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The acoustic radiation impedance of a rectangular panel

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ABSTRACT

This paper extends the definition of the one sided radiation impedance of a panel mounted in an infinite rigid baffle which was previously used by the authors so that it can be applied to all transverse velocity wave types on the panel rather than just to the possibly forced travelling plane transverse velocity waves considered previously by the authors. For the case of travelling plane waves on a rectangular panel with anechoic edge conditions, and for the case of standing waves on a rectangular panel with simply supported edge conditions, the equations resulting from one of the standard reductions from quadruple to double integrals are given. These double integral equations can be reduced to single integral equations, but the versions of these equations given in the literature did not always converge when used with adaptive integral routines and were sometimes slower than the double integral versions. This is because the terms in the integrands in the existing equations have singularities. Although these singularities cancel, they caused problems for the adaptive integral routines. This paper rewrites these equations in a form which removes the singularities and enables the integrals in these equations to be evaluated with adaptive integral routines. Approximate equations for the azimuthally averaged one sided radiation impedance of a rectangular panel mounted in an infinite baffle are given for all the cases considered in this paper and the values produced by these equations are compared with numerical calculations.
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1. Introduction

The acoustical radiation impedance of one side of a finite rectangular panel mounted in an infinite rigid baffle is of importance for the prediction of sound insulation [1–5], sound absorption [1,6–8], sound directivity [9] and sound scattering. It occurs naturally when variational techniques are used to solve these phenomena [1,2,7,8]. The normalized real part of the acoustical radiation impedance of one side of a finite rectangular panel mounted in an infinite rigid baffle is also the panel's one sided acoustic radiation efficiency.

The authors [10–12] have recently defined the radiation impedance of a plane panel mounted in an infinite plane baffle as the average of the specific acoustic impedance over the surface of the rectangular panel when a possibly forced plane transverse velocity wave is propagating on the surface of the rectangular panel. It was assumed that the edges of the panel were anechoic. This is the appropriate assumption for a forced wave, because after the forced wave is reflected at the edges of the panel, it propagates with the free wave number of the panel rather than with the forced wave number and hence has a different radiation impedance unless the incident wave was also freely propagating.

This definition works because the possibly forced plane wave has the same root mean square (rms) transverse velocity over time at all points of the panel. When the radiation impedance of other wave types on the panel, such as standing waves, is considered, this definition breaks down because the rms transverse velocity over time will possibly differ over the panel and may be zero at some points. Where the rms transverse velocity over time is zero, the specific acoustic impedance will be infinite and its average over the panel may not be finite. This paper gives a definition of the radiation impedance of a transverse wave on a panel which gives the same result for a travelling plane wave as the definition previously used by the authors.

The definition of radiation impedance involves a quadruple integral. For a rectangular panel with a travelling plane wave or for a mode of a simply supported panel, this quadruple integral can be reduced to a double integral using a standard technique [1,13–15]. In both these cases this double integral can be reduced to a much more complicated single integral. However when the single

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integral equations for real part of the impedance for the travelling plane case [15] were evaluated using adaptive integral routines, the integral did not converge when the wave number of the travelling transverse plane velocity wave was equal to the wave number in the fluid medium into which the panel was radiating. Also, at low frequencies, the single integral evaluation was slower than the double integral evaluation. These problems are due to singularities in terms of the integrand. Although the singularities do cancel out each other, they do cause problems for the adaptive integral routines. Singularities also appear in the single integral formulae for the real part of the impedance for the simply supported mode case [13]. This paper rewrites these integrands in a form that removes the singularities, so that the adaptive integral routines work correctly and effectively. This paper also derives the single integral formulae for the imaginary part of the impedance for both the travelling wave case and the simply supported mode case. Most previous papers only treat the travelling plane wave case or the simply supported mode case. This paper gives a uniform treatment of both cases.

Even with one less level of integration, the numerical evaluation can be fairly time consuming, especially as the products of the wave number of the transverse velocity wave in the panel and the wave number of the sound in air with the half side lengths of the panel become large. Thus, this paper also gives approximate formulae and compares their output with the numerical calculations for the azimuthally averaged one sided impedance of a square panel mounted in an infinite rigid baffle. Approximate formulae are also given for the case when the waves in the panel are excited by a diffuse sound field which is incident on one side of the panel.

When a panel is actually excited, there are usually at least two types of transverse vibrational fields excited in the panel. One is a freely propagating resonant field and the other is a forced non-resonant field or a near field. Equations are given for calculating the impedance of a panel in an infinite baffle which is excited by an incident diffuse sound field, by transverse point forces or by transverse line forces.

This paper also examines the difference in radiation impedance between different types of waves. At first sight, it is surprising that there are differences in some cases between the radiation impedances of travelling plane waves and simply supported modes on a rectangular isotropic panel, because the simply supported modes can be expressed as a sum of travelling waves. The reason for the differences are that one wave on the panel can alter the impedance experienced by another wave. This also applies to the real part of the normalized radiation impedance of different modes on a panel, but Xie et al. [16] have shown that these modal interactions cancel out when the position of the transverse excitation point is averaged over the surface of the panel. The authors suspect that a similar cancellation of the interactions between different travelling waves or simply supported modes occurs when azimuthal averaging or incident diffuse field averaging is used. This is because the results of such averaged results have proved useful in making acoustical predictions. Such cancellation does not always occur when the travelling plane waves are summed to form a mode because the relative phase of the travelling plane waves is fixed by the boundary conditions of the panel. Hence these differences in impedance survive the azimuthal averaging.

2. Definition of radiation impedance

In this paper, the sinusoidal variation with time is assumed to be proportional to exp ($j\omega t$), where ω is the angular frequency, t is the time, j is the square root of -1. It should be noted that the assumption of exp ($-j\omega t$) for the sinusoidal variation with time gives the opposite sign for the imaginary part of the impedance. The impedances in this paper are normalized by dividing by the characteristic impedance of the fluid medium Z_c, which is the product of the ambient density of the fluid medium ρ_0 and the speed of sound in the fluid medium c. Note that root mean square (rms) amplitudes rather than peak amplitudes are used in this paper.

Consider a plane surface area S whose area is also denoted by S, mounted in an infinite rigid plane baffle in the x-y plane $z = 0$, in which a two dimensional transverse velocity wave is propagating. The rms transverse velocity of the wave over the surface area of the panel in the positive z-axis direction is $u\,(\mathbf{r}_0)$ where $\mathbf{r}_0=(x_0,y_0,z_0)$ is the position on the panel. The sound pressure in the fluid medium on the positive z side of the baffle at position $\mathbf{r}_1=(x_1,y_1,z_1)$ is given by the Rayleigh integral (See Eq. (2.4) of [17])

$$p(\mathbf{r}_1) = jkZ_c \iint_S u(\mathbf{r}_0)g_\omega(\mathbf{r}_1,\mathbf{r}_0)d\mathbf{r}_0 \tag{1}$$

where g_ω is the Green's function for a point source on an infinite rigid baffle which is given by

$$g_\omega(\mathbf{r}_1,\mathbf{r}_0) = \exp(-jkr)/(2\pi r) \tag{2}$$

where

$$r = |\mathbf{r}_1 - \mathbf{r}_0| = \sqrt{(x_1-x_0)^2 + (y_1-y_0)^2 + (z_1-z_0)^2} \tag{3}$$

and k is the wave number in the fluid medium into which the wave is radiating on the positive z side of the baffle.

The sound power W radiated by one side of the panel is

$$W = \mathrm{Re}\left[\iint_S p(\mathbf{r}_1)u^*(\mathbf{r}_1)d\mathbf{r}_1\right] = \mathrm{Re}\left[jkZ_c \iint_S \iint_S u(\mathbf{r}_0)u^*(\mathbf{r}_1)g_\omega(\mathbf{r}_1,\mathbf{r}_0)d\mathbf{r}_0 d\mathbf{r}_1\right]. \tag{4}$$

It is desirable to be able to write the sound power W radiated by one side of the panel as

$$W = \mathrm{Re}\left[zZ_c S\left\langle u^2\right\rangle\right] \tag{5}$$

where

$$\left\langle u^2\right\rangle = \iint_S |u(\mathbf{r}_0)|^2 d\mathbf{r}_0 \Big/ S = \iint_S u(\mathbf{r}_0)u^*(\mathbf{r}_0)d\mathbf{r}_0 \Big/ S \tag{6}$$

is the mean square transverse velocity of the plane surface area S. Hence it is convenient to define the normalized radiation impedance z of a wave on the surface S as

$$z = jk \iint_S \iint_S g_\omega(\mathbf{r}_1,\mathbf{r}_0)u(\mathbf{r}_0)u^*(\mathbf{r}_1)d\mathbf{r}_0 d\mathbf{r}_1 \Big/ \left(S\left\langle u^2\right\rangle\right). \tag{7}$$

If the transverse velocity of the plane wave on the surface S in the positive z-axis direction is

$$u(\mathbf{r}_0) = u_0 \exp(-j\mathbf{k}_b.\mathbf{r}_0) \tag{8}$$

where $\mathbf{k}_b=(k_x,k_y,0)$ is the wave number vector of the wave and u_0 is the complex amplitude of the wave, then

$$\left\langle u^2\right\rangle = \left|u_0\right|^2 \tag{9}$$

and

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