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Efficient Localization of Sound Bridges by Structure-Borne Sound Intensity Measurements

Short Report

1. Introduction

The possibility of an accurate localization of sound bridges in double walls has already been demonstrated some 15 years ago [1]. The road to success was the approximate measurement of the intensity of bending waves: With measurements at only seven points on the lime-sand-brick double wall a sound bridge could be located within 10 cm. The method worked equally well with sound bridges in floating floors. However, since the effort of performing such measurements with equipment available at that time was considerable, the method found no application to building acoustic problems in the field. Now a practical solution using modern PC technology can be presented.

2. Measuring Principle

The x-component of the bending wave intensity is approximately obtained from the output of two accelerometers aligned with the x-direction by

$$I_x \approx -\frac{\sqrt{B h \rho}}{\omega^2 d} \operatorname{Im}\left\{\hat{a}_2 \hat{a}_1^*\right\} \tag{1}$$

with the plate properties bending stiffness *B,* thickness *h,* mass density ρ and the distance *d* between the accelerometers, which deliver the complex acceleration amplitudes $\hat{a}_1$ and $\hat{a}_2$ for time-harmonic wave fields with frequency ω (time factor convention: $\exp(-\mathrm{i}\omega t)$). In this formulation the intensity is proportional to the imaginary part of the cross spectrum of the two sensor signals. Equation (1) is valid for homogeneous thin plates at positions sufficiently far from the boundary or from inhomogeneities of the plate and for bending wavelengths large compared to the distance *d*. An appropriate distance may be chosen in consideration of the expression for the relative error,

$$\frac{\varepsilon}{k d} + \frac{(k d)^2}{6} \tag{2}$$

with phase mismatch ε of the two measuring channels and bending wavenumber *k* and minimum at $kd = \sqrt[3]{3\varepsilon}$. A typical value of $\varepsilon \approx 0.01$ results in $kd \approx 0.3$ and a relative-error minimum of about 5%. The y-component of the intensity vector is measured accordingly with two additional accelerometers along the y-direction. The error in the direction of the vector is typically a few degrees. (For general theoretical information about structure-borne sound intensity the reader is referred to the monograph [3]).

3. Measuring System

Modern data acquisition boards made the measurement of bending-wave intensity possible on a personal computer. A 16-channel 16-bit board with a maximum sampling rate of 250 kHz has been integrated in a portable PC. Thus data acquisition and subsequent evaluations controlled by the program 'Locate it!' are combined in one piece of equipment. Whereas with the two-channel analyzer in [1] the two intensity components had to be measured one after the other, a 'simultaneous' measurement of both components has now been realized using four accelerometers in a self-made mounting. This makes the method faster and applicable also to transient excitations like hammer blows even without measuring the exciting force. Future extensions of the software envisage the additional acquisition of the force signal from, e. g., an impulse hammer.

4. Measurement of structure-borne sound intensities on a floating floor

In the test facility for floating floors at the Fraunhofer Institute of Building Physics a screed floating on a foamed material was built. Its size was 4,75 x 3,75 x 0,05 m^3. The accelerometers were mounted with wax. The screed was excited by hammer blows at the point (X = 2.50 m, Y = 2 m) and the structure-borne sound intensity field was scanned in a 0,5 m raster. The results for the frequency range 400 - 800 Hertz are shown in Fig. 1. In this arrow-circle representation the sound intensity (arrow) is visualized together with the vibrational level (circle with the radius of the square of the displacemant amplitude). Intensities and levels are scaled in such a way that for the case of a plane bending wave the arrow ends at the circumference. For a totally reverberating field the intensity disappears. The radial structure of the field is clearly observable in Fig. 1. Note that in this figure the intensities are magnified by a factor of 50. Thus the reverberant field portions outweighs the direct wave and the radial structure is perturbed.

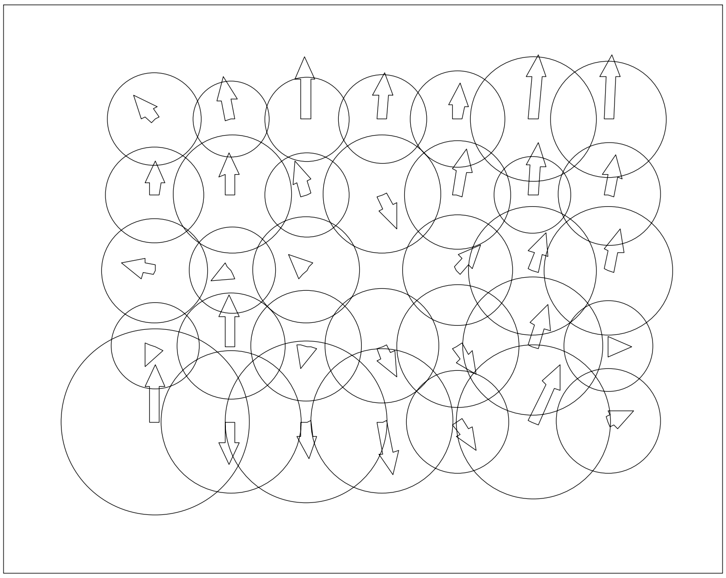

Figure 1: Intensities, in frequency range 400 - 800 Hz measured on a screed. Excition was at the centre of the plate

5. Search Strategy for sound bridges

The implemented strategy for localization of sound bridges is essentially the same as described already in [1] except for the error estimation. Initially the intensity vectors are determined from the acceleration signals at all measurement positions within some predefined frequency range. Then frequency averages including standard deviations are computed over some appropriately chosen frequency bands within the frequency range of the data acquisition. The selection of such frequency bands may be guided by looking at the direction of an intensity vector as a function of frequency: Regions with roughly constant values are an obvious choice. The frequency-band averages are the basis of the actual localization procedure: Firstly, the intersection points of the straight lines which are obtained by the elongation of the intensity vectors are calculated. Secondly, these intersection points are classified as source, sink or neither of them. An intersection point is called source (sink), if the two arrows of the involved intensity vectors point away from (towards) it. If the straight lines are nearly parallel or if the measuring points coincide, the intersection-point calculation is omitted. The uncertainty of the averaged intensity components is characterized by their standard deviations. Thereupon a corresponding uncertainty is ascribed to the position of the intersection points and visualized as a rectangle centered on the intersection point, which is drawn as a circle. In the third step average source and sink positions are determined. The user may exclude intersection points from the averaging either individually or by specifying, e. g., a maximum standard deviation or a rectangle containing the desired intersection points only. On averaging each selected intersection point is weighted by its reciprocal standard deviation. Additionally, a standard deviation of the average intersection point is determined. This final result is plotted on the screen as a differently colored rectangle. For an overview the user will typically begin the investigation with intensity measurements at a few points spread all over the plate. After the definition of a couple of suitable frequency bands (see above) a sources-and-sinks calculation will provide a basis for a first guess at the number and locations of sound bridges. Then intensity measurements will be conducted at additional points in the vicinity of each of the supposed sound-bridge positions. Finally, the average source and sink positions - one after the other – are determined as described above. If desired, refinements may be attempted with further measurements.

6. Localisations

6.1. Chipboard on mineral-wool layer with up to three sound bridges

A chipboard (2.5 m x 1.25 m x 2.5 cm) was laid on a 3 cm thick layer of mineral wool on a concrete floor. Sound bridges have been created by screwing the board to the concrete floor at up to three positions. Excitation was by a hammer on the concrete floor beside the chipboard. Intensity measurements (distance between accelerometers d = 4 cm) and subsequent evaluations have been carried out by different persons. Thus it was possible to perform the localization procedure without the knowledge of the actual positions of the sound bridges. Fig. 2 shows intensity vectors and circles, the radii of which are a measure of the vibrational level. The chipboard was rather reverberant, which means adverse conditions for localization. Nevertheless, the existence of three sound bridges can be inferred by mere visual inspection of Fig. 2.

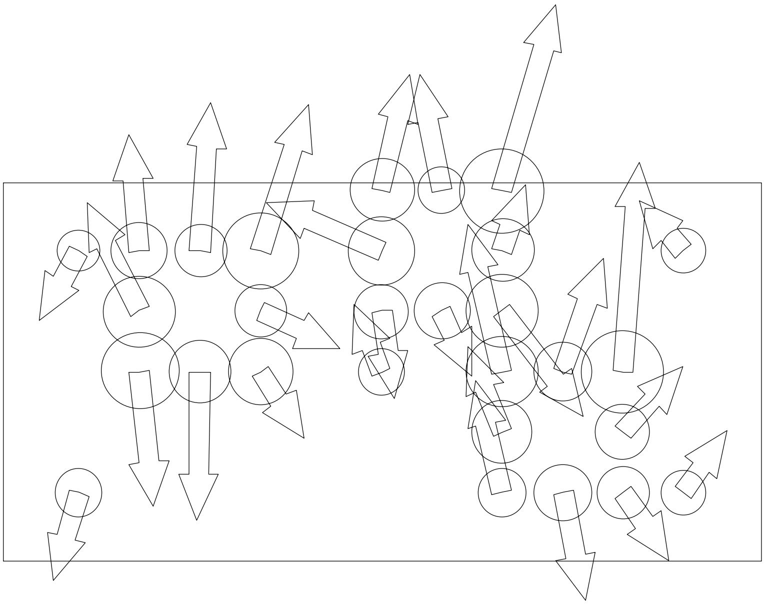

Figure 2 Intensity vectors (arrows) and vibrational levels (circles) on the chipboard with three sound bridges (averaged from 400 Hz to 800 Hz; arbitrary units).

Fig. 3 is a plot from the actual localization procedure. The white rectangle represents the chipboard. The source intersection points are shown as blue circles, their uncertainties as blue hatched rectangles. The average source position is marked by the red checkered rectangle. Table 1 summarizes the results. The discrepancies between the actual coordinates of the sound bridges and those obtained from the localization procedure in no case exceeded 15 cm. With one exception all discrepancies lie within the error bounds calculated from the standard deviations.

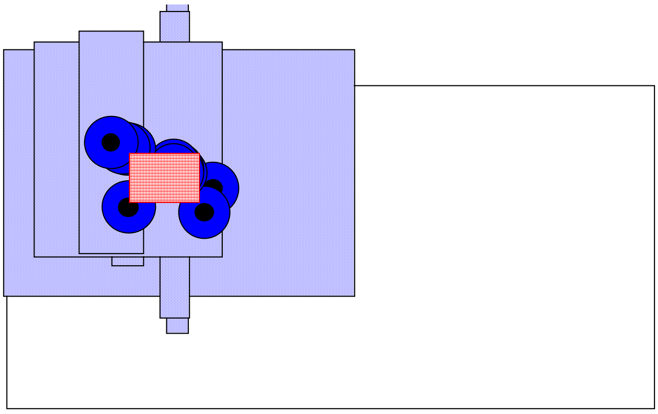

Figure 3 Graphical representation of estimated source positions during the localization procedure (explanation of symbols: see text).

Table 1 Localization of up to three sound bridges in a chipboard screwed to the floor.

Number of sound bridges	Positions of sound bridges	Positions estimated by the localization procedure	Frequency band [Hz]
1	X = 1.85 m Y = 0.43 m	X = 1.98 ± 0.20 m Y = 0.41 ± 0.23 m	400 ... 800
2	X = 1.85 m Y = 0.43 m	X = 1.86 ± 0.04 m Y = 0.56 ± 0.19 m	200 ... 400
	X = 0.65 m Y = 0.83 m	X = 0.63 ± 0.12 m Y = 0.76 ± 0.25 m	
3	X = 1.85 m Y = 0.43 m	X = 1.90 ± 0.14 m Y = 0.39 ± 0.12 m	400 ... 800
	X = 0.65 m Y = 0.83 m	X = 0.59 ± 0.14 m Y = 0.89 ± 0.09 m	
	X = 1.45 m Y = 1.03 m	X = 1.55 ± 0.07 m Y = 0.91 ± 0.06 m	

6.2. Floating floor

Another test was performed on a floating floor (4.75 m x 3.75 m x 5 cm cement plate on foam plastic) in a testing facility. At the position (X = 3.50 m, Y = 1.50 m) a hole was drilled into the floating floor and covered by a metal plate plugged to cement plate. Through a threaded hole of the metal plate a thread rod – the sound bridge – was screwed down to the concrete floor and firmly tightened. The measurements were carried out with an accelerometer distance d = 4 cm and hammer excitation at two places: At (X = 2.50 m, Y = 1.50 m) on the floating floor and on the concrete floor in the door opening of the room. Some results are collected in Table 2. Excitation of the concrete floor (sound bridge acts as a source) leads to very similar results of the two selected frequency bands and to significantly smaller localization uncertainties. Obviously this is to be preferred to excitation of the floating floor (see Fig. 4), which means both a source (the hammer) with strong influence on the intensity direction and a sink (the sound bridge) with weaker effect. The hammering position on the floating floor, which was not searched for with additional measurements in its vicinity, could be localized as shown in Table 3.

Table 2 Localization of a sound bridge at (X = 3.50 m, Y = 1.50 m) in a floating floor.

Excitation	Frequency band [Hz]	Positions estimated by the localization procedure
on floating floor	200 … 400	X = 4.00 ± 0.38 m Y = 1.52 ± 0.22 m
	400 … 800	X = 3.68 ± 0.33 m Y = 1.73 ± 0.85 m
on concrete floor	200 … 400	X = 3.44 ± 0.05 m Y = 1.23 ± 0.24 m
	400 … 800	X = 3.46 ± 0.04 m Y = 1.26 ± 0.17 m

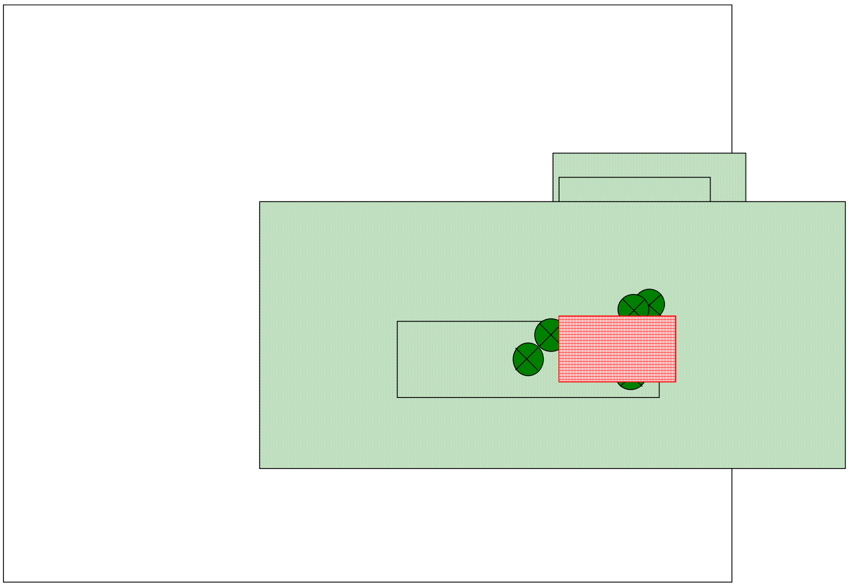

Figure 4 Sound bridge localization via sink positions (averaged from 200 Hz to 400 Hz).

Table 3 Localization of the excitation position at (X = 2.50 m, Y = 1.50 m) on the floating floor.

Frequency band [Hz]	Position estimated by the localization procedure
200 … 400	X = 3.24 ± 0.78 m Y = 1.50 ± 0.44 m
400 … 800	X = 2.72 ± 0.14 m Y = 1.48 ± 0.20 m

7. Conclusions

A PC-based and easy-to-use measuring system for structure-borne sound intensity and localization of sound bridges has been realized and tested. Although the test situations have been unfavorable (like often in reality) because of small damping of the plates, the sound bridges could be localized with an accuracy of 15 cm to 30 cm. Even the case of three simultaneously acting sound bridges was successfully accomplished. However, some knowledge and experience is still required in order to get optimal results. Localization of a sound bridge is more accurate, if the excitation is via the sound bridge, i. e. not on the plate where the measurements take place. Since the estimated uncertainties have occasionally turned out to be too optimistic, one might think about safer error bounds during future development. In addition, further tests with other types of building elements are intended.

Acknowledgements

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References

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