Comparison of Acoustic Holography Methods for Surface Vibration Reconstruction from a Vibrating Panel

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NOMENCLATURE

\( p \)  
Sound pressure

\( v_n \)  
Normal velocity

\( \omega \)  
Angular frequency

\( \rho \)  
Fluid or material density

\( G(P,Q) \)  
Green’s function

\( H \)  
Transfer function

\( F \)  
Spatial Fourier transform

\( G(k_x,k_y,z) \)  
Inverse propagator kernel

\( F_d \)  
Doppler frequency

\( \lambda \)  
Wavelength of laser beam

\( F_c \)  
Eigenfrequency

\( c \)  
Speed of sound

\( D \)  
Bending stiffness

\( E \)  
Young’s modulus

\( \nu \)  
Poisson’s ratio

ABSTRACT

Two different acoustic holography methods for surface vibration reconstruction are compared by experiment: Inverse Boundary Element Method (IBEM) and Planar Near-field Acoustical Holography (PNAH). While IBEM enables the estimation of surface vibration on arbitrary geometries, the PNAH method provides vibration estimates in a plane close to the structure under investigation. Both methods make use of acoustic near-field measurements. The quality of the surface vibration reconstruction from the acoustic holography methods are assessed for an experiment using a vibrating panel and compared to the results from using a Laser Doppler Vibrometry (LDV) method, where a point-by-point sampling of the structure’s surface is performed and the vibration directly obtained. Good agreement is found between absolute vibration levels determined by the different non-contact methods.

INTRODUCTION

Non-contact measurement techniques for vibration analysis have the advantage compared to more traditional transducer mounting methods that they totally eliminate mass loading and thereby do not change the structure’s inherent dynamics. Furthermore, they allow for doing measurements under demanding conditions like e.g. measuring on surfaces with high temperatures. As the different techniques have different unique advantages, non-contact measurement techniques are not “just” used for applications where traditional contact transducers are inapplicable, but also as a fast alternative to traditional contact measurement techniques.
In this paper, three different non-contact techniques are compared: IBEM, PNAH and Single-point LDV. As LDV is a well-established and accurate vibration measurement technique, this method serves here as a reference method for determining the validity of vibration distributions and absolute levels obtained by the IBEM and PNAH methods.

IBEM has previously been compared to the Scanning LDV (SLDV) method using a loudspeaker as measurement object [1] and to the Single-point LDV method using a vibrating panel as measurement object [2]. This paper is a further development of the latter by including PNAH, by using a complete LDV scan of the measurement surface for comparison and by further investigation of the differences between the techniques.

THEORY – INVERSE BOUNDARY ELEMENT METHOD

The Inverse Boundary Element Method (IBEM), based upon the boundary element method (BEM) in acoustics [3], is one of the most interesting novel non-contact vibration measurement techniques. The idea behind BEM is the possibility to express the sound pressure at a given location exterior to a radiating structure in terms of variables, usually sound pressure and normal velocity, defined on an arbitrary surface. In that way the 3D sound field outside a radiating structure can be simulated if sound pressure and normal velocity are known on the structure itself, i.e. on a 2D boundary.

\[ p_j(P) = \int_S (p(Q) \hat{c} G(P,Q) / \hat{c} n + j \omega p v_n(Q) G(P,Q)) dS(Q) \]  

\[ G(P,Q) = e^{-jkR / 4\pi R} , \quad R = |P - Q| \]

In mathematical terms, this relationship can be expressed as the Helmholtz integral equation:

where \( P \) and \( Q \) are a field point and a surface point, respectively, \( p \) denotes sound pressure, \( v_n \) is normal velocity and \( G \) is the Green’s function:

In order to make use of the Helmholtz integral equation, we must know both the sound pressure and the normal velocity on the surface \( S \) before we can compute the sound pressure at a field point \( P \). However, in many cases only for example the normal velocity is known so in this case one must solve for the unknown sound pressure on \( S \) before using equation (1). In practice a surface mesh of the boundary surface is made by a number of
interconnected elements, e.g. triangles or squares, and equation (1) can be written as a linear matrix system with the use of numerical integration. The process described here can be classified as a forward BEM problem.

In contrast to this approach, the IBEM uses acoustic sound field measurements around the structure to reconstruct the surface normal vibration and is based on a numerical model of the acoustic environment surrounding the structure. The numerical model relates the measured sound field around the structure, as represented by a vector of discrete sound pressure sampling points, to the surface normal velocity of the structure as represented by a vector of discrete surface velocity sampling points. These points correspond to the nodes of a surface mesh discretizing the surface of the structure. The model should thus include the structure under test and any other obstacles close to it and in many cases also the hard ground under the structure. The relation between field sound pressures and surface node velocities may be written in matrix-vector form as:

\[
\begin{bmatrix}
 p_1 \\
 p_2 \\
 \vdots \\
 p_m \\
\end{bmatrix} = \begin{bmatrix}
 H_{11} & H_{12} & \cdots & H_{1j} & \cdots & H_{1n} \\
 H_{21} & H_{22} & \cdots & H_{2j} & \cdots & H_{2n} \\
 \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
 H_{m1} & H_{m2} & \cdots & H_{mj} & \cdots & H_{mn} \\
\end{bmatrix} \begin{bmatrix}
 v_1 \\
 v_2 \\
 \vdots \\
 v_j \\
 \vdots \\
 v_n \\
\end{bmatrix}
\]

where \( p_i \) is the measured sound pressure at the \( i \)'th microphone and \( v_j \) is the surface normal velocity at the \( j \)'th node of the boundary element mesh. The relation between \( p_i \) and \( v_j \) is established through the transfer function \( H_{ij} \) determined numerically by the Boundary Element Method. Note that the linear system of equations is only valid at a single frequency and must therefore be recalculated for different frequencies.

The purpose of the IBEM algorithm is to reconstruct the normal velocity at every node from the measured field sound pressures. This is essentially an inverse problem involving inversion of the transfer function matrix of (3). The matrix inversion is done by imposing some sort of regularisation since the solution would otherwise become meaningless. This is a consequence of the matrix being almost singular for nearly every case. The physical explanation for this near-singularity is that evanescent source radiation information (radiation components corresponding to fast varying surface velocity components) dies out quickly when radiating from the structure, i.e. it doesn’t give rise to any pressure field far away from the source. Consequently this information can hardly be measured by the microphones and is therefore difficult to reconstruct especially in the presence of noise. In such a case it is better to avoid some of the evanescent information at the price of a reduced surface resolution.

In practice the linear system of equations is most often solved using an approach based on Singular Value Decomposition (SVD) of the matrix of transfer functions followed by a regularisation step essentially grouping the SVD components into useful and unwanted components. Computing the desired solution, i.e. the structural surface velocity vector, is then done via the set of useful components. Deciding on the number of useful components is, however, not trivial but some methods for automatic detection of this subset can be found [4]. Further details about the IBEM method may be found in [5] and [6].

The numerical sound field model used in IBEM assumes a harmonic, totally coherent sound field as input. In general, this is achieved by deriving a cross spectral sound field description from the measured field sound pressures, based on a number of reference signals representing the uncorrelated or partially correlated radiation mechanisms of the test object under investigation. To deal with partially correlated source mechanisms a principal component decomposition [7] of the sound field is carried out and each component then processed in turn by IBEM. Finally the individual results are added on a power basis to form the total result. However, when using a single reference it is in principle possible to include phase information in the resulting surface vibration output.
Another method for non-contact vibration measurement is the Planar Near-field Acoustical Holography (PNAH) method, sometimes also referred to as Spatial Transformation of Sound Fields (STSF) [7]. This method uses purely acoustic measurements in a plane near the structural surface to reconstruct the surface particle velocity. Reconstruction is only possible in planes parallel to the measurement plane and thus the method is best suited for planar structures. PNAH is based on the fact that in the wavenumber domain, under free-field conditions, calculation of the sound field in a plane \( z = z_m \) parallel to the measurement plane \( z = z_c \) amounts to multiplication with a simple kernel function. The mathematics behind PNAH may be summarized as:

\[
v(x,y,z_c) = F_x^{-1}F_y^{-1}\left[F_xF_y[p(x,y,z_m)]G(k_x,k_y,z_c - z_m)\right]
\]

(4)

where \( p(x,y,z) \) and \( v(x,y,z) \) are the sound pressure and particle velocity in the \((x,y)\)-plane at distance \( z \) from the source, \( F_x \) and \( F_y \) denote spatial Fourier transforms in the \( x \)- and \( y \)-directions respectively and \( G(k_x,k_y,z) \) is the inverse propagator kernel. In practice, because PNAH is an inverse problem in the same way as IBEM is, care must be taken when applying the propagator kernel and some sort of regularisation must be applied in order to prevent measurement noise from destroying the reconstruction.

The two-dimensional spatial Fourier transformations may be implemented using FFT which makes PNAH calculation extremely fast even for large arrays. Another practical aspect of PNAH is the windowing effects caused by applying a finite array. Such effects may be dealt with by applying spatial windowing functions to the measured field before the PNAH process. Still, the size of the array must be large enough to cover the full surface of the source (a new Statistically Optimal variant of PNAH overcomes this limitation [8]). Finally, spatial aliasing must be avoided by maintaining a spatial sampling distance of at least half the acoustical wavelength at the highest frequency of analysis. As in the case of IBEM, PNAH may be combined with the use of principal components to handle the case of multiple partially correlated or uncorrelated sources.

At this point it should be noted that while the LDV methods provide measurements of the actual surface vibration, the IBEM and PNAH methods provide an estimate of the vibration based on acoustic near-field measurements. Only the part of the vibration causing a measurable acoustic signal at the receiver microphones may be reconstructed by the methods. However, when considering structure-borne noise problems such an estimate is indeed relevant. Moreover, the IBEM method provides overall source location on arbitrary geometries without need for line-of-sight (the PNAH method is limited to planar geometries). Both methods allow for estimation of acoustic quantities like surface sound pressure and intensity. In addition, since conventional BEM can be used to simulate the radiated sound field if the structural vibration pattern is known, the result of an IBEM analysis provides an acoustic source model that may be used in simulations of acoustic radiation in different environments or of the effect on sound radiation of damping parts of the vibrating surface. Similar source modelling may be done via PNAH but again with the limitations of planar geometry.

**THEORY – LASER DOPPLER VIBROMETRY**

One of the most well-established and well-proven non-contact measurement techniques is based on Laser Doppler Vibrometers (LDVs), either a Single-point LDV, where one point is measured and the laser sensor head is moved to measure another point or a Scanning LDV (SLDV), where an internal system of mirrors position the laser beam at specified scan positions without moving the laser sensor head.

The LDV principle is based on interferometry, where a laser beam is divided into an internal reference beam and a measurement beam. The measurement beam is directed onto a vibrating test surface and the back-reflected light recombined with the internal reference beam. When the test surface moves, the path difference between the routes followed by the reference and measurement beams changes, resulting in light-intensity modulation of the recombined beam due to interference between the reference and the measurement beams. The frequency of the intensity modulation, known as the Doppler frequency \( F_d \), is directly proportional to the surface velocity \( v \) and the wavelength of the laser \( \lambda \), being 632.8 nm for a Helium-Neon laser:

\[
F_d = 2v / \lambda
\]

(5)
The recombined beam is split into two paths. A quarter-wave plate is used in one of the paths so that the two paths are in quadrature allowing the direction of motion to be determined. By mixing and demodulating the signals, a voltage output with mean value proportional to the surface velocity is obtained. This output is then fed into an analyzer for vibration analysis.

In addition to the before mentioned general advantages of using non-contacting measurement techniques, the LDV principle allows for measurement of structures containing inaccessible parts, measurement of large or distant structures and measuring in demanding environments such as high-radiation fields, high-voltage areas, clean rooms or wind tunnels. Furthermore, LDVs support higher frequency ranges than traditional contact transducers. Where a Single-point LDV can be the ideal choice when only a few points have to be measured, a SLDV provides additional benefits such as high spatial resolution and faster and more flexible data acquisition.

MEASUREMENT OBJECT

The measurement object was originally designed to simulate the interior of a car cabin for a study of measurement-based modelling of sound sources. It consists of a solid concrete tub of internal dimensions 0.75 m × 1.70 m × 0.60 m, giving an interior volume of 0.77 m³. The walls and bottom have a thickness of 0.10 m. The tub is closed by a tightly sealed steel plate of thickness 1 mm and dimensions 0.75 m × 1.70 m. Figure 2 shows pictures of the test object with and without the top cover steel plate mounted.

Figure 2. The measurement object with (left) and without (right) the steel plate mounted.

To get an idea of the dynamic behaviour of the test object, the Neumann eigenfrequencies, $f_c$, of the closed empty tub may be calculated as:

$$f_c = \frac{c}{2} \sqrt{\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2}, \quad n_x, n_y, n_z = 0, 1, 2...$$

(6)
where \( c \) is the speed of sound (343 m/s at 20 °C) and \( l_x, l_y \) and \( l_z \) are the interior dimensions of the tub. A number of the lowest eigenfrequencies are listed in Table 1.

<table>
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<th>( n_y )</th>
<th>( n_z )</th>
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Table 1. Neumann eigenfrequencies of the closed empty tub.

It follows that in the frequency range below 1 kHz a large number of cavity modes are present. Moreover, the modes are very lightly damped since almost no damping material is present inside the concrete tub. Although the exact boundary conditions of the top cover steel plate are unknown they can be assumed to lie somewhere between clamped and simply supported edges. By assuming simply supported edges one can get an idea of the frequency range of the plate modes. The eigenfrequencies of a simply supported rectangular plate of dimensions \( a \) and \( b \) and thickness \( h \) are given by:

\[
f_c = \frac{1}{2\pi} \sqrt{\frac{D}{\rho h}} \left[ \left( \frac{m\pi}{a} \right)^2 + \left( \frac{n\pi}{b} \right)^2 \right], \quad m, n = 1, 2, \ldots
\]

where \( D \) is the bending stiffness of the plate given by \( D = Eh^3/12(1-\nu^2) \), \( E \) is the Young's modulus and \( \nu \) is the Poisson's ratio of the plate material, and \( \rho \) is the density of the plate material. For steel the material parameters are \( E = 2.1\times10^{11} \text{ Nm}^2 \), \( \nu = 0.31 \) and \( \rho = 7.8\times10^{-3} \text{ kgm}^3 \). A number of modes and their corresponding eigenfrequencies calculated this way are listed in Table 2. Note that only odd-odd modes are listed since these will be the ones contributing the most to the sound radiation from the plate.

<table>
<thead>
<tr>
<th>( m )</th>
<th>( n )</th>
<th>( f_c ) (Hz)</th>
<th>( m )</th>
<th>( n )</th>
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<td>7</td>
<td>81</td>
<td>7</td>
<td>5</td>
<td>236</td>
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Table 2. Frequencies of the plate modes assuming simply supported edges.

It follows that already below 1 kHz the modal density of the top cover plate is very high. Moreover, since the plate is quite thin compared to the size of the cavity the acoustic and structural subsystems will be coupled to some degree. All in all these results indicate that the test object is a highly resonant and quite complicated vibro-acoustic system.

In the interior of the tub a loudspeaker was placed to excite the steel plate. Only the steel plate was assumed to vibrate. The loudspeaker was fed with a white noise signal having a 10 kHz frequency range. The sound pressure
level from the loudspeaker was chosen as a compromise between avoiding non-linear behaviour of the plate and excessive background noise at the microphone positions.

IBEM AND PNAH MEASUREMENT AND ANALYSIS

The setup for the IBEM and PNAH measurements is shown in Figure 3. A planar array configured with 12 x 7 B&K Type 4935 microphones was positioned in 12 locations to cover the total surface of the vibrating panel in order to spatially sample the sound field radiated. In total 42 x 21 = 882 microphone positions were sampled. In principle, for a general sound source, the sound field on all sides of the source should be sampled in the case of IBEM. However, since the present source was known to radiate mainly from the top cover it was decided to place microphones on this side only. To avoid spatial aliasing effects the microphone spacing should, as a guideline, be less than half the acoustic wavelength at the maximum analysis frequency. In the present setup the microphone spacing was chosen to be 50 mm, thus corresponding to an upper analysis frequency limit of 3.4 kHz.

The average distance to the source was also kept at 50 mm. This distance was chosen as a compromise between ensuring the highest possible surface vibration resolution with the given microphone spacing and at the same time ensuring sufficient decay of very fast spatially varying radiation components so that the spatial sampling criterion would indeed be fulfilled at the microphone positions [6]. Moreover, for IBEM the spacing should not be smaller than the mesh element size of the BEM mesh. The positions of all field sampling points relative to the test object geometry were furthermore measured, since this information is required for setting up the numerical BEM model relating the surface vibration to the field pressures. Note that the same measurement data was used as input for both the PNAH and IBEM.

![Figure 3. The IBEM/PNAH measurement setup (left) and numerical mesh model and field point positions (right).](image)

Each of the 84 microphones were connected to individual input channels of a B&K Type 3561 Intelligent Data Acquisition (IDA) front-end, which in turn was connected by LAN to a laptop PC running dedicated B&K data acquisition software. All microphones were individually calibrated before measurement. With the loudspeaker source running, simultaneous acquisition from all microphones was done using a sampling rate of 8192 Hz, corresponding to an upper frequency limit of 3.2 kHz. The measurement time was 30 seconds in each scan position. Following the measurement, a cross-spectral sound field description with 3200 frequency lines suitable as input for IBEM was calculated by FFT averaging. The output from a B&K Type 4935 microphone placed inside the tub, close to the loudspeaker source, was used as reference signal for all scan positions.

A boundary element surface mesh of the measurement object was constructed from a rough sketch but still including the main features of the object. The triangular mesh was designed to a maximum edge length of 45 mm.
As a rule of thumb, the edge length should not exceed one quarter of the acoustic wavelength at the maximum analysis frequency [6]. This means that the upper frequency limit for BEM with this mesh was 2 kHz. The resulting mesh consisted of 3444 elements and 1724 nodes as shown in Figure 3. Note that this figure also shows the microphone positions relative to the test object geometry.

The PNAH and IBEM calculations were carried out using dedicated B&K software. As stated earlier, in both cases regularization must be applied when performing the inverse sound field calculations. In this work a fixed regularization dynamic range of 40 dB was applied in both cases. This range was found to be adequate based on inspection of result data.

LASER MEASUREMENT AND ANALYSIS

The setup for the LDV measurement is shown in Figure 4. The instrumentation consisted of the Ometron VH300+ Laser Doppler Vibrometer Type 8329, the Portable PULSE™ Type 3560-B front-end and a laptop PC running dedicated PULSE™ data acquisition and analysis software. The LDV was mounted on a tripod that was positioned on a wooden frame with four soft rubber feet. This arrangement eliminated vibrations being transferred to the LDV and ensured that the laser beam was practically perpendicular to the panel surface at all measurement points. No cosine corrections needed to be applied. The precise distance between the LDV and the panel was not critical but was held at approximately 0.945 m corresponding to one of the optimum working distances. The resulting focus depth was approximately 11 mm.

A rectangular mesh consisting of 462 points (14 x 33) and with a resolution of 50 mm in both directions was created to cover the plate surface. The measurements were performed directly on the steel surface without dithering – a technique by where the laser beam is moved to a nearby position until sufficient light is reflected to optimize the signal-to-noise ratio – or treatment of the panel's surface (paint, powder, reflective tape etc.) to enhance reflectivity. FFT analysis in 3.2 kHz, 3200 frequency lines and with 50 averages per mesh point was performed.
RESULTS AND DISCUSSION

Surface normal velocity results obtained with the three methods are compared in two different ways. For a few selected fixed frequencies the spatial distribution of velocity is compared via contour plots. Additionally, for selected fixed positions, corresponding velocity spectra are compared. Figure 5 shows example surface velocity contour plots obtained using the IBEM (Figure 5.A), the PNAH (Figure 5.B) and the LDV (Figure 5.C) methods at 142 Hz. At this frequency clearly the (5,5) mode is dominating the vibration pattern.

Figure 5. Surface velocity contour plots of (5,5) mode at 142 Hz obtained with IBEM (A), PNAH (B) and LDV (C).

Figure 6. Surface velocity contour plots of (5,7) mode at 162 Hz obtained with IBEM (A), PNAH (B) and LDV (C).
Figure 6 shows similar plots at 162 Hz where the (5,7) mode is dominating. Clearly the qualitative agreement between the results is good in both cases. In particular, the agreement between the results obtained with IBEM and PNAH are excellent with detailed information being represented in almost exactly the same way in both cases. The agreement with the velocity distribution obtained with LDV is also quite good, with clear identification of the vibration patterns. Differences between the results obtained with LDV on one hand and IBEM/PNAH on the other may be explained by the fact that the IBEM and PNAH methods provide only an estimate of the surface velocity based on sound radiation. In other words, only the parts of the vibration pattern creating measurable acoustic signals at the receiver microphones may be reconstructed. Moreover, it should be noted that the LDV measurement points were positioned in the interior of the plate (see Figure 8) whereas the IBEM and PNAH methods provide results all the way to (and beyond) the plate border. Also, the LDV results contain phase information which is the reason for the alternating colors in the LDV plots. Finally sources of error such as position errors and non free-field conditions may affect the quality of the results.

Comparing the IBEM and PNAH methods to the LDV method, it is already clear that they do not yield identical surface vibration maps since the IBEM and PNAH methods provide only an estimate based on sound radiation. Only the slowly spatially varying (smooth) surface vibration components may be reconstructed by the IBEM and PNAH methods, since the fast varying components generate exponentially decaying acoustic waves that are difficult to pick up and reverse. The obtainable resolution depends on the signal-to-noise ratio of the decaying waves at the microphone positions. This is clearly illustrated by the surface contour plots shown in Figure 7 corresponding to an example analysis frequency of 974 Hz. Again, the agreement between IBEM and PNAH is excellent. From these results it appears as if only the borders of the plate are vibrating significantly. However, the LDV method provides a very different result with a very fast spatially varying surface velocity distribution of equal absolute levels throughout the entire plate area. The physical explanation for this discrepancy is that as frequency increases, the structural wavelengths of the plate vibrations become so small compared to the acoustical wavelength that hydrodynamical “short circuiting” largely prevents the plate from radiating sound efficiently, except at the plate borders where no cancellation takes place. Thus, in the interior of the plate, exponentially decaying waves are emitted that decay below the dynamic range capabilities of the IBEM and PNAH methods, and as a result no vibration is detected in this area. While this phenomenon is also present at the lower example frequencies 142 Hz and 162 Hz, the decay rate of the radiated waves at these frequencies is within the dynamic range of IBEM/PNAH and the surface velocity patterns are thus reconstructed well at these frequencies.
It is interesting to use LDV as a reference method in order to investigate further the accuracy of the absolute surface normal velocity estimate (as a function of frequency) obtained by the IBEM and PNAH methods. Because of the spatially averaged nature of IBEM and PNAH results these are not directly comparable to the single-point measurements obtained using LDV. To compensate for this, spatial averaging of the LDV results was applied before comparison.

Two areas on the plate surface were selected for comparison. The first area (A) was positioned in the middle part of the plate while the second area (B) was positioned close to the plate border. The position and size of the areas are shown in Figure 8. Within each area a number of LDV measurement results were averaged to produce an average vibration level representing the given area. In a similar way average IBEM and PNAH results were obtained by reading off IBEM nodal values and PNAH result values within the area and averaging the data to produce a single value for the given area.

Figure 9 shows the spatially averaged surface velocity at area A (plate centre) as determined by the IBEM, PNAH and LDV methods. The agreement between the absolute levels as determined by the three methods is quite good in the frequency range between 30 Hz and 600 Hz. Again, the agreement between IBEM and PNAH is excellent, whereas the agreement between IBEM/PNAH and LDV is characterized by the LDV method giving - in general - slightly higher absolute vibration levels than the other methods. Above 600 Hz the difference in absolute levels between IBEM/PNAH and LDV becomes more outspoken. Below 30 Hz results cannot be compared due to the use of high-pass filters in the measurement chains. The upper frequency limit of 1 kHz was chosen because of the calculation time of the IBEM method.

Figure 10 shows the spatially averaged surface velocity at area B (plate border) as determined by the three methods. Below 600 Hz the agreement between absolute levels obtained with the three methods follows the same pattern as for area A. However, at frequencies above 600 Hz the differences between levels obtained with IBEM/PNAH and LDV become significantly smaller than those in the case of area A. This is again a consequence of the fact that cancellation of sound radiation takes place in the plate interior but not at the plate border. Thus at the plate border significant radiation information may be picked up by the microphones, and the agreement between levels at the plate border may therefore be expected to be better than at the plate centre as frequency increases.
Figure 9. Comparison of vibration levels determined using IBEM, PNAH and LDV at area A.

Figure 10. Comparison of vibration levels determined using IBEM, PNAH and LDV at area B.
Two different acoustical holography methods for surface vibration reconstruction have been compared by experiments on a vibrating panel: The Inverse Boundary Element Method (IBEM) and Planar Near-field Acoustical Holography (PNAH). The IBEM method allows for vibration reconstruction on arbitrary 3D surfaces while PNAH is limited to 2D planar surfaces. Although quite different in principle and implementation the two methods have shown excellent agreement in terms of both spatial vibration distribution and absolute measured levels.

Results obtained with the IBEM and PNAH methods have furthermore been compared to results obtained by the well-established Laser Doppler Vibrometry (LDV) method for non-contact vibration measurement. Good agreement both in spatial distributions and absolute levels has been found in the cases where the plate vibration generates sufficient sound field information at the IBEM/PNAH receiver microphones. Conversely, deviations between levels obtained with IBEM/PNAH and with LDV may be explained by the fact that only the part of the plate vibration causing significant radiation may be reconstructed by the holography methods.

The IBEM and PNAH methods provide a limited resolution estimate of the surface vibration from acoustic measurements. This means that for detailed surface vibration analysis the LDV method is superior – especially at high frequencies where the demands on mesh density and microphone spacing in IBEM become prohibitive. However, for overall source location and structure-borne sound analysis, the IBEM method is a viable alternative to LDV. Moreover, the surface BEM solution obtained with IBEM may be used directly in further simulations. Future work will include validation of measurements on industrial applications like a running car engine.

REFERENCES


