the detection of the sound bridge.

Based on the relation between the radiation and the response of a structure, another important equivalence can be derived. The sum of the air-borne sound insulation and the standardized impact noise level turns out to be only dependent of frequency and independent of all structural properties. This relation can be a useful indicator for leakage and flanking transmission, as shown in a case study.

2 The principles of reciprocity

In general, reciprocity is stated as

\[
\frac{v_2}{F_2} = \frac{v_1}{F_1}
\]

(1)

If a force \( F_1 \) that acts at a point \( P_1 \) produces a velocity \( v_1 \) at a point \( P_2 \) then this same force \( F_2 = F_1 \) acting at point \( P_2 \) will produce a velocity \( v_2 = v_1 \) at point \( P_1 \). In other words, the ratio of the exciting force to the observed velocity remains the same if the excitation and observation points are interchanged, provided that the direction in which the force acts in each case is the same as that in which the velocity is measured in the other case. As a second condition the dynamic system should be linear. Common acoustic problems are all covered by the field of linear acoustics, so this last condition is generally satisfied [6].

Because a homogeneous fluid at rest behaves like a linear, elastic medium with respect to small disturbances, a particular form of the postulate namely the acoustic form can be stated in the same way as (1), that is
The point forces $F$ in (1) are now replaced by the volume velocities $Q$ of an omnidirectional sound source and the velocities $v$ by the sound pressures $p$. Relationship (2) is valid irrespective of the presence of arbitrary, linear elastic solid structures contiguous to the fluid. These structures can simply be incorporated into the total linear, dynamic system to which the theory of reciprocity applies [4].

When in fact a solid is present in the fluid the relationship (2) can be further extended, as one of the sound sources can be replaced by a small vibrating area $dS$ on the otherwise rigid body. This implies the vibro-acoustic reciprocity principle

$$\left( \frac{\rho v}{Q} \right)_s = \left( \frac{\rho v}{Q} \right)_r$$

by which the sound radiation of a structure can be determined [2].

In general, vibro-acoustic reciprocity expresses that the transfer function between a vibrational point force applied to an elastic structure and the resulting sound pressure in a contiguous fluid at rest may be determined by insonifying the structure with an omnidirectional sound source or

$$\left( \frac{\rho v}{Q} \right)_r = \left( \frac{\rho v}{Q} \right)_s$$

as formulated in [4].

When a vibrational force $F$ is applied to a certain point of a structure, this will cause the structure to vibrate. As a consequence the structure will radiate sound into the reverberant space. The radiated sound power is proportional to the produced mean square velocity averaged over the radiating surface, $v$, and therefore also to the square of the applied force:

$$W = \alpha F^2$$

$\alpha$ can be regarded as a measure for the radiation of a structure. The response of a structure to reverberant sound field $p$ can on the other hand be measured by $\beta$:

$$v^2 = \beta p^2$$

The response of a structure to a reverberant sound field as measured by $\beta$ can thus be found if its radiation due to point excitation as measured by $\alpha$ is known and vice versa.

Based on (1) and following [7] another interesting reciprocity relation can be derived:

$$\frac{p_1}{Q_1} = \frac{p_2}{Q_2}$$

In closing, also based on [7] and starting from relation (7) the following remarkable equivalence can be derived:

$$L_N + R = 38.2 + 30 \log f_n - 10 \log \sigma$$

where $L_N$ is the standardized impact noise level, $R$ is the air-borne sound insulation, $f_n$ is the terts band center frequency and $\sigma$ is the radiation efficiency. At supercritical frequencies the radiation efficiency can be set to one and so the sum (8) is only dependent of frequency and independent of all structural properties. A prior condition for the validity of this equivalence is the contact between the hammers of the tapping machine and the floor surface to be hard enough, since the derivation assumes an infinitely short impacting time.

3 Reciprocity in connection with floating floors

3.1 Relation between radiation and response

Equation (7) relates the vibrational response of a structure to its sound radiation or in other words, the structural sensitivity of a wall or floor to its air-borne sensitivity. Because of the great practical interest in the relationship, this was tested under laboratory conditions for two different test walls. For each wall two measurement points were randomly chosen and for each of these points the measurement was repeated twice. The measurement setup was realised in the Laboratory of Acoustics and Thermal Physics at the K.U.Leuven. The test walls were built between the transmission rooms of the laboratory. A diffuse sound field was created by means of two loudspeakers (Mackie, type SRM 450) positioned in the corners of the sending room. Sound pressures were measured using a 1/2” microphone (B&K, type 4165). For the velocity measurements a laser Doppler vibrometer (sensor head POLYTEC, OFV-505 and vibrometer controller POLYTEC, OFV-5000) was employed. Finally, for the point force excitation a shaker (B&K, type 3385-031) was used in combination with an ICP force transducer (PCB, type 208A03). Figure 1 shows the different set-ups.
Because the relationship under testing requires absolute values of pressure, velocity and force, all the sensors had to be calibrated with great care. Two types of calibrators were used. A first one (B&K, type 4230) enabled the calibration of the pressure sensor and the other one (B&K, type 4231) the calibration of the laser Doppler vibrometer and the force transducer. In addition to the calibrator, the force transducer calibration also required a known mass and the use of Newton’s first law. The three calibration set-ups are shown in Figure 2.

First, a single wall consisting of special gypsum blocks was tested. From the four measurement results, the lower and upper limit of the measured values are considered in each case. Figure 4 shows that the relationship is satisfied quite well in the frequency range of interest for building acoustics.

Several reasons can be stated for the existing deviations. First of all, the setup of the shaker and the force sensor is very sensitive. To avoid subjecting the force sensor to a moment of any kind, a small rod is placed between the wall and the force sensor (see Figure 1). That way only normal forces are transmitted. The smallest bending moment interfered with the measured force magnitude. The condition of a diffuse field is an additional reason for deviations. Especially in the low frequency range, where the modal density is low, this condition is often not completely satisfied.

The second test wall was a double wall, composed of two leaves of hollow, plastered bricks and with the air cavity partially filled with mineral wool. The results for this wall are shown in Figure 4.
The global insulation value $R_w$ decreased with 2 dB, that is from 54 dB to 52 dB. The consequence for the insulation spectrum is even more pronounced. The insulation drop seen in Figure 5 is a function of frequency. At higher frequencies the drop becomes more and more distinct. This frequency dependence is caused by the finite length of the bridge, as written in [7]. The insulation drop caused by a sound bridge increases with increasing bridge length, and so it has to increase with increasing frequency, because the bridge must be considered in comparison to the longitudinal wavelength.

Because the wall was installed between the laboratory transmission rooms, one can presume that neither flanking transmission paths nor sound leakage will interfere with the measurements. This means that the transmission loss can be derived from the velocity measurements on the wall. The results are shown below.

The radiation efficiency was found by use of the empirical formulas stated in [9]. In each case the two curves are very similar. The high frequent deviation for the case without sound bridge is the result of the low signal-to-noise ratio of the laser Doppler vibrometer, as explained for Figure 4 (right). These results should be considered in relation with in situ measurements. When one encounters for instance a very well insulating wall, the presence of background noise can thoroughly disturb the measurement of the sound pressure level in the receiving room when using the pressure method. Velocity measurements are not faced with these kinds of difficulties.

The reciprocity relation (7) was also tested in case of the double wall with sound bridge, as shown in Figure 8.

The results are comparable to these of Figure 4 (left). Yet, the tendency for the measurement values to increase in the high frequent region is less. This is an effect of the sound bridge, since it causes the velocity
levels on the receiving wall to be higher. What is important is that even in Figure 8 the global tendency is present, denoting for instance that a the air-borne sound insulation of a floating floor reacts in the same way to sound bridging as the structure-borne insulation does. This information can be used in combination with Figure 5. The effect of sound bridging in a floating floor structure will show a comparable frequency dependence. This means that when, in situ, one measures a higher impact noise level then expected, this can point to the presence of one or more sound bridges. Detecting these sound bridges can be done by use of an intensity measurement, but it is much easier to use relation (7) in the reciprocal measurement. Here, the floor structure is excited by means of a diffuse sound field and a velocity scan is done on the other side. In the laboratory, a non-contact scan of the wall was performed using a laser Doppler vibrometer. A mesh was made on the wall by use of reflecting tape. Only one fourth of the wall was considered (see Figure 9).

Figure 9: Measurement mesh on test wall

Figure 10 shows the results of the velocity scan.

Figure 10: Velocity levels of measurement mesh

The measurement points and belonging velocity levels are divided into four groups based on the distance to the sound bridge and thus the magnitude of the velocity levels. In Figure 7 the two curves differ especially in the high frequency range. The same behavior was found for the velocity levels measured with the laser Doppler vibrometer, as shown in the figure below. The sound bridge could be clearly distinguished from about 630 Hz.

3.2 Sum of air-borne sound insulation and impact noise level

A small test building was constructed to consist of two storeys between which a test structure was placed. The test structure was a type of floating floor. The purpose was to improve it as much as possible with respect to both structure-borne and air-borne sound insulation. After each intervention a series of tests were done. Logically, the air-borne and structure-borne sound insulation were also measured each time. Therefore the sum formula could be checked. In all cases an amount of flanking transmission was detected. [9] gives a greatly simplified calculation method for the prognosis of the expected insulation loss resulting from flanking transmission. According to this method, in a building counting two storeys above each other, the air-borne sound has three additional transmission paths per junction, and thus twelve in total, while the structure-borne sound only has one additional path per junction and four in total as shown in the figure below.

Figure 11: Flanking paths per junction for air-borne sound (left) and structure-borne sound (right)

This means that as a result of flanking transmission, the air-borne sound insulation decrease will not be compensated by the accompanying structure-borne transmission increase. In addition, according to [10], the effect of flanking transmission on the overall sound insulation is likely to be independent of frequency for most building structures. This is shown in both Figure 12 and Figure 13. The curves are shifted down with a certain amount with respect to the theoretical curve, what can be seen as an indication of flanking transmission.

Figure 12 handles a first intervention. The structure was tested before and after the detectable leakage was sealed. The two curves diverge mutually in the mid and high frequency range. The deviation of the first curve from the theoretical one is an indication of leakage. After the detectable leaks were sealed, the second curve obviously followed the theoretical slope longer. The high frequent drop in this case was caused by either smaller leaks or the contact between the hammers and the floor that was not perfectly hard.
Theoretical values \[ R + \text{LN} = 38.2 + 30 \log (f) \]

With leakage
Leakage sealed
>Theoretical values \[ R + \text{LN} = 38.2 + 30 \log (f) \]

Figure 12: Control of sum formula for floating floor with and without leakage

The following graph compares two cases, where one deals with a bare floor while the other handles a tiled floor. In case of the tiles, the contact between hammers and floor can be considered as harder. And so the theory predicts the drop to be postponed until a higher frequency.

The results of the above case study show that the sum formula can be used as a simple tool for detecting both leakage and/or flanking transmission. Checking the formula can only be used as an indicator. Velocity or intensity measurements are required to give the decisive answer. Nevertheless, since air-borne and structure-borne sound insulation are mostly measured anyhow, this formula can serve as a useful indicator.

4 Conclusion

The reciprocity relation between the sound radiation and the vibration response of a structure was experimentally verified for different test walls. In each case, the global tendency corresponds well with the theory. The same conclusion came out for the double wall with sound bridge. This means that for the testcases sound bridges in floating floors have the same effect on the air-borne sound insulation as on the structure-borne insulation. For this reason, a reciprocal technique can be used for the detection of sound bridges in floating floors in laboratory conditions, based on air-borne excitation of a floating floor structure and a non-contact velocity scan on the other side. The reciprocity relation can be translated in a relationship between the standardized impact noise insulation and the air-borne sound insulation of a structure. An in situ case study showed that this relation can be used as indicator for flanking transmission and leakage.

References


