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ACOUSTICS AND VIBRATION

SOME NUMERICAL CALCULATIONS OF SOUND RADIATION FROM VIBRATING SURFACES

by

George Chertock
and
Marie A. Grosso

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ACOUSTICS AND VIBRATION LABORATORY
RESEARCH AND DEVELOPMENT REPORT

March 1966 Report 2109

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ABSTRACT

Three particular problems in sound radiation from vibrating surfaces are solved by a method which is based on the numerical solution of the Helmholtz integral equation for the sound pressure at the vibrating surface. Numerical results are given for the near and far field of (1) a circular piston vibrating on the surface of a sphere, (2) the radial pulsations of a finite cylinder, and (3) a narrow zonal piston vibrating on a spheroid. In all cases, the results are considered more accurate than previous values reported in recent literature.

ADMINISTRATIVE INFORMATION

This study represents part of the independent in-house research program of the David Taylor Model Basin. It was funded under Bureau of Ships Subproject S-R011 01 01, Task 0401.

Except for the appendixes, this report is essentially the text of a paper presented at the 69th meeting of the Acoustical Society of America on 5 June 1965 in Washington, D. C.

INTRODUCTION

This report describes numerical solutions to three problems in sound radiation from vibrating surfaces. The computations were made with a computing program[1] which was based on the theory and method described in a recent report.[2]

To use this program, the vibrating surface must be idealized as a smooth surface of revolution. And the vibration velocity, in the direction normal to the surface, must be of the form

$$v(x, y, \phi, t) = v_0 \psi(x) \cos(m\phi) \cos(\omega t + \delta) \qquad [1]$$

where x, y, and ϕ are the cylindrical coordinates of a point on the surface, v_0 is a velocity amplitude, and $\psi(x)$ is an arbitrary function of axial position. The angle number m, the frequency ω, and the phase δ are all arbitrary.

The method essentially is to compute the sound pressure at any point in the near field or far field by simple quadratures from the Helmholtz integral

$$p(P) = \frac{-i\rho\omega}{4\pi} \iint v(S) \frac{e^{ikr}}{r} d\sigma + \frac{1}{4\pi} \iint p(S) \frac{\partial}{\partial n} \left(\frac{e^{ikr}}{r} \right) d\sigma \qquad [2]$$

[1]References are listed on page 16.

where $v(S)\exp(-i\omega t)$ is the vibration velocity at the surface point S, $p(S)\exp(-i\omega t)$ is the sound pressure at the same point, r is the distance from P to S, k is the wave number, and n is a normal at S. However, it is first necessary to determine the surface pressure $p(S)$ by solution of the following integral equation

$$p(S') = \frac{-i\rho\omega}{2\pi}\iint v(S)\,\frac{e^{ikr}}{r}\,d\sigma + \frac{1}{2\pi}\iint p(S)\,\frac{\partial}{\partial n}\left(\frac{e^{ikr}}{r}\right)\,d\sigma \qquad [3]$$

where S and S' are both points on the vibrating surface, and where the principal value of the improper integral is to be taken.

In order to solve this integral equation, the integrand of the first integral and the kernel function of the second integral are each evaluated at a finite number of stations S_i on the vibrating surface, and Equation [3] is replaced by a set of simultaneous linear algebraic equations in $p(S_i)$. The calculation of these kernel functions and the method of solution of the set of algebraic equations are described in detail in References 1 and 2. A further discussion and derivation of Equations [2] and [3] are given in Appendix A.

CIRCULAR PISTON ON SPHERE

The first problem considered is that of a circular zone vibrating with uniform radial velocity on the surface of a sphere, the remainder of the sphere being rigid. An exact solution to this problem is given by Morse[3] in the form of an infinite series in spherical wave functions. It is considered here because a numerical solution was recently described by Chen and Schweikert.[4] Their procedure is to replace the actual surface shape by a mesh of triangular surface elements each of which is in turn replaced by an equivalent simple source in a free field.

They calculate the near-field sound pressure at $R = 2a$ for the case where $ka = 2$ and the half-angular width of the piston is 29.1 degrees. Their first calculation was made by dividing the spherical surface into 80 triangular elements; a subsequent, more accurate, calculation was based on 320 triangular elements.

We solved the same problem using 60 ring-shaped elements, or zones, on the sphere. The zones were spaced unequally with a high concentration on the piston and near the boundary.

Figure 1 shows the computed sound pressure versus angular position and compares all the calculations including the exact solution. The present results agree with the exact solution to the accuracy of the plot, or to within 1 percent, whereas the Chen and Schweikert results are off by as much as 8 and 18 percent on the back side for 320 and 80 elements respectively. Furthermore, our calculation takes about 10 minutes of machine time compared to as much as an hour and three-quarters for the more precise calculation of Chen and Schweikert. It should, however, be noted that their method is more general than ours; it could be used for bodies which do not have axial symmetry and presumably it could also be used to solve shell vibration problems as well as radiation problems.

This problem is a rather obvious calculation for our method. However, it does demonstrate that the method can handle discontinuous velocity patterns and that it does work in the near field.

RADIAL PULSATIONS OF FINITE CYLINDER

The second problem considered is that of sound radiation from a cylinder of finite length, where the curved surface vibrates with uniform radial velocity and the flat end surfaces are stationary. There is no exact solution available for this problem, but there is an approximate solution for the far-field pressure which was given by Williams, Parke, Moran, and Sherman in a recent article.[5] Their procedure is to express the far field as a series in spherical Hankel functions, despite the fact that the vibrating surface is not a sphere, and to determine the coefficients of this series so as to approximately satisfy boundary conditions on the finite cylinder.

Our method of solution will be compared with theirs for the case where the cylinder length is twice the diameter and where k times the diameter is equal to four. For this case, Williams et al used 12 terms in their series; our calculation is again based on 60 elements with a high density near the circular edges. Since our computer program does not easily handle the flat end pieces of the cylinder, each end was replaced with half an oblate spheroid which fits smoothly to the lateral surface. Separate calculations were made, with the combined width of the two end pieces being 1.2, 2.5, 5, and 10 percent of the length of the lateral surface.

Figure 2 shows our calculations of the far-field pressure distribution for comparison with the results of Williams et al[5] and also for comparison with the known field (Reference 5, Equation [28]) of an *infinite* cylinder with the same length, diameter, and velocity of moving surface. All the values are expressed as ratios of the sound pressure to the far-field pressure off the side (90 degrees) of the infinite cylinder.

Note in our results that as the length of the end-piece baffles increases from 1.2 to 10 percent of the total length, there are only minor changes in the pressure distribution pattern. Generally, the radiation off the side increases, the radiation off the ends decreases, and the net power output increases (see Table 1). The apparent decrease in power as the length increases from 2.025 to 2.05 is probably due to inadequate precision in the computation and might have been avoided by increasing the number of iterations in the computation process. However, the results do show that the pressure distribution pattern for the finite cylinder is appreciably different, particularly off the ends, from that calculated in Reference 5.

Furthermore, our calculations are accurate in detail for the near field adjacent to the surface whereas the method of Reference 5 satisfies the boundary conditions only in a mean square sense.

TABLE 1

Total Power Output

Source	Length	Relative Power Output
Reference 5	2.0	0.935
TMB	2.025	0.978
	2.05	0.976
	2.10	0.982
	2.20	0.992
Infinite Cylinder	∞	1.0

RING PISTON ON SPHEROID

The third problem was anticipated as being quite routine, but it turned out to be the most interesting. In this problem, a narrow band on the surface of a prolate spheroid vibrates with uniform velocity normal to the longitudinal axis while the remainder of the surface is stationary. A solution by Hanish[6] is based on an expansion in spheroidal wave functions, and, in principle, it can be made as accurate as desired by the inclusion of sufficient terms. In practice, however, numerical values for these functions are not available and are extremely laborious to compute.

We considered the case shown in Figure 3, using 64 elements for the computation, mostly on or near the moving band. The length-to-diameter ratio of the spheroid is 1 to 0.42, the width of the band is 4.1 percent of the length, and k times the half length is 7.26. As derived by Hanish, the angular distribution of the far-field pressure is of the shape shown in Figure 3.

Our method of calculation gives completely reasonable and presumably accurate results when $ka=6.7$ or when $ka=7.7$, both of which are shown in Figure 3. There is also no difficulty (and Hanish's results are verified) when $ka=7.26$, but with *two* vibrating bands in symmetric positions on both ends of the spheroid. However, when $ka=7.26$ and there is only one vibrating band, the iterative procedure used to calculate the surface pressure does not converge.

The reason is associated with the fact that the vibrating surface is a perfect spheroid. For in that case, the kernel function of Equation [3] is symmetric in the coordinates of points S and S' and there are a series of functions, namely the spheroidal surface wave functions, which satisfy a homogeneous modification of Equation [3].

The homogeneous equation may be written as

$$\gamma_i S_i = \frac{1}{2\pi}\iint S_i \;\frac{\partial}{\partial n}\left(\frac{e^{ikr}}{r}\right)\; d\sigma \qquad [4]$$

where $p(x)$ has been replaced by the surface function $S_i\,(x, y, \phi)$, $i = 0, 1, \ldots,$ the inhomogeneous term in the integral equation has been dropped, and the complex factor γ_i has been added; γ_i can be expressed in terms of the radial spheroidal wave function as

$$\gamma_i = [1 - 2h\;(\xi^2 - 1)\,R^{(1)}\,R^{(2)\prime}] + i\,[2h\,(\xi^2 - 1)\,R^{(1)}\,R^{(1)\prime}] \qquad [5]$$

$R^{(1)}$ and $R^{(2)}$ are the radial spheroidal functions of the first and second kinds of appropriate order. The primes denote derivatives with respect to the coordinate ξ, which is the reciprocal eccentricity of the elliptic section, and h is a reduced frequency. Equation [5] will not be derived here.

If $|\gamma_i| < 1$, the presence of these solutions to the homogeneous equation has no effect on the solution to the original integral equation. If $\gamma_i = 1$, the original integral equation has no unique solution because to any solution, we could add any multiple of S_i. This occurs only when $R^{(1)} = 0$ and $S_i = 0$ and the case is trivial. Finally, if $|\gamma_i| > 1$, the original integral equation does have a unique solution, but the simple iteration process for obtaining the solution does not converge. For if the velocity distribution $v(S)$ in the first integrand of the inhomogeneous equation (Equation [2]) had some component proportional to S_i, then every iteration would amplify this component and the iteration process would diverge.

This condition occurs at $ka = 7.26$, for then by Equation [5], the $|\gamma_1|, |\gamma_2|, |\gamma_3|$, and $|\gamma_4|$ are all greater than unity and so the simplest iteration process does not converge. However, a modified process we use does converge except for the S_1 component. When $ka = 7.7$ or 6.7, $|\gamma_1|$ is less than one, and when $ka = 7.26$ and two symmetric bands are moving, the velocity $v(S)$ has no component in the S_1 mode, and for these cases, the modified iteration process does converge.

There are several alternative methods for solving the integral equation in cases where the simple iteration method fails to converge. One method is described in Appendix B.

APPENDIX A

THE HELMHOLTZ INTEGRAL FORM FOR THE FIELD AT A SURFACE POINT

The derivation of Equation [3] for the sound pressure at a point on the vibrating surface is implied in the general analysis of Reference 7 and is virtually the same as in Reference 8. However, since the question continually recurs as to how the 4π factor of Equation [2] becomes 2π of Equation [3], an explicit derivation and discussion is given here.

To a region V bounded by the surface S, we apply Green's identity

$$\iiint_{V}(\phi_1 \nabla^2\phi_2 - \phi_2\nabla^2 \phi_1)\, d\tau = \iint_S (\phi_1 \nabla \phi_2 - \phi_2 \nabla \phi_1)\, d\sigma \qquad [6]$$

where $\phi_1 = p(P)$ and $\phi_2 = e^{ikr}/r$; r is the distance between a field point $P$and a surface point S, and the surface S consists of three parts–the vibrating surface S_v, a sphere S_∞ at infinity, and an infinitesimal sphere S_0 enclosing point P.

In this region V, there are no singularities of either ϕ_1 or ϕ_2. Also $\nabla^2 \phi_1 + k^2 \phi_1 = 0$, and $\nabla^2 \phi_2 + k^2\phi_2 = 0$, and so the volume integral in Equation [6] is zero.

The surface integral over S_v becomes

$$-\iint_{S_v - A} \frac{\partial p}{\partial n} \frac{e^{ikr}}{r}\, d\sigma + \iint_{S_v - A} p \frac{\partial}{\partial n}\left(\frac{e^{ikr}}{r}\right) d\sigma \qquad [7]$$

where the integral extends over all of S_v external to S_0 (A being the part of S_v which is within S_0).

The surface integral over S_∞ vanishes on the usual assumption that Sommerfeld's radiation condition is applicable, i.e., for large r

$$p = O\left(\frac{1}{r}\right) \qquad [8]$$

and

$$\left(\frac{\partial p}{\partial r} - ikp\right) = O\left(\frac{1}{r^2}\right) \qquad [9]$$

The surface integral over S_0 becomes

$$\iint\left[-\frac{\partial p}{\partial r} \frac{e^{ikr}}{r} + p \frac{\partial}{\partial r}\left(\frac{e^{ikr}}{r}\right)\right] d\sigma = \iint\left[p \frac{e^{ikr}}{r}\left(ik - \frac{1}{r}\right) - \frac{e^{ikr}}{r} \frac{\partial p}{\partial r}\right] r^2\, d\Omega$$

$$\xrightarrow[r\to 0]{} - p(P) \iint d\Omega \qquad [10]$$

where $d\Omega$ is the element of solid angle subtended by $d\sigma$ at P and the integral extends over all of S_0 external to S_v. It is convenient to distinguish three cases, depending on whether (1) P is a finite distance h off S_v (Figure 4a), (2) P is on a smooth and continuous part of S_v (Figure 4b), or (3) P is at a point on S_v where there is a discontinuity in the slope of the tangent plane (Figure 4c). In all cases

$$\lim_{r \to 0} \iint d\Omega = 4\pi - \Omega_A \qquad [11]$$

where Ω_A is the solid angle ($0 \leq \Omega_A < 4\pi$) subtended at P by the intersection of S_v and S_0. In case (1), $\Omega_A = 0$; in case (2), $\Omega_A = 2\pi$; and in case (3), Ω_A is equal to the finite solid angle between the tangent planes at P. In all three cases, the surface area $A \to 0$.

Hence Equation [6] becomes

$$p(P)\,(4\pi - \Omega_A) = \lim_{A \to 0} \iint_{S_v - A} \left[-\frac{\partial p}{\partial n}\,\frac{e^{ikr}}{r} + p\,\frac{\partial}{\partial n}\left(\frac{e^{ikr}}{r}\right)\right] d\sigma \qquad [12]$$

which includes both Equations [2] and [3].

This result does *not* mean that there is a discontinuity in the numerical value for $p(P)$ as the field point approaches the vibrating surface. There is a change in the *form* of the equation, but the numerical value derived from Equation [3] for the pressure at a surface point is continuous with the values computed from Equation [2] for the pressure at nearby points.

The supposed discontinuity arises from assuming that the pressure at the surface could be calculated from

$$p(S') = \lim_{h \to 0} p(P)$$

$$= \lim_{h \to 0} \frac{\displaystyle \lim_{A \to 0} \iint_{S_v - A} \left[-\frac{\partial p}{\partial n}\,\frac{e^{ikr}}{r} + p\,\frac{\partial}{\partial n}\left(\frac{e^{ikr}}{r}\right)\right] d\sigma}{\displaystyle \lim_{r \to 0} \iint_{S_0 - \Omega_A} d\Omega} \qquad [13]$$

But the denominator is equal to 4π only for $h > 0$. The convergence is *not* uniform with respect to h if h is an infinitesimal, and we cannot replace the denominator by 4π in that case.

APPENDIX B

ALTERNATIVE TO THE ITERATIVE SOLUTION OF THE INTEGRAL EQUATION

One possible solution of Equation [3] in the problem of the vibrating zone on a spheroid is by the Hilbert-Schmidt method[9] which expresses the solution in terms of the eigenfunctions and eigenvalues of Equation [4]. The eigenfunctions are simply the spheroidal surface wave functions $S_i(x, y, \phi)$, and the eigenvalues are the reciprocals of γ_i and can be evaluated from Equation [5]. The difficulty with this method of solution to the integral equation is the same as with Hanish's solution to the original problem, namely that the spheroidal wave functions have not been tabulated over a sufficiently wide range. By using values for the radial wave functions computed by Hanish,[6] we can compute 20 eigenvalues, γ_i, $i = 0, 1. \ldots .19$, and we can probably compute S_1 over the same range $i = 0, 1. \ldots 19$. However, in the present problem, the width of the moving zone is about 1/25 of the length of the spheroid, and we expect that in order to adequately represent the pressure distribution on the surface, more than 25 terms in the series expansion are necessary.

An alternative method of solution is based upon the fact that it is only that component of $p(x, y, \phi)$ in the S_1 mode which does not converge in the modified iteration process we use. Hence, we separate $p(x, y, \phi)$ into two components, a component $q(x, y, \phi)$ which is orthogonal to $S_1(x, y, \phi)$ on the surface of the spheroid and a component which is proportional to $S_1(x, y, \phi)$; we compute each component separately.

$$p(x, y, \phi) = q(x, y, \phi) + A\, S_1(x, y, \phi) \qquad [14]$$

where

$$A = \left\{ \oiint p_0 S_1 \, dx \right\} \Big/ \left\{ (1 - \lambda_1) \oiint S_1^2 \, dx \right\} \qquad [15]$$

and

$$p_0(x, y, \phi) = \frac{-i\rho\omega}{2\pi} \iint \frac{v e^{ikr}}{R} \, d\sigma \qquad [16]$$

The second term in Equation [14] is in the form of the Hilbert-Schmidt series. $S_1(x, y, \phi)$ is easily calculated from its expansion in Legendre polynomials by using the expansion coefficients tabulated in Reference 6; the single eigenvalue γ_1 is computed from Equation [5].

The first term, $q(x, y, \phi)$, in Equation [14] satisfies the integral equation

$$q(x, y, \phi) = [p_0(x, y, \phi) - A\, S_1(x, y, \phi)] + \frac{1}{2\pi} \oiint q(x, y, \phi) \frac{\partial}{\partial n} \left(\frac{e^{ikr}}{r} \right) d\sigma \qquad [17]$$

and is computed by the usual iterative procedure. The initial trial function in this iteration is $p_0 - AS_1$ and presumably has a negligible component proportional to S_1. But after many iterations, the component in this mode can accumulate to a significant amount. Accordingly, the solution $q(x, y, \phi)$ is taken as the result of the 50th iteration less whatever amount of S_1 is then present. That is,

$$q(x, y, \phi) = q^{(50)} - S_1 \left\{ \oiint S_1 \, q^{(50)} \, dx \Big/ \oiint S_1^2 \, dx \right\} \qquad [18]$$

The results of this calculation, from Equation [14] are shown in Figure 5 for comparison with the results of Reference 6. The quantity plotted is a nondimensional transfer impedance at the spheroid surface, the real and imaginary parts of $p/\rho c v_0$, versus longitudinal position x. Note that Hanish does not report the detailed distribution but only average values, averaged over the width of particular zones as indicated by the length of the bars. The two calculations are in fair agreement except for the imaginary values of $p/\rho c v_0$ in the neighborhood of the moving zone. At these points, we believe that Reference 6 is about 25 percent too low because too few terms were taken in the series expansion.

Figure 6 shows the far-field pressure pattern as calculated by the two methods. The two curves have not been normalized in the same way, but it is clear that the directivity patterns are essentially the same. Furthermore, since the total power radiated to the far field depends only on the real component of the sound pressure at the moving zone, it appears from Figure 5 that our calculation for the mean sound pressure level in the far field is about 6 percent higher than in Reference 6.

Finally, it should be noted that an alternative and independent calculation (undertaken subsequent to this study) agrees with the results of Equation [14] within 1 percent. This later calculation is a new modified form of an iterative solution to Equation [3] and requires no prior tabulation of the spheroidal wave functions. The method will be discussed in a subsequent paper.[10]

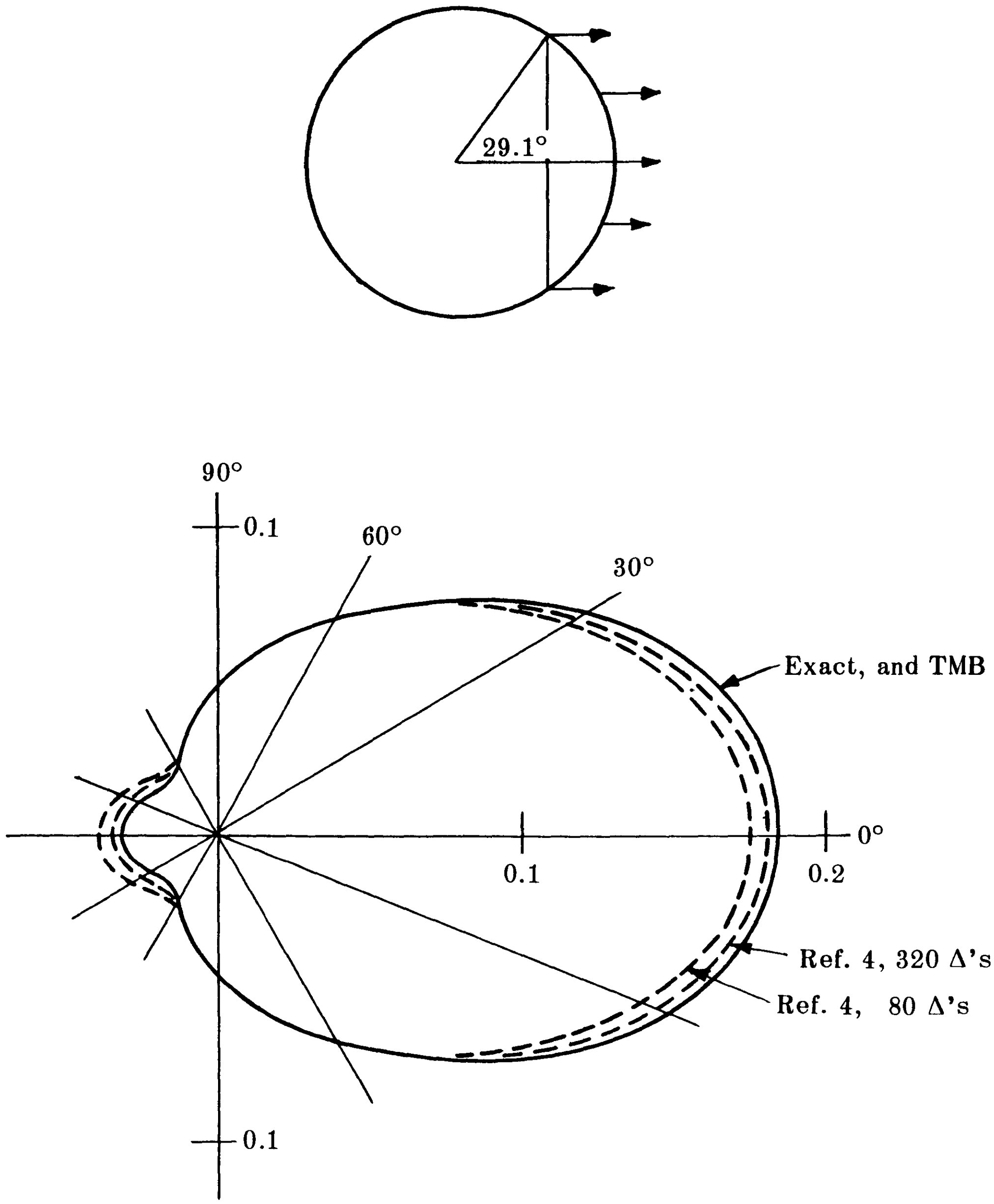

Figure 1 – Polar Graph of (Sound Pressure)/($\rho c v$) at $R = 2a$

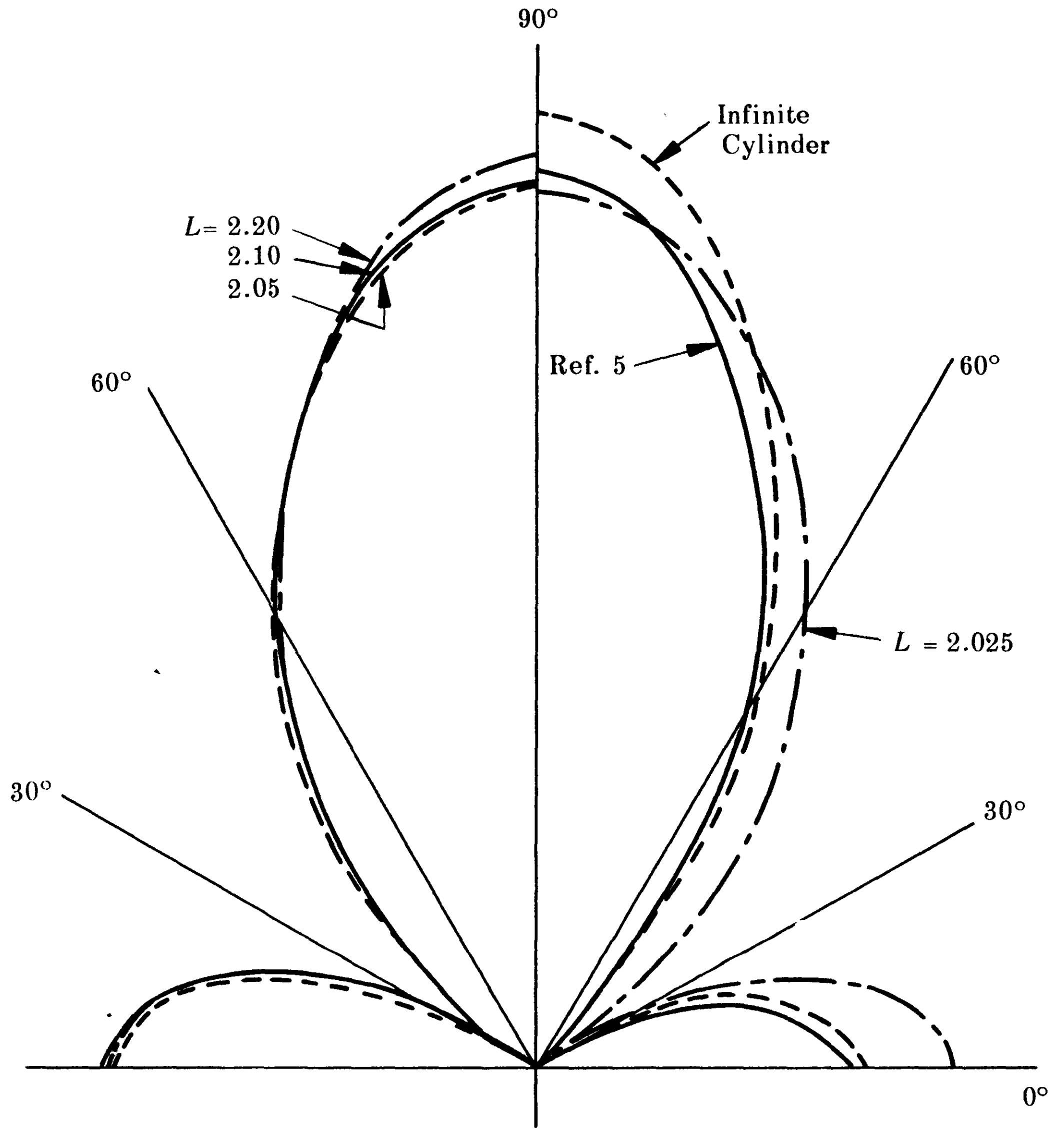

Figure 2 – Polar Graph of Far-Field Pressure Pattern from a Vibrating Cylinder

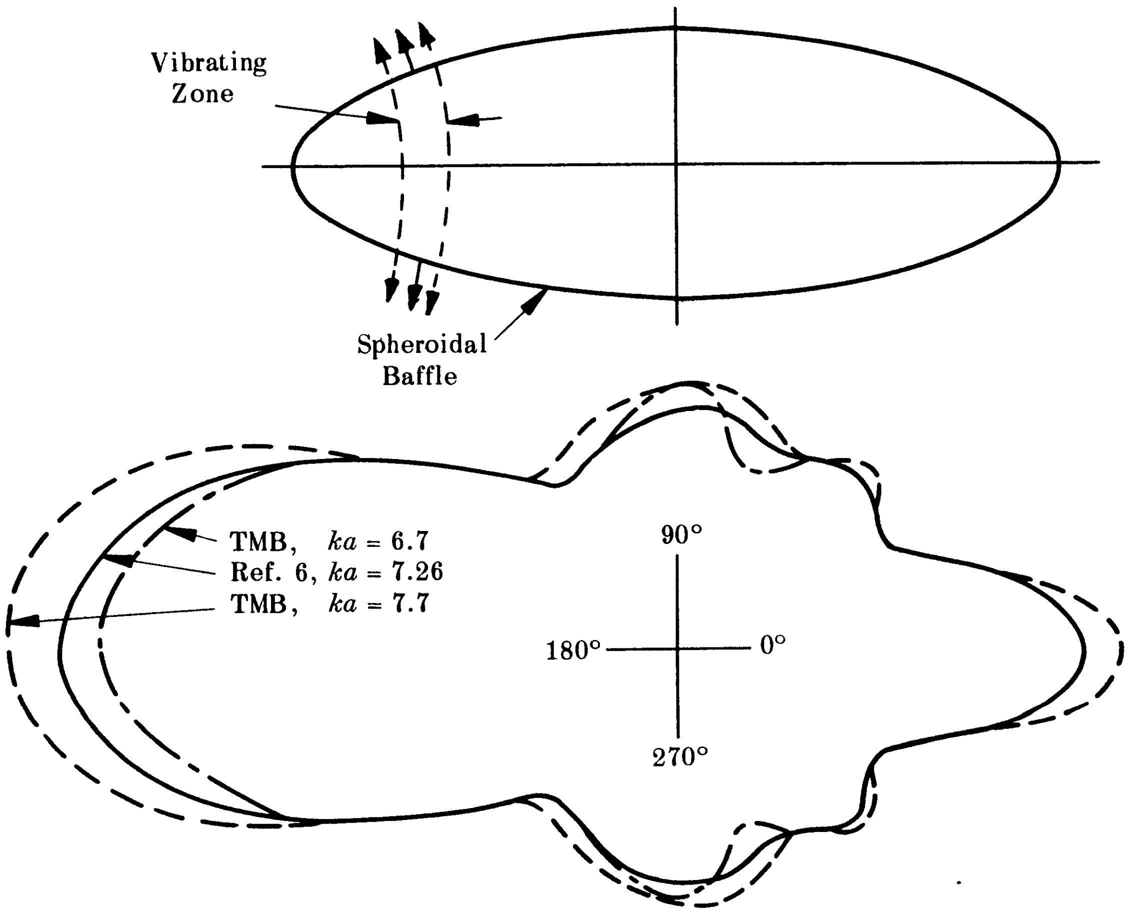

Figure 3 – Polar Graph of Far-Field Pressure Pattern from a Ring Piston on a Spheroid

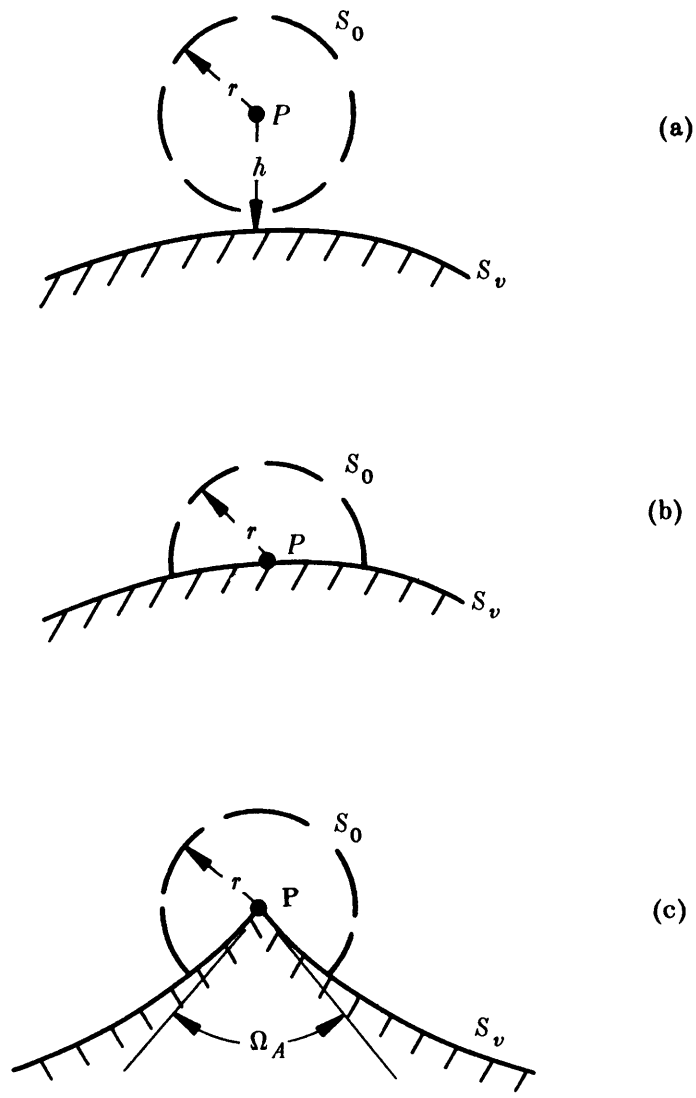

Figure 4 – Field Point and Vibrating Surface

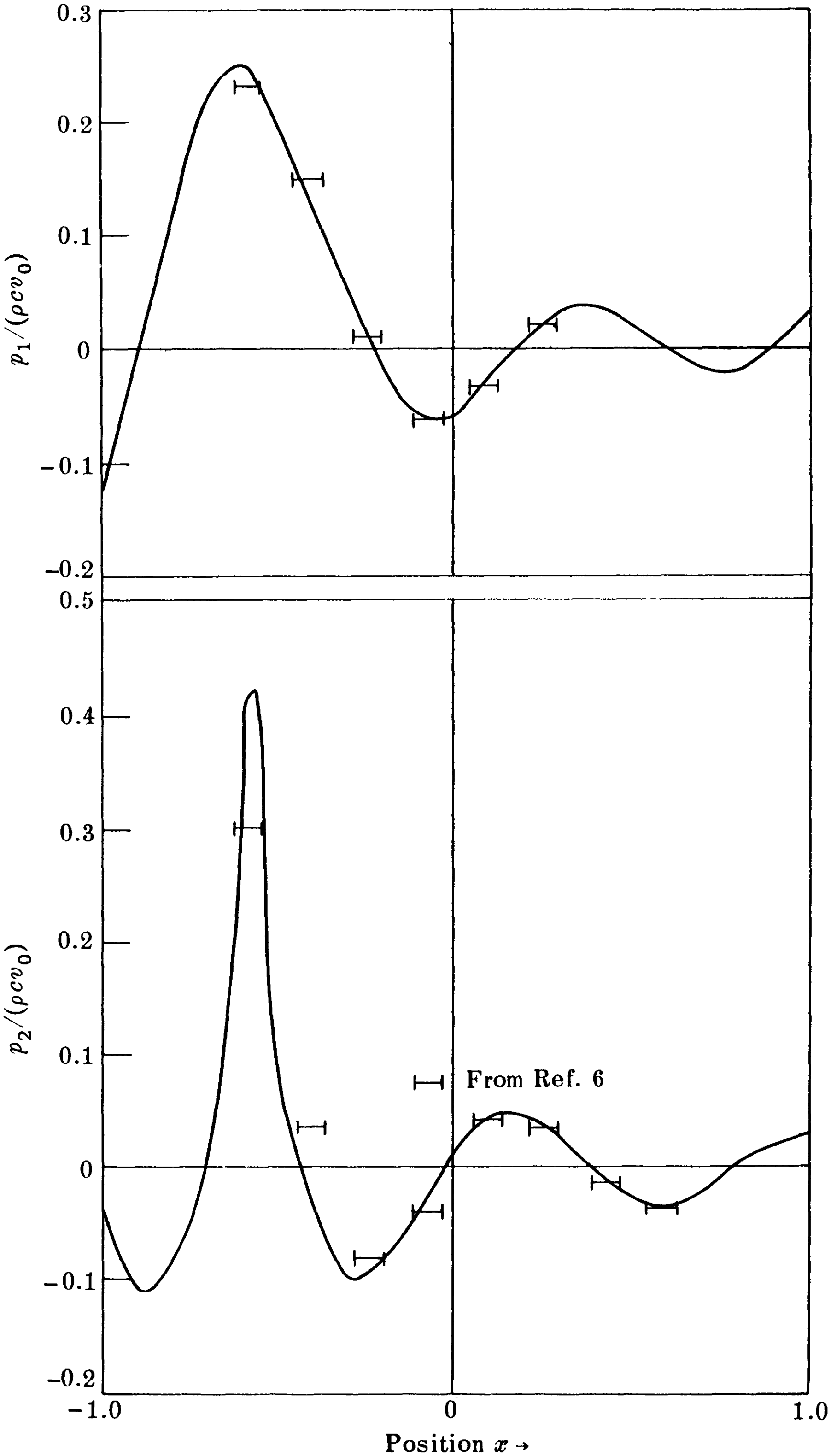

Figure 5 – Sound Pressure at Surface of Spheroid

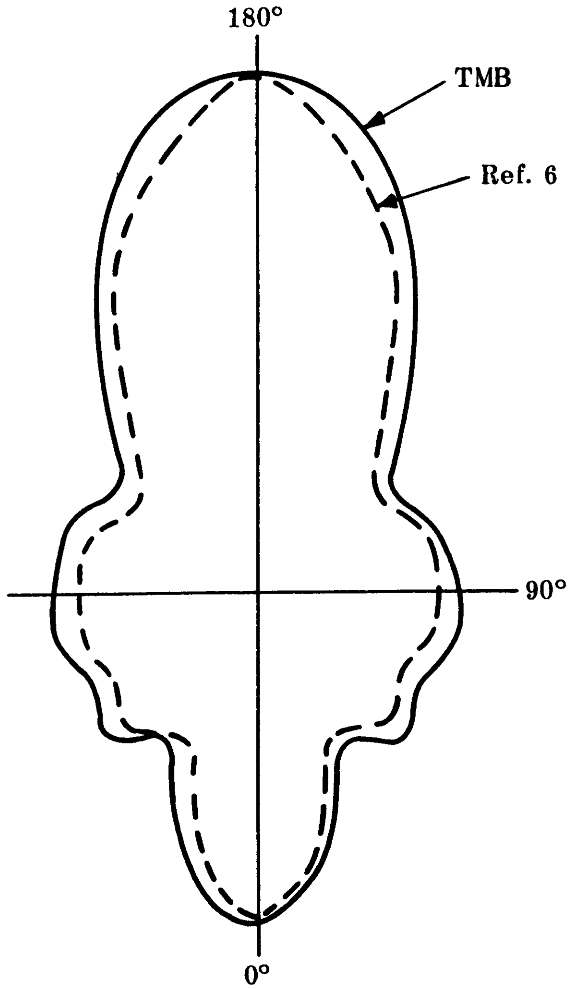

Figure 6 – Far-Field Pressure Pattern from a Ring Piston on a Spheroid

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13 ABSTRACT

Three particular problems in sound radiation from vibrating surfaces are solved by a method which is based on the numerical solution of the Helmholtz integral equation for the sound pressure at the vibrating surface. Numerical results are given for the near and far field of (1) a circular piston vibrating on the surface of a sphere, (2) the radial pulsations of a finite cylinder, and (3) a narrow zonal piston vibrating on a spheroid. In all cases, the results are considered more accurate than previous values reported in recent literature.

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