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Transmission of a spherical sound wave through a single-leaf wall: Mass law for spherical wave incidence

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Abstract

This paper examines the sound insulation of a single-leaf wall driven by a spherical wave. The transmitted sound field of an infinite elastic plate under a spherical wave incidence is theoretically analyzed and insulation mechanisms are considered. The displacement of the plate is formulated using the Hankel transform in wavenumber space and the transmitted sound pressure in the far-field is obtained by Rayleigh's formula in an explicit closed form. Moreover, a reduction index is also derived in a closed form by introducing an approximation into the vibration characteristics of the plate. Deterioration of the insulation performance under the spherical wave incidence is caused by an apparent decrease of wall impedance that depends on the directivity of the transmitted sound wave. The mass law for a spherical wave incidence is different from that for a normal plane wave incidence: doubling the weight of the wall or the frequency gives an increase of 3 dB (c.f. 6 dB for a normal plane wave incidence), which is also smaller than the field incidence mass law.

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I. INTRODUCTION

The fundamental theory of the mass law for the sound insulation of a single-leaf wall is widely used in architectural acoustics today[1]. The mass law is simply derived from the relationship between a normal plane wave incidence and the mechanical impedance of an infinite plate, and indicates that doubling the weight of the wall or the frequency yields a 6 dB increase in the reduction index.

The normal incidence mass law has been conventionally developed into random incidence conditions[2] by considering oblique incidence, because normal incidence is not practical for evaluating actual walls. Random incidence is obtained by averaging the transmission coefficients for oblique incidences over a hemisphere. This approach, which is based on a completely diffuse sound field, does not fully reflect the actual sound field incidence conditions in rooms, and so various methods of truncating the angle of incidence up to a certain limit angle have been proposed.[3, 4].

The angle of incidence also affects the bending vibration of the plate, which is well known as the coincidence effect. When elastic plates are accompanied by bending vibrations due to an oblique plane wave incidence, the reduction index becomes lower than the mass law above a critical frequency. A fundamental theory for the range above the critical frequency has been established,[5] and a number of researchers have developed it further[6, 7].

In order to increase the insulation performance of walls, various multiple-leaf walls have been proposed and widely used in actual buildings. For example, the insulation characteristics of a double-leaf wall, each of which is an isolated single-leaf wall, are basically governed by the sum of the mass law of each leaf. In practice, sound is transmitted via the structural coupling and the acoustic coupling due to the air between the two leaves and so the insulation performance is lower than that expected by a simple sum of the mass law[8]. Since the coupling mechanisms between leaves are very complicated, a number of theoretical and empirical models for predicting the sound insulation have been proposed.[9, 10]

In this way, the mass law of a single-leaf wall is the fundamental principle of sound insulation in architectural acoustics, which consider various plane wave incidences, i.e. normal, oblique and diffuse (random). In actual buildings, however, a wall may be excited by a small sound source nearby, in which case, the wall is expected to be driven not by a plane wave but by a spherical wave. Takahashi et al.[11] initially analyzed the sound insulation for a spherical wave incidence. In the literature, they gave a numerical solution for executing the wavenumber space integral for the transmitted sound power. Based on numerical examples, they concluded that the reduction index for the spherical wave incidence was lower than that for the plane wave incidence. Villot et al.[12] also studied the transmission of sound through a wall excited by a small sound source by using a numerical solution, and obtained similar results.

As described above, the sound insulation for spherical wave incidence has been investigated to some extent, but neither the reason why the reduction index for a spherical wave is lower than that for a plane wave, nor the quantitative difference between them is clear. To gain a physical insight into the differing insulation performance between a spherical wave incidence and normal plane wave incidence, this paper theoretically analyzes the transmitted sound field of an infinite elastic plate driven by a spherical wave, and obtains a solution in an explicit closed form. Using the solution, the insulation mechanism under the spherical wave incidence is clarified. Furthermore, a mass law formula for a spherical wave incidence is derived and discussed in comparison with that for normal and diffuse plane waves.

II. THEORY

Consider an infinite elastic plate lying in the plane, z=0, in Fig. 1, that vibrates under spherical wave incidence from a point source, (0, 0, d_s). The sound pressure, $p_1(\mathbf{r})$, at a certain point, $\mathbf{r}$, in Region I is expressed by the following integral:

$$p_1(\mathbf{r}) = p_0(\mathbf{r}) + p_0'(\mathbf{r}) + \iint_{S_1} \frac{\partial p_1(\mathbf{r}_0)}{\partial n_0} G(\mathbf{r}\,|\,\mathbf{r}_0) dS_0 , \tag{1}$$

where $p_0(\mathbf{r})$ is the direct sound pressure from a point source and $p'_0(\mathbf{r})$ is the pressure contributed from its image source. The double integral denotes the integral over all regions of the boundary, i.e., the plate's source side surface, S_1 and n_0 denotes the outward normal of the region I. G($\mathbf{r}|\mathbf{r}_0$) denotes Green's function satisfying the Neumann condition for a single boundary with infinite extent, and is as follows:

$$G(\mathbf{r}\,|\,\mathbf{r}_0) = \frac{\exp(ik_0\,|\,\mathbf{r}-\mathbf{r}_0\,|)}{4\pi\,|\,\mathbf{r}-\mathbf{r}_0\,|} + \frac{\exp(ik_0\,|\,\mathbf{r}-\mathbf{r}_0'\,|)}{4\pi\,|\,\mathbf{r}-\mathbf{r}_0'\,|} , \tag{2}$$

where, k_0 is the acoustic wavenumber in air with ω the angular frequency and c_0 the sound speed in air. The time dependence of $\exp(-i\omega t)$ is suppressed throughout. In region II, the sound pressure at a certain point, $\mathbf{r}$, $p_2(\mathbf{r})$ is written in a similar form:

$$p_2(\mathbf{r}) = \iint_{S_2} \frac{\partial p_2(\mathbf{r}_0)}{\partial n_0} G(\mathbf{r}\,|\,\mathbf{r}_0) dS_0 , \tag{3}$$

where, the double integral in this equation denotes the integral over all regions of the boundary, i.e., the plate's back side surface, S_2, and n_0 denotes the outward normal in region II. The boundary conditions on the plate surfaces are:

$$\left.\frac{\partial p_1(\mathbf{r})}{\partial \mathbf{n}_0}\right|_{z=0} = -\left.\frac{\partial p_1(\mathbf{r})}{\partial z_0}\right|_{z=0} = -\rho_0 \omega^2 w(\mathbf{r}) : \text{ source side}, \tag{4}$$

$$\left.\frac{\partial p_2(\mathbf{r})}{\partial \mathbf{n}_0}\right|_{z=0} = \left.\frac{\partial p_2(\mathbf{r})}{\partial z_0}\right|_{z=0} = \rho_0 \omega^2 w(\mathbf{r}) : \text{back side}, \tag{5}$$

where $w(\mathbf{r})$ is the displacement of the plate and ρ_0 is the air density. Considering these conditions and using the cylindrical coordinate system, $\mathbf{r}=(\rho, z)=(r, \phi, z)$ and $\mathbf{r}_0=(\rho_0, z)=(r_0, \phi_0, z_0)$, $p_1(\mathbf{r})$ and $p_2(\mathbf{r})$ become:

$$p_1(\mathbf{r}) = p_0(r,0) + p_0'(r,0) - \rho_0\omega^2 \int_0^\infty W(k) \frac{\exp(-\sqrt{k^2 - k_0^2}\,|z|)}{\sqrt{k^2 - k_0^2}} J_0(kr)kdk\,, \tag{6}$$

$$p_2(\mathbf{r}) = \rho_0\omega^2 \int_0^\infty W(k) \frac{\exp(-\sqrt{k^2 - k_0^2}\,|z|)}{\sqrt{k^2 - k_0^2}} J_0(kr)kdk\,, \tag{7}$$

where the polar angle, ϕ is suppressed because the problem is axisymmetrical. J_0 denotes the Bessel function of order zero and k is the transform variable. $P_j(k)$ and $W(k)$ are the angular spectrums with respect to r of $p_j(r)$ and $w(r)$, respectively, as defined by the following Hankel transform pairs:

$$\begin{cases} P_j(k,z) = \int_0^\infty p_j(r,z) J_0(kr)rdr \quad j = 1,2 \\ p_j(r,z) = \int_0^\infty P_j(k,z) J_0(kr)kdk \quad j = 1,2 \end{cases}, \tag{8}$$

$$\begin{cases} W(k,z) = \int_0^\infty w(r,z) J_0(kr)rdr \\ w(k,z) = \int_0^\infty W(r,z) J_0(kr)kdk \end{cases}. \tag{9}$$

Since the pressure of spherical waves from the real and image source become identical on the plate's surface, i.e., $p_0(r)=p'_0(r)$ on $z=0$, these can be written by considering the amplitude of the spherical wave from a unit power point source, i.e., $(8\pi\rho_0 c_0)^{1/2}$:

$$p_0(r,0) = p_0'(r,0) = \frac{\sqrt{8\pi\rho_0 c_0}\, \exp(-ik_0\sqrt{r^2 + d_s^2})}{4\pi\sqrt{r^2 + d_s^2}}\,. \tag{10}$$

The plate is forced into vibration by the difference in sound pressure between both sides of the plate. In accordance with the classical thin plate theory, the equation of motion for the plate is as follows:

$$(D\nabla^4 - \rho_p h\omega^2)w(r) = p_1(r,0) - p_2(r,0), \tag{11}$$

where $D=E(1\text{-}i\eta)h^3/12(1\text{-}\mu^2)$ is the flexural rigidity of the plate with E Young's modulus, h the thickness, η the loss factor μ the Poisson's ratio and ρ_p the density of the plate. Solving Eqs. (6), (7), (10) and (11) for $W(k)$ by using the Hankel transform gives the displacement of the plate in the wavenumber space[13]:

$$W(k) = \frac{2\sqrt{8\pi\rho_0 c_0}\exp[-d_s\sqrt{k^2-k_0^2}]}{4\pi\sqrt{k^2-k_0^2}}\left[2\frac{\rho_0\omega^2}{\sqrt{k^2-k_0^2}} - (Dk^4 - \rho_p h\omega^2)\right]^{-1}. \tag{12}$$

The transmitted sound pressure, $p_2(\mathbf{r})$, can be calculated by substituting $W(k)$ into Eq. (7), however, the integral in this equation cannot generally be executed by analytical means. The chief purpose of the analysis is to obtain a closed form solution. Therefore, the following Rayleigh's formula for far-field pressure should be employed[14]:

$$p_2(r,\theta) \cong \rho_0\omega^2 W(k_0\sin\theta)\frac{e^{ik_0 r}}{r}. \tag{13}$$

Substituting $W(k)$ into Eq. (13) gives an asymptotic solution to the far-field transmitted sound pressure, $p_2(r,\theta)$ in region II, which is:

$$p_2(r,\theta) \cong -i\frac{\sqrt{8\pi\rho_0 c_0}}{K(\omega)}\frac{\exp[ik_0(r + d_s\cos\theta)]}{4\pi r}, \tag{14}$$

where

$$K(\omega) = 1 + i\frac{\cos\theta}{2\rho_0 c_0\omega}(Dk_0^4\sin^4\theta - \rho_p h\omega^2). \tag{15}$$

In this equations, the closed form of the transmitted wave is obtained from Rayleigh's formula for far-field pressure which has the origin as the coordinate system, and the system's transfer function, $K(\omega)$, includes θ, which denotes the angle between the direction of the receiving point and the negative direction of the z-axis. This means that the transmitted wave has directivity even for a non-directional spherical wave incidence. This should be distinguished from an oblique plane wave incidence, in which the transmitted wave depends on the angle of incidence (see Fig. 1).

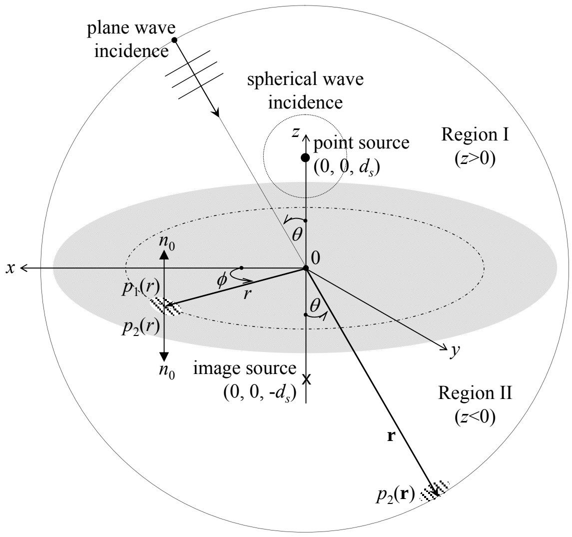

FIG. 1 Analytical model in cylindrical coordinates. An infinite elastic plate (shaded) lies in the plane, z=0. The plate vibrates under spherical wave incidence from a point source, (0, 0, d_s).

III. REDUCTION INDEX AND NUMERICAL EXAMPLES

The reduction index for a spherical wave incidence, $R_{spherical}$, can be defined by:

$$R_{spherical} = 10\log_{10}\frac{\Phi_i}{\Phi_t}, \tag{16}$$

where Φ_i is the total sound power incident on the entire surface of the infinite elastic plate, i.e., Φ_i=1/2. The transmitted sound power, Φ_t, is obtained by integrating the radial intensity, $|p_2(r,\theta)|^2/2\rho_0 c_0$, over a hemisphere of radius r:

$$\Phi_t = \frac{r^2}{2\rho_0 c_0}\int_0^{2\pi} d\phi \int_0^{\pi/2} |p_2(r,\theta)|^2 \sin\theta\, d\theta,\ k_0 r >> 1. \tag{17}$$

Clearly, the reduction index for a spherical wave incidence is equivalent to that for a plane wave incidence.

A typical numerical example calculated by Eq. (16) is shown in Fig. 2 and compared with the reduction index for the diffuse incidence by Eq. (24) (see section IV. B). The behavior of the reduction index for the spherical wave incidence is very similar to that for the diffuse incidence, however, its values are lower at all frequencies. These tendencies almost agree with the discussions given in previous papers[11, 12]. Note that the author's theory shows fairly good agreement with Takahashi et al.'s theory[11] in this example (see Fig. A in Appendix). The behavior of a significant notch around 1.8 kHz caused by the coincidence effect is also the same as the diffuse incidence. The critical frequency, f_c, is obtained when the imaginary part of $K(\omega)$ becomes zero with $\theta=\pi/2$ in Eq. (15), hence:

$$f_c = \frac{1}{2\pi}\sqrt{\frac{\rho_p h c_0^4}{D}}. \tag{18}$$

This frequency corresponds to the critical frequency for the diffuse plane wave incidence condition[5].

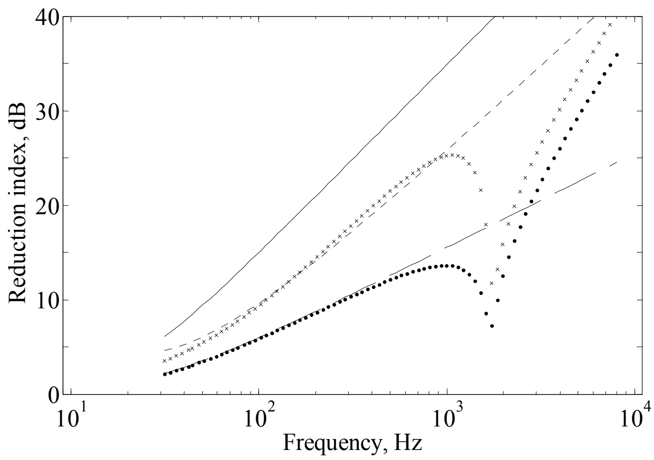

FIG. 2 Numerical examples of the reduction index for spherical wave incidence (•), normal plane wave incidence (solid line) and diffuse plane wave incidence (×). The parameters of the plate are E=6.18×10^9 N/m^2, h=0.012 m, η=0.01 μ=0.03 ρ_{p}=600 kg/m^3. The mass law for spherical wave incidence (broken line) and diffuse plane wave incidence (dashed line) are also plotted.

IV. MASS LAW FOR SPHERICAL WAVE INCIDENCE

A. Comparison with a normal plane wave incidence

In order to gain a physical insight into the insulation mechanism for spherical wave incidence, Eq. (14) should be simplified, because the integral in Eq. (17) cannot generally be executed by analytical means. Hence, neglecting the effect of the flexural rigidity, D, in Eq. (15), $p_2(r,\theta)$ becomes:

$$p_2(r,\theta) \cong \frac{\sqrt{8\pi\rho_0 c_0}}{1+\dfrac{-im\omega\cos\theta}{2\rho_0 c_0}} \frac{\exp[ik_0(r+d_s\cos\theta)]}{4\pi r}, \tag{19}$$

where m=$\rho_p h$ is the surface density of the plate. This approximation is valid at frequencies below the critical frequency. In this equation, “the wall impedance, $-im\omega$, multiplied by $\cos\theta$” can best be understood such that the wall impedance becomes apparently small depending on the directivity of the transmitted sound wave. In comparison, the transmitted sound pressure, p_{normal}, of a wall for a normal plane wave incidence with unit amplitude is given by:

$$p_{normal} = \frac{1}{1+\dfrac{-im\omega}{2\rho_0 c_0}} \exp(ik_0 z)\,. \qquad (20)$$

In this case, the wall impedance is constant because of its single directivity.

Now, when $p_2(r,\theta)$ is expressed by Eq. (19), the integral in Eq. (17) is analytically executed as follows:

$$\Phi_t = \frac{\pi r^2}{\rho_0 c_0} \int_0^{\pi/2} \left| \frac{\sqrt{8\pi\rho_0 c_0}}{1+\dfrac{-im\omega\cos\theta}{2\rho_0 c_0}} \frac{\exp[ik_0(r+d_s\cos\theta)]}{4\pi r} \right|^2 \sin\theta\, d\theta = \frac{1}{2} \frac{\tan^{-1}\dfrac{m\omega}{2\rho_0 c_0}}{\dfrac{m\omega}{2\rho_0 c_0}}\,. \qquad (21)$$

Hence, the reduction index for a spherical wave incidence, $R_{spherical}$ can be written as:

$$R_{spherical} = 10\log_{10}\left(\frac{m\omega}{2\rho_0 c_0}\right) - 10\log_{10}\left(\tan^{-1}\frac{m\omega}{2\rho_0 c_0}\right). \qquad (22)$$

Here, compare Eq. (22) with the following classical formula for the reduction index for normal plane wave incidence, R_{normal}[1]:

$$R_{normal} = 10\log_{10}\left[1+\left(\frac{m\omega}{2\rho_0 c_0}\right)^2\right]. \qquad (23)$$

The remarkable difference between Eq. (22) and (23) is the existence or lack of a square in the factor of $m\omega/2\rho_0 c_0$. Therefore, the mass law for sound insulation of a wall driven by a spherical wave is that doubling the weight of the wall or the frequency yields an increase of 3 dB in the reduction index, cf., 6 dB for normal plane wave incidence (also see Fig. 2).

The discussions above are for an elastic plate of an infinite extent. In practical situations, however, the plate is finite, and the sound transmission loss due to a point source should be related to the size of the plate and as well as the distance between the source and the plate. Therefore, it should be noted that Eq. (23) is effective when the radius of the plate is much larger than the distance between the source and the plate.

B. Comparison with diffuse incidence

A comparison of the mass law for spherical wave incidence with that for diffuse incidence has no real physical meaning, because the latter is obtained by calculating the statistical average value. However, the diffuse incidence mass law is widely used in actual evaluations for walls today, so it is important to consider each value quantitatively.

The reduction index for the diffuse incidence, $R_{diffuse}$, is defined by the following equation[2]:

$$R_{diffuse} = 10\log_{10}\left[2 \Big/ \int_0^{\pi/2} \tau(\Theta)\cos\theta \sin\theta d\theta \right], \tag{24}$$

where Θ denotes the angle between the direction of the incident wave and the z-axis (see **Fig. 1**), and the $\cos\Theta$ term is the cross-sectional area of the plane sound wave. $\tau(\Theta)$ is the transmission coefficient for an obliquely incident wave including the effect of bending vibration of the plate, which is written as[1]:

$$\tau(\Theta) = \left[\left[1 + \eta \frac{\omega\rho_p h\cos\Theta}{2\rho_0 c_0} \frac{\omega^2 D\sin^4\Theta}{c^4\rho_p h} \right]^2 + \left[\left(\frac{\omega\rho_p h\cos\Theta}{2\rho_0 c_0} \right)^2 \left(1 - \frac{\omega^2 D\sin^4\Theta}{c^4\rho_p h} \right)^2 \right] \right]^{-1}. \tag{25}$$

A numerical example of $R_{diffuse}$ is shown in Fig. 2. Here, the same approximation as in the previous section is applied to Eq. (25), and thus $\tau(\Theta)$ becomes[2]:

$$\tau(\Theta) \cong \left[1+\left(\frac{m\omega\cos\Theta}{2\rho_0 c_0}\right)^2\right]^{-1}. \tag{26}$$

In this equation, again note that the angle of the transmitted wave depends on the angle of incidence Θ and should be distinguished from the directivity of the transmitted wave for the spherical wave incidence. Under the assumption of Eq. (26), the reduction index for the diffuse incidence is as follows[1]:

$$R_{diffuse} \cong 10\log_{10}\left(\frac{m\omega}{2\rho_0 c_0}\right)^2 - 10\log_{10}\left[\ln\left[1+\left(\frac{m\omega}{2\rho_0 c_0}\right)^2\right]\right]. \tag{27}$$

Note that the mass law for spherical wave incidence is also smaller than that for diffuse incidence (also see Fig. 2):

$$R_{normal} > R_{diffuse} > R_{spherical}. \tag{28}$$

V. CONCLUSIONS

In this paper, the transmission of spherical sound wave through an infinite elastic plate was theoretically analyzed. A far-field expression of the transmitted wave was presented in an explicit closed form.

The reduction index for the spherical wave incidence is lower than that for a normal plane wave incidence at all frequencies. This is caused by an apparent decrease of wall impedance that depends on the directivity of the transmitted sound wave.

The mass law for spherical wave incidence is different from that for normal plane wave incidence: doubling the weight of the wall or the frequency gives an increase of 3 dB in the reduction index, which is also smaller than the field incidence mass law. Considering the assumption of the theoretical analysis, the above discussion is, strictly speaking, only effective when the radius of plate is much larger than the distance between the source and the plate.

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APPENDIX

In order to calculate the transmitted sound power, Φ_t, the authors integrate the radial intensity obtained by using Rayleigh's formula over a hemisphere in the far-field. The transmitted sound power is also obtained by integrating the surface intensity of the plate over the entire surface to an infinite extent. Takahashi et al.[11] have derived it by using the latter procedure, thus,

$$\Phi_t = \iint_{S_2} \frac{1}{2} \mathrm{Re}[p_2(r,0)\hat{v}(r,0)]\, dS_0 \ , \tag{A1}$$

where $v(r,0)$ is the velocity of the plate with ^ complex conjugate and is as follows:

$$v(r,0) = -i\omega w(r,0) \ . \tag{A2}$$

Solving Eqs. (A.1), (7), (A.2), (9) and (12), they have obtained the following equation:

$$\Phi_t = \pi\rho_0\omega^3 \,\mathrm{Re}\left[\int_0^\infty dk \int_0^\infty dk' \frac{W(k)\hat{W}(k')}{\sqrt{k_0^2 - k^2}} kk' \int_0^\infty J_0(kr)J_0(k'r)rdr\right]$$

$$= \pi\rho_0\omega^3 \,\mathrm{Re}\left[\int_0^\infty dk \int_0^\infty \frac{W(k)\hat{W}(k')}{\sqrt{k_0^2 - k^2}} \delta(k-k')dk'\right] \quad , \qquad \text{(A3)}$$

$$= \pi\rho_0\omega^3 \int_0^{k_0} \frac{|W(k)|^2}{\sqrt{k_0^2 - k^2}} kdk$$

where, the integral for the Dirac delta function is used: [15]

$$k'\int_0^\infty J_0(kr)J_0(k'r)rdr = \delta(k-k') \,. \qquad \text{(A4)}$$

They obtained a numerical example by using Eq. (A.3) (see Fig. A), because the integral in this equation cannot generally be executed by analytical means.

Here, the authors show that the mass law formula for a spherical wave incidence derived in Section IV can also be derived from Eq. (A.3). The same approximation in Section IV is applied to Eq. (12) and substituted into Eq. (A.3), hence, Φ_t becomes:

$$\Phi_t = \pi\rho_0\omega^3 \int_0^{k_0} \left| \frac{2\sqrt{8\pi\rho_0 c_0}\,\exp[-d_s\sqrt{k^2 - k_0^2}\,]}{4\pi\sqrt{k^2 - k_0^2}} \left[2\frac{\rho_0\omega^2}{\sqrt{k^2 - k_0^2}} + m\omega^2\right]^{-1} \right|^2 \frac{kdk}{\sqrt{k^2 - k_0^2}} \quad . \qquad \text{(A5)}$$

$$= \frac{1}{2}\frac{\tan^{-1}\dfrac{m\omega}{2\rho_0 c_0}}{\dfrac{m\omega}{2\rho_0 c_0}} \equiv \text{Eq.(21)}$$

Hence, the author's theory is in complete agreement with that of Takahashi et al.[11] assuming that the effect of the flexural rigidity of the plate is neglected.

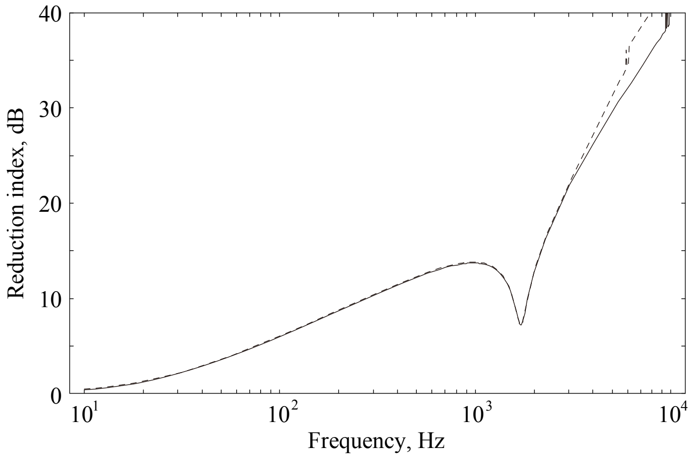

FIG. A Comparison with the theory of Takahashi et. al. (broken line). The parameters of the plate are the same as in Fig. 2.

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LIST OF FIGURES