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NEAR-FIELD LIMIT IN POSITIONING THE MICROPHONE FOR PRESSURE MEASUREMENTS IN USING THE NEARFIELD ACOUSTICAL HOLOGRAPHY

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ABSTRACT
The recently developed BEM-based NAH (nearfield acoustical holography) is a useful technique for identifying the sound source of vibrating objects. The acoustic parameters of a sound source can be reconstructed by using the vibro-acoustic transfer matrix, which is determined by means of BEM, and the sound pressure measured in the nearfield. Theoretically, one can come up with a very nice reconstructed result as the field plane gets near to the source surface. However, when a microphone is placed in the very close nearfield of the source surface, the scattering, reflection, or resonance in the gap between the source and the microphone can distort the acoustic field, and therefore, the measured field pressure would differ from the actual one in the absence of the microphone. In order to analyze this problem, the interference effect of the microphone is numerically calculated by using the non-singular BEM that yields very small error in the nearfield. From this analysis, it is found that the prediction error of the field pressure decreases firstly and then increases as the microphone approaches the vibrating surface from the farfield to the close nearfield. It is noted that the microphone should be separated from the source surface by at least a diameter of the microphone for an error ratio less than about 2%. This means that if one wants to put a microphone in the very close nearfield, a microphone with small diameter should be used

1 - INTRODUCTION
The BEM-based NAH technique is known to be very powerful in dealing with the sources having irregular shaped boundaries [1-4]. When the vibro-acoustic source field is reconstructed by using this conformal NAH, one tends to position the sensors as close as possible to the source surface in order to get rich information on the non-propagating wave components. If the microphones are placed in a very close nearfield for reducing the reconstruction error, the scattering, reflection, or resonance in the space between the vibrating sound source and the microphone can distort the acoustic field. In this case, the measured field pressure can differ from the actual radiating pressure. In this paper, the interference effect of the microphone is analyzed in order to characterize this problem and to suggest a guideline to reduce the measurement error.

2 - ACOUSTIC HOLOGRAPHY EQUATION
Discrete form of acoustic boundary integral equation can be used in realizing BEM and its matrix-vector form can be written as

$$\{p\}_f = [D]_f \{p\}_s + [M]_f \{v\}\text{, in the domain,} \tag{1a}$$

$$[D]_s \{p\}_s = [M]_s \{v\}_s \,, \text{ on the boundary.} \tag{1b}$$

Here, $\{p\}_s$, $\{v\}_s$ are the pressure and velocity vector on the surface, respectively, $\{p\}_f$ denotes the field pressure vector in the domain, $[D]_s$, $[M]_s$ mean the dipole and monopole matrices on the surface, and $[D]_f$, $[M]_f$ are those corresponding to field pressures, respectively. From Eqs. (1a) and (1b), the following field pressure can be described only by the surface velocity provided $[D]_s^{-1}$ exists:

$$\{p\}_f = \left([M]_f + [D]_f [D]_s^{-1} [M]_s \right) \{v\}_s \equiv [G] \{v\}_s \tag{2}$$

Here, $[G]$ is the vibro-acoustic transfer matrix correlating the surface normal velocity and the field pressure that contains the geometric information of the system. If the field pressure at m points is known, the surface velocity at n ($\leq m$) nodes can be uniquely determined. By virtue of the least-squared solution and the singular value decomposition (SVD), the inverse of Eq. (2) can be expressed as follows:

$$\{v\}_s = [G]^+ \{p\}_f = \left([G]^H [G] \right)^{-1} [G]^H \{p\}_f = [W] [\Lambda]^{-1} [U]^H \{p\}_f \tag{3}$$

Here, $[G]^+$ denotes the $n \times m$ pseudo-inverse matrix of $[G]$ and the superscript H signifies the Hermitian operator. By the SVD, the transfer matrix $[G]$ can be decomposed by $[G] = [U] [\Lambda] [W]^H$, where $[\Lambda] = diag\,(\lambda_1, \lambda_2, \ldots, \lambda_n)$, $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_n \geq 0$. Here, λ_i denotes the singular values of $[G]$. The columns of $[U]$ and $[W]$ comprise the left and right singular vectors of $[G]$. Eq. (3) enables the reconstruction of the velocity field of source surface, in principle, if the near-field pressures are measured and the transfer matrix is generated by BEM. Now, using $\{v\}_s$, it is possible to determine other acoustic parameters on the surface or in the field such as the pressure, velocity, surface impedance, acoustic intensity or acoustic power distribution.

3 - SINGULARITY IN THE NEARFIELD

When the conventional BEM is utilized for NAH simulation, the field pressures can not be predicted accurately when the field points are located within about 20% of characteristic length of BEM model [5]. This inaccuracy is generated from the singular behavior of Green function near the numerical integration points, and increases as the field points move close to the surface. Consequently, the transfer matrix cannot be built precisely in this range, and significant error can be included in the restored results. In order to realize the experimental source identification by using the BEM-based NAH, the field pressures should be measured by using the microphones. Theoretically, the reconstruction error should be reduced with closing the field points to the surface because the ratio of measured field pressure to the background noise can be increased, the non-propagating wave component can be included in the measurement, and the singularity of transfer matrix can be further reduced. Consequently, in order to collect such rich information on the sound signal from the source, the microphones should be placed as close as possible to the source surface. In this situation, the acoustic interference effect between the microphones and source surface becomes influential to the final reconstructed results. By employing the nonsingular BEM [5], the very accurate field parameters can be calculated in the nearfield.

4 - INTERFERENCE EFFECT DUE TO THE MICROPHONE

To analyze the interference effects of microphone for measuring the field pressure in the nearfield, the nonsingular BEM simulation was carried out. The simulation model is illustrated in Fig. 1(a). A baffled piston of 13.2 mm diameter was assumed as the sound source, and a 1/2-inch microphone was modeled by a cylinder of 13.2 mm diameter and 5 mm height. The maximum frequency limit of BEM model was about 20.8 kHz for $\lambda/10$ criterion because the linear elements were adopted. Three sets of phase condition of the piston were considered as shown in Figs. 1(b)-(d). For set-I, the piston was vibrating with in-phase at all nodes. For sets-II and III, two and four segments of the piston were vibrating out-of-phase, respectively. If the pressures on the vertical axis of the piston are compared, the results cannot be observed because the on-axis pressures are canceled by the opposite phase condition. In this analysis, when the origin is the center of the piston, the pressures calculated at (x, y, z)=(1, 1, 1) mm are compared in Fig. 2 for several different distances between the microphone and the source surface. When the microphone is located far enough from the source, the field pressure converges to the pressure level in the absence of the microphone. But, if the microphone is placed closely to the source, the pressure level is increased and the resonance occurs in the high frequency range. The pressure amplitudes of the out-of-phase conditions are reduced very much compared with those of in-phase condition while the overall trend is the same. At 1 kHz, the error ratio of the field pressure is compared in Fig. 3. Note that the prediction error increases as approaching the microphone to the vibrating surface in the nearfield, and the distance between the microphone and the source surface should be larger than the diameter of the microphone in order to get an error ratio less than 1.7%. Therefore, the microphone should be located at least its diameter away from the source surface in order to prevent the unwanted interference effect in the measurement. If one wants to place the microphone in the very close nearfield, the diameter of the microphone should be as small as possible.

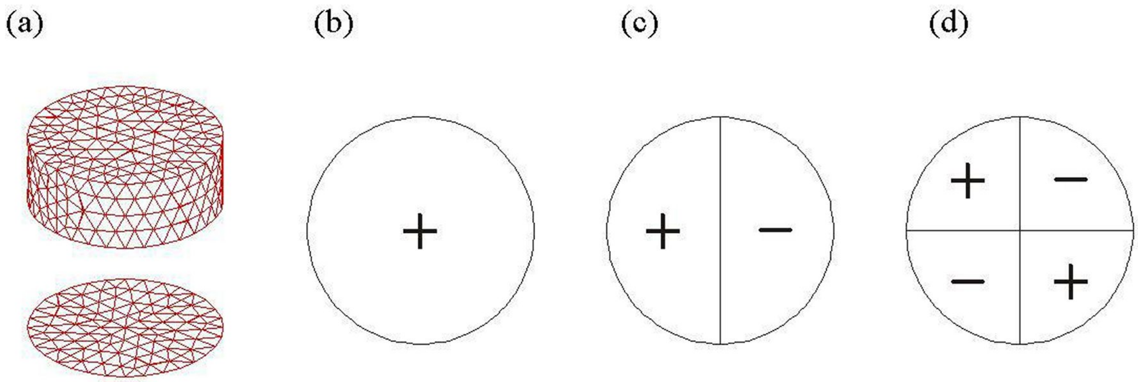

Figure 1: (a) BEM model of a baffled piston and a microphone (diameter of microphone = 13.2 mm, height of microphone = 5 mm, 428 nodes, 818 linear triangular elements), and the phase sets of the piston are: (b) set-I; (c) set-II; (d) set-III.

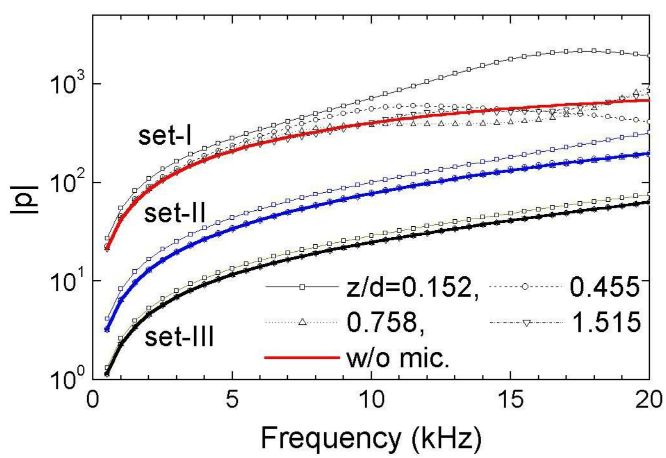

Figure 2: Amplitude of field pressure at $(x,y,z) = (1,1,1)$ mm for a baffled piston by varying the distance of microphone from the source surface (z = relative distance of the microphone, d = diameter of the microphone).

5 - CONCLUSIONS

In this study, the interference effect of the microphone is analyzed in the nearfield. When the microphone is placed in the very close nearfield of the source surface, the reflection or resonance between the vibrating sound source and the microphone can distort the acoustic field. It is found that the microphone should be placed at least its diameter away from the source surface in order to reduce the interference error of the measured field pressure less than 2%. If one wants to measure the field pressure accurately in the very close nearfield, the microphone with small diameter should be employed. It is already shown in the vibroacoustic problems that the nearfield error caused by the singularity in conventional BEM can be greatly reduced by the use of nonsingular BEM. However, in the viewpoint of measurement, one should keep in mind that the meaningful measurement by the microphone placed in the nearfield is subject to the error due to the interference between the microphone and the source surface.

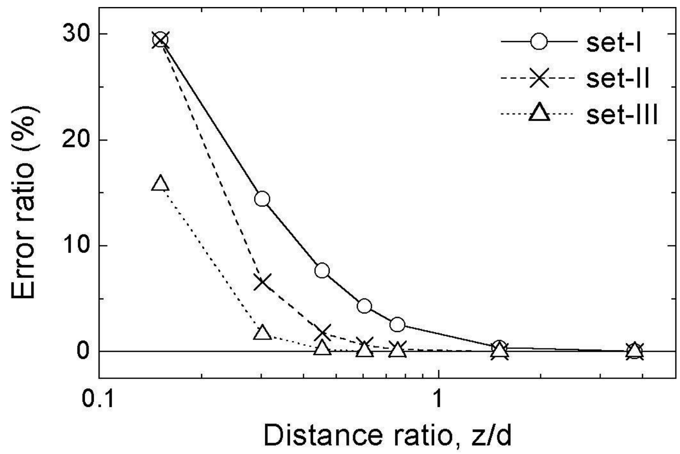

Figure 3: Error ratio of field pressure at (x,y,z) = (1,1,1) mm for a baffled piston by varying the distance of microphone from the source surface (1 kHz, z = relative distance of the microphone, d = diameter of the microphone).

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