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THESIS

CALCULATION OF THE TRANSITION MATRIX FOR THE SCATTERING OF ACOUSTIC WAVES FROM A THIN ELASTIC SPHERICAL SHELL USING THE ATILA FINITE ELEMENT CODE

by

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March, 1994

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CONTENTS

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I. INTRODUCTION

The utilization of sonar systems in operations at sea depends on the ability to forecast their performance during the design and production phases of their development. For low frequency active sonar systems, arrays of large transducers are required to produce the necessary power output. Because of their size and power output, interactions among the elements of an array may need to be considered in modelling a given array.

Professors S. R. Baker of the Physics Department and C. L. Scandrett of the Mathematics Department of the Naval Postgraduate School are engaged in a joint research effort with the objective of developing the models necessary to predict the performance of arbitrary dense active sonar arrays.

The approach used in this research is based on the T-Matrix method. [Ref. 3].

The T-matrix method uses the superposition of spherical harmonics to represent the total radiated pressure from a transducer. The radiated pressure from one such transducer for each incoming harmonic will be calculated in an effort to produce the transition matrix or T-matrix. The elements of the T-matrix may then used to calculate scattered pressures resulting from the interaction between transducers.

The T-matrix method is useful in computing the scattered pressure resulting from an arbitrary incident pressure on a given scatterer. This thesis is concerned with the application of the T-matrix method on an array of thin-shelled elastic spheres.

Once the theoretical results from scattering of spherical harmonics incident on a sphere have been obtained, the calculations from the T-matrix method can be compared for each harmonic with the computation from the Finite Element Code ATILA for the purpose of validation.

Furthermore, the acoustic impedance calculated from the thin shell theory (Chapter II) can be compared with the acoustic impedance computed by ATILA's results.

The remainder of this thesis is divided into five chapters. Chapter II describes the theory involved in the T-Matrix method, the Pritchard Approximation, the finite element analysis of a structure excited by an impinging wave, and the theory of forced vibration of a spherical shell. Chapter III describes the spherical model used in the ATILA code. Chapter

IV presents and discusses the results. Chapter V presents the conclusions. Appendix A contains a copy of the FORTRAN program used to generate the spherical harmonic impinging wave. Appendix B presents a copy of the code used in ATILA. Appendix C presents a FORTRAN code [Ref. 17] to calculate elements of the Transition Matrix.

II. THEORY

A. "T-MATRIX" METHOD

The "T-Matrix" method is a procedure for computing the acoustic field due to multiple radiating and/or scattering bodies. An outline is given below of how this method may be applied to compute the acoustic pressure due to a pair of piezoelectric spherical shell transducers.

If a voltage is applied to a thin piezoelectric spherical shell in a free-field environment, a displacement of the surface of the shell can be obtained by the canonical equations [Ref. 1]. This movement generates an acoustic pressure field in the surrounding medium. This is indicated in Figure 1 , where a sphere excited by a voltage V produces a radial velocity u over the surface of the sphere. The perturbation of the sphere on the environment yields a radiated pressure $p^R(r,\theta,\phi)$.

The acoustic pressure at a field point z , located at spherical coordinates r, θ, and ϕ, equals $p^R(r,\theta,\phi)$, since the sphere is in a free-field environment. Numerical values of $p^R(r,\theta,\phi)$ can be found by application of a finite-element analysis code such as ATILA [Ref. 2].

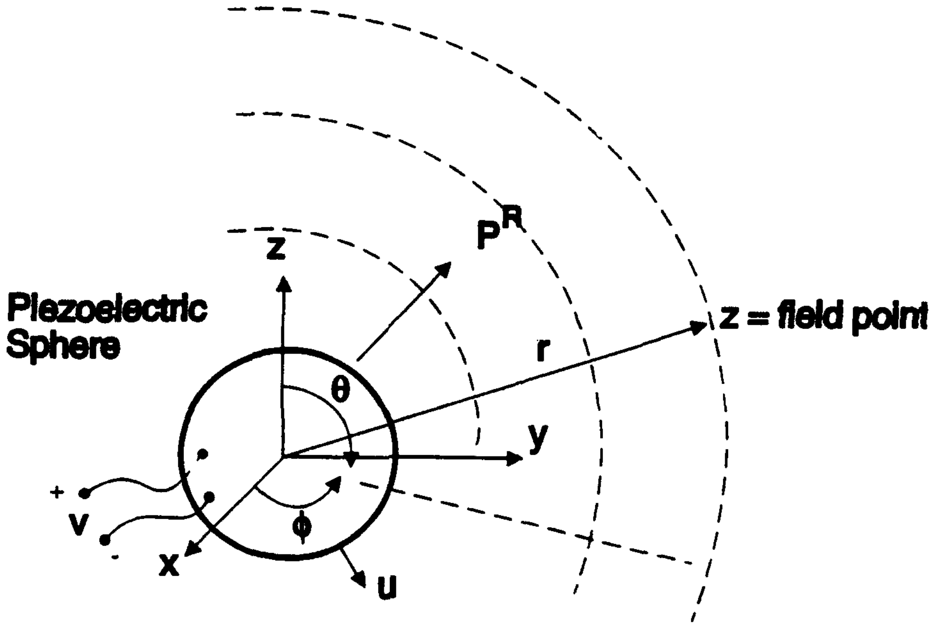

Figure 1. Single Radiation from a Piezolectric Sphere.

Next, consider the case of an array of two thin piezoelectric spherical shell transducers that are close enough to be considered "in the near field" of one another (see Figure 2).

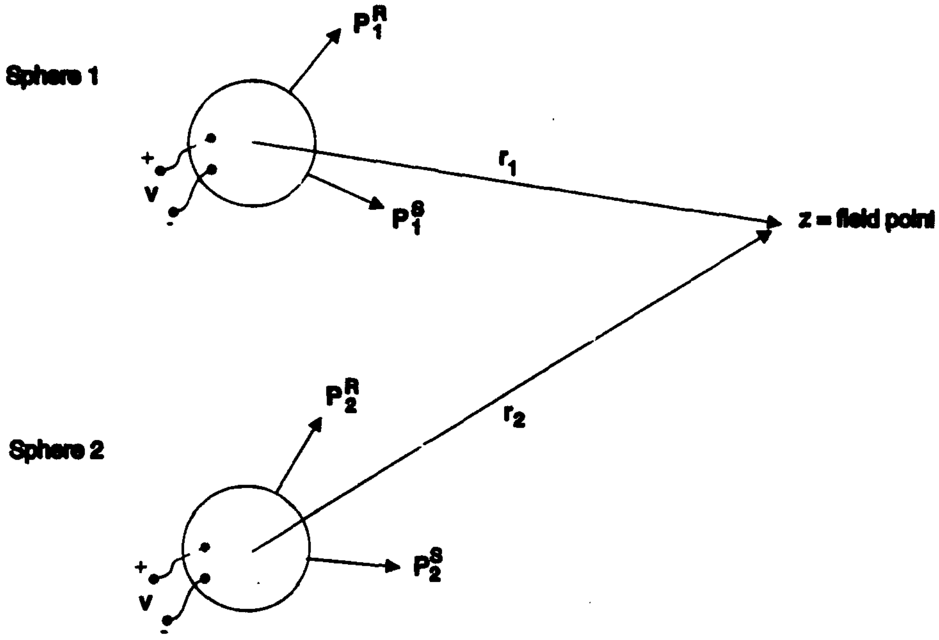

Figure 2. An Array of Two Thin Piezoelectric Spheres.

Outgoing waves at sphere 1 are composed of a radiated wave, p_1^R, resulting from the applied voltage V, and a scattered wave, p_1^S, due to the incident wave from sphere 2, p_1^I. The scattered pressure field can be mathematically represented by outgoing spherical Hankel functions and surface harmonics in the sphere 1 coordinate system as [Ref. 3]

$$p_1^S(r_1,\theta_1,\phi_1) = \Sigma_{n=0}^{\infty} \Sigma_{m=-n}^{n} P_{1nm}^S h_1^{(2)}(kr_1) P_n^m(\cos\theta_1) e^{im\phi_1} \tag{1}$$

where $h_n^{(2)}(kr_1) = j_n(kr_1) - iy_n(kr_1)$ is the Hankel function of the second kind (note that an $e^{i\omega t}$ harmonic time dependence has been assumed; for $e^{-j\omega t}$ harmonic time dependence $h_n^{(1)}(kr_1) = j_n(kr_1) + iy_n(kr_1)$ must be used instead of $h^{(2)}$, P_{1nm}^{S} is the amplitude of the n, mth scattered wave component, k is the radial wave number, $P_n^m(\cos\theta_1)$ is the associated Legendre function, and r_1 , θ_1 and ϕ_1 are the spherical coordinates of the field point z with origin at center of sphere 1. The radiated pressure field is similarly represented:

$$p_1^R(r_1,\theta_1,\phi_1) = \Sigma_{n=0}^{\infty}\Sigma_{m=-n}^{n} P_{1nm}^R h_n^{(2)}(kr_1)P_n^m(\cos\theta_1)e^{im\phi_1} \tag{2}$$

The incident pressure p_1^I is assumed to be of the form:

$$p_1^I(r_1,\theta_1,\phi_1) = \Sigma_{n=0}^{\infty}\Sigma_{m=-n}^{n} P_{1nm}^I j_n(kr_1)P_n^m(\cos\theta_1)e^{im\phi_1} \tag{3}$$

This form is valid provided r_1 is less than the distance between the origins of spheres 1 and 2.

By definition, the coeficients of the scattered pressure P_{1nm}^S are related to the coefficients of the incident pressure P_{1nm}^I by

$$\{P_1^S\} = [T]\{P_1^I\} \tag{4}$$

Where {} denotes a column vector of coefficients and [T] is the so-called "transition matrix" or T-Matrix , a property of the transducer.

Similar expressions to the above apply to the corresponding fields on sphere 2, i.e.,

$$p_2^S(r_2,\theta_2,\phi_2) = \Sigma_{n=0}^{\infty}\Sigma_{n=-n}^{\infty} P_{2nm}^S h_n^{(1)}(kr_2)P_n^m(\cos\theta_2)e^{im\phi_2} \tag{5}$$

$$\{P_2^s\} = [T]\{P_2^I\} \qquad . \tag{6}$$

Note that it is assumed here for the sake of simplicity that the two transducers are identical, so that their T-matrices are also; in the general case this need not be so.

To proceed fruther it is necessary to be able to transform from one coordinate system into another. This is done using an "addition theorem", by which a spherical wave relative to one origin is expressed as a series of spherical waves relative to another [Ref. 3 and references therein]. Thus, for example, the incident pressure on sphere 1 can be expressed as the sum of the radiated and scattered pressures from sphere 2, transformed into the sphere 1 coordinate system using the addition theorem. In matrix form, this can be written

$$\{P_1^I\} = [G_{21}]\{P_2^R + P_2^S\}, \tag{7}$$

where $[G_{21}]$ represents the matrix of coefficients that transforms outgoing spherical harmonics at sphere 2 into standing wave spherical harmonics at sphere 1. Similarly, the incident pressure on sphere 2 is related to the radiated and scattered pressure on sphere 1 by

$$\{P_2^I\} = [G_{12}]\{P_1^R + P_1^S\}. \tag{8}$$

Using Equations (4) and (6) in Equations (7) and (8), we have a system of two equations in two unknowns:

$$\{P_1^S\} = [T][G_{21}]\{P_2^R + P_2^S\}, \tag{9}$$

$$\{P_2^S\} = [T][G_{12}]\{P_1^R + P_1^S\}. \tag{10}$$

Equations (9) and (10) may be written

$$\begin{bmatrix} I & -TG_{21} \\ -TG_{12} & I \end{bmatrix} \begin{Bmatrix} P_1^S \\ P_2^S \end{Bmatrix} = \begin{bmatrix} 0 & TG_{21} \\ TG_{12} & 0 \end{bmatrix} \begin{Bmatrix} P_1^R \\ P_2^R \end{Bmatrix} \tag{11}$$

where [I] is the identity matrix.

If $\{P_1^R\}, \{P_2^R\}$, and [T] can be found, such as by using the finite-element code ATILA, then, since $[G_{12}]$ and $[G_{21}]$ are known from the positions and orientations of the transducers through application of the addition theorem, the scattered pressures $\{P_1^S\}$ and $\{P_2^S\}$ can be determined. Then the resulting pressure at the field point z, p(z), is given by

$$p(z) = p_1^R(z_1) + p_1^S(z_1) + p_2^R(z_2) + p_2^S(z_2) \quad , \tag{12}$$

with the forms for the radiated and scattered pressure fields given previously, where z_i represents the coordinates of the field point z relative to the origin of the ith sphere.

The above development may be generalized to an array composed of an arbitrary number N of identical elements. For the ith element,

$$\{P_i^S\} = [T]\{P_i^I\}. \tag{13}$$

Here the scattered pressure from the ith transducer is represented. The components of the radiated pressure, P^R_{imn}, may be found using such a: ATILA finite-element code. Then the acoustic pressure at a field point z is the sum of the radiated and scattered pressures of each transducer.

$$p(z) = \Sigma\ _{i=1}^{N}[p_i^R(z_i) + p_i^S(z_i)]\quad . \tag{14}$$

B. THE "PRITCHARD APPROXIMATION"

The analytical calculation of mutual-radiation impedance, Z_{ij}, is made through the solution of the wave equation for the sound pressure produced by one transducer and by integrating that pressure over the radiating surface of another transducer [Ref. 4].

In Pritchard's original paper [Ref. 5], the mutual-radiation impedance was approximated for the case of flat circular pistons on an infinite rigid baffle. For small pistons and large separation, the Pritchard equation can be reduced to

$$Z_{12} = \frac{1}{2}(ka)^2\left(\frac{\sin kd}{kd} + i\frac{\cos kd}{kd}\right)\rho c A. \qquad (15)$$

Here an $e^{-i\omega t}$ harmonic time dependance is assumed. This approximation neglects secondary scattered pressures.

It can be noted that Z_{12} has a real and an imaginary part,

$$Z_{12} = R_{12} + jX_{12}\ . \qquad (16)$$

Here, Z_{12} is the mutual-radiation impedance between transducers 1 and 2, d is the distance between the centers of two transducers (see Figure 3), a is the piston radius, k is the acoustic wave number, ρc is characteristic impedance of the environment, and A is the area of the pistons.

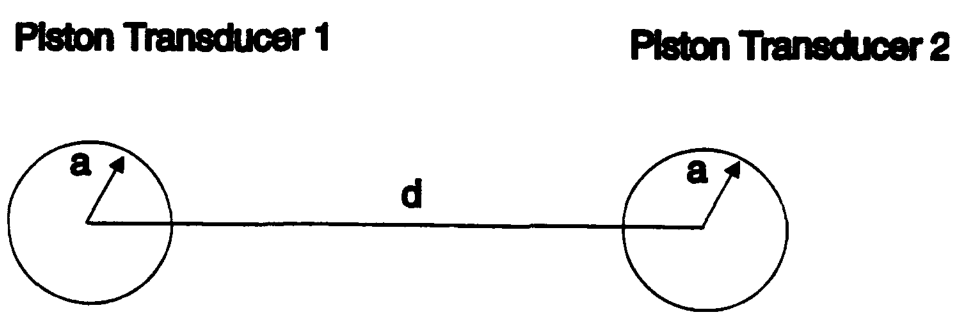

Figure 3. The Circular Pistons derived by Pritchard.

The self radiation resistance R_{ii}, for small ka, can be approximated by

$$R_{ii} = \tfrac{1}{2}(ka)^2 \rho c A. \tag{17}$$

The self radiation resistance is the real part of the transducer self-radiation impedance, written

$$\mathrm{Re}(Z_{self}) = \tfrac{1}{2}(ka)^2 \rho c A. \tag{18}$$

Therefore, for small ka, the mutual-radiation impedance can be expressed as

$$Z_{12} = \mathrm{Re}(Z_{self})\left(\frac{\sin kd}{kd} + i\frac{\cos kd}{kd}\right) = \mathrm{Re}(Z_{self})\frac{e^{ikd}}{kd}. \tag{19}$$

The so-called "Pritchard Approximation" refers to the application of Equation (19) to find the mutual radiation impedance of an array of identical transducers, not restricted to baffled pistons, i.e., Equation (19) has been applied to volumetric arrays. To calculate the mutual-radiation impedance, the wave number, the distance between transducers, and the self-radiation resistance of the transducer must be known in order to apply Pritchard's approximation.

C. THE ATILA CODE AND THE HARMONIC ANALYSIS

1. The Code

ATILA is a finite element code developed at Institut Superieur d'Electronique du Nord (ISEN) in France, and is intended for finite element analysis of underwater transducers. It uses the variational formulation of the governing mathematical equations of fluid-structure interactions [Refs. 6,7,8,9,10].

ATILA can solve a variety of problems, including: Static Analysis, Modal Analysis, and Harmonic Analysis.

Static Analysis yields the displacement field, the pressure field, and the electrical potential of an elastic or piezoelectric structure. Modal Analysis computes the eigenfrequencies and normal modes of an elastic, piezoelectric or magnetostrictive structure. Harmonic Analysis corresponds to a forced vibration problem where the excitation of the structure comes from an incident wave or from the voltage applied across the electrical terminals at a prescribed frequency. The analysis can be for a radiation or a scattering problem, for the given frequency in which the displacement field, electrical potential, electrical impedance of the structure, pressure field, reflection and transmission coefficients, and transmitting voltage response are found.

For scattering problems, an incident wave is defined by the user. A default function is provided with ATILA which creates a plane wave traveling in the negative x axis direction. One can excite the structure with an arbitrary incident wave by adding a proper function at the end of the main FORTRAN program. Appendix A contains the FORTRAN program used to generate the incident spherical harmonic waves on the structure of the transducer.

ATILA calculates either the resulting "total pressure" or only the "scattered pressure." The total pressure, for the code, is the sum of the pressure generated by the electrical potential and the pressure of the scattered wave, plus the pressure of the impinging wave. In the case of scattered pressure, the pressure of the incident wave is not included .

The ATILA library has 46 different types of elements, used to model elastic, composite, piezoelectric, magnetostrictive, and magnetic materials as well as fluids, solid-fluid interfaces, and radiation dampers. Most of the elements use the same polynomial (quadratic) interpolation for both geometry and field variation (isoparametric elements).

2. Harmonic Analysis of an Elastic or Piezoelectric Structure Excitation by an Impinging Wave

ATILA transforms equations of the Harmonic Analysis of a Radiating Piezoelectric Transducer into a matrix form. The motion equation is used for piezoelectric and elastic structures, Poisson's equation is used for piezoelectric material, and Helmholtz's equation is used for fluids [Ref. 2,11].

On the interfaces between the structure and the fluid, kinematics and dynamic continuity conditions hold under the assumption of no fluid cavitation at the fluid-structure interface. A radiation condition is applied to the external fluid boundary. Furthermore, to represent the condition of an impinging wave, the pressure and the flux fields are separated into incident and scattered parts.

In ATILA, the governing equations are written in matrix form as

$$\begin{bmatrix} [K_{uu}]-\omega^2[M] & [K_{u\phi}] & -[L] \\ [K_{u\phi}]^T & [K_{\phi\phi}] & [0] \\ -[L]^T & [0]^T & \frac{[H]}{A}-\frac{[M_1]}{B} \end{bmatrix} \begin{bmatrix} U \\ \Phi \\ P_{es} \end{bmatrix} = \begin{bmatrix} F-[L]P_i \\ -Q \\ \frac{1}{A}[G]P_{es}+\frac{\psi_i}{\rho\omega^2}+\left(\frac{[H]}{A}-\frac{[M]}{B}\right)P_i \end{bmatrix}$$

(20)

where:

U : vector of the nodal values of the components of the displacement field
Φ : vector of the nodal values of the electrical potential
P_i : vector of the nodal values of the incident pressure field
P_{es} : vector of the nodal values of the scattered pressure field
F : vector of the nodal values of the applied forces
Q : vector of the nodal values of the electrical charges
Ψ_i : vector of the nodal values of the integrated normal derivative of the incident pressure on the surface boundary S (the externally applied pressure field is proportional to the externally applied flux)
K_{uu} : stiffness matrix
$[K_{u\phi}]$: piezoelectric matrix
$[K_{\phi\phi}]$: dielectric matrix
$[M]$: consistent mass matrix
$[M_l]$: consistent fluid (pseudo-) mass matrix
$[H]$: fluid (pseudo-) stiffness matrix
$[L]$: coupling matrix at the fluid structure interface (connectivity matrix)
$[G]$: complex linear operator that is frequency dependent
$[0]$: zero matrix
ω : angular frequency
ρ : fluid density
c : fluid sound speed
A : constant of the material
B : constant of the material
$[]^T$: the superscript T means the matrices transpose.

The incident flux field can be expressed with the nodal values of the incident pressure normal derivative,

$$\psi_i = [D]\frac{\partial P_i}{\partial n}. \tag{21}$$

Here, [D] is a matrix that the code dispenses for the damping elements.

The constants A and B are

$$A = \rho^2 c^2 \omega^2 \tag{22}$$

and

$$B = \rho^2 c^2 \ . \tag{23}$$

Note that ATILA assumes a harmonic time dependance of $e^{j\omega t}$. The incident pressure is provided by the user through a FORTRAN program (see Appendix A), and for each input frequency the code outputs the complex displacement, the complex pressure, rotational and electric potential fields at each node, and the complex electrical impedance and admittance. For a more detailed discusion of ATILA's operation, the reader is advised to consult the manual [Ref. 2].

D. FORCED VIBRATION OF A SPHERICAL SHELL.

1. Theory

The mathematical equations governing the true vibrations and deformation of thin elastic shells were first derived by Love in 1888 [Ref. 12]. It assumes the following postulates:

- The shell is thin, compared to the smallest radius of curve of shell
- Deflections of the shell are small, relative to the shell's thickness
- There is no transverse normal stress acting on planes parallel to the middle surface of shell
- There are no changes to the normals of the reference surface after and no changes in length during deformation

The equations are

$$u_{\theta\theta} + u_\theta \cot\theta + (1+\upsilon)w_\theta - u\cot^2\theta - \upsilon u - \tfrac{1}{2}(3-\upsilon)\tfrac{\cos\theta}{\sin^2\theta}v_\phi + \tfrac{1}{2}(1+\upsilon)\tfrac{1}{\sin\theta}v_{\theta\phi} +$$

$$\tfrac{1}{2}(1-\upsilon)\tfrac{1}{\sin^2\theta}u_{\phi\phi} = \tfrac{a^2}{C_p^2}u_{tt}, \tag{25}$$

$$\tfrac{1}{2}(1-\upsilon)[v_{\theta\theta} + v_\theta \cot\theta] + \tfrac{1}{2}(1-\upsilon)(2-\csc^2\theta)v + (1+\upsilon)\tfrac{1}{\sin\theta}w_\theta + \tfrac{1}{2}(3-\upsilon)\tfrac{\cos\theta}{\sin^2\theta}u_\phi +$$

$$\tfrac{1}{\sin^2\theta}v_{\phi\phi} + \tfrac{1}{2}(1+\upsilon)\tfrac{1}{\sin\theta}u_{\phi\theta} = \tfrac{a^2}{C_p^2}v_{tt}, \tag{26}$$

and

$$-(1+\upsilon)[u_\theta + u\cot\theta + \frac{1}{\sin\theta}v_\phi + 2w] + \frac{(1-\upsilon^2)}{Eh}a^2\sigma_a = \frac{a^2}{C_p^2}w_{tt}, \qquad (27)$$

where the subscripts θ, ϕ, and t indicate partial differentiation and

ν : Poisson's ratio.
h : shell thickness.
C_p : shell's "plate" velocity.
E : Young's modulus.
σ_a : outward normal stress applied to shell.
a : spherical shell radius.
θ,ϕ,ρ : spherical coordinates (see Figure 1).
u,v,w : components of displacement (see Figure 4).

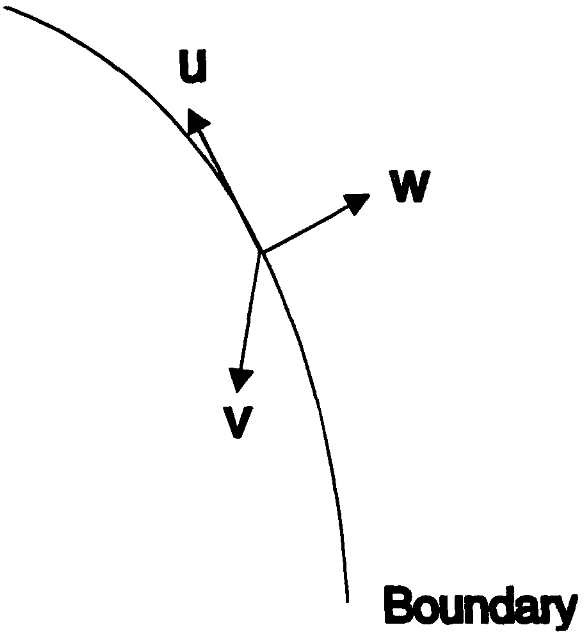

Figure 4. Components of Displacement.

To calculate the shell's plate velocity, C_p,

$$C_p = \sqrt{\frac{E}{\rho_s(1-\upsilon^2)}}\ \text{m/s} \tag{27}$$

is used [Ref.1].

Here, ρ_s is the density of shell's material.

By a series of manipulations detailed in Love's work, u and v are eliminated from the three equations, resulting in

$$w_{\theta\theta} + \cot\theta\, w_\theta + \left[\frac{(\Omega^2+1-\upsilon)[\Omega^2-2(1+\upsilon)]}{\Omega^2-(1-\upsilon^2)} - \frac{m^2}{\sin^2\theta}\right]w =$$

$$\frac{-a^2}{Eh[\Omega^2-(1-\upsilon^2)]}\left\{\sigma_{a\theta\theta} + \sigma_{a\theta\theta}\cot\theta + (\Omega^2+1-\upsilon-\frac{m^2}{\sin^2\theta})\sigma_a\right\}, \tag{28}$$

where the frequency dependent term, Ω, is

$$\Omega = \frac{\omega a}{C_p}, \tag{29}$$

and all ϕ dependence is of the form $e^{im\phi}$. A harmonic time dependance of the form $e^{i\omega t}$ has been assumed.

Here,

$$\omega = 2\pi f, \tag{30}$$

and f is the excitation frequency.

If the new independent variable η is introduced:

$$\eta = \cos\theta. \tag{31}$$

The derivations with respect to θ can be replaced by

$$\frac{\partial}{\partial\theta} = -\sqrt{1-\eta^2}\,\frac{\partial}{\partial\eta}, \tag{32}$$

and

$$\frac{\partial^2}{\partial\theta} = -\eta\frac{\partial}{\partial\eta} + (1-\eta^2)\frac{\partial^2}{\partial\eta^2}. \tag{33}$$

Writing Equation (28) in terms of (32) and (33):

$$(1-\eta^2)w_{\eta\eta} - \eta w_\eta + \frac{\eta}{\sqrt{1-\eta^2}}(-\sqrt{1-\eta^2}\,w_\eta)$$

$$+\left[\frac{(\Omega^2+1-\upsilon)\,[\Omega^2-2\,(1+\upsilon)]}{\Omega^2-(1-\upsilon^2)} - \frac{m^2}{1-\eta^2}\right]w =$$

$$\frac{-a^2(1-\upsilon^2)}{Eh[\Omega^2-(1-\upsilon^2)]}\times$$

$$\left[-(1-\eta^2)\sigma_{a\eta\eta} - \eta\sigma_{a\eta} + \frac{\eta}{\sqrt{1-\eta^2}}(-\sqrt{1-\eta^2}\,\sigma_{a\eta}) + \left\{(\Omega^2+1-\upsilon) - \frac{m^2}{1-\eta^2}\right\}\sigma_a\right.,$$

(34)

and it can be seen that w and σ_a are being operated on by Legendre's differential equation.

Representing the applied stress σ_a, and the normal component, w, in terms of the Legendre polynomial yields

$$w = \Sigma_{n,m} w_{nm} P_n^m(\eta) e^{im\phi} \tag{35}$$

and

$$\sigma_a = \Sigma_{n,m} F_{nm} P_n^m(\eta) e^{im\phi}, \tag{36}$$

where $P_n^m(\eta)$ are the associated Legendre eigenfunctions weighted by the excitation stress amplitude F_{nm} and the normal displacement amplitude w_m. Legendre's equation can be written

$$(1-\eta^2)\frac{\partial^2}{\partial\eta^2}P_n^m(\eta) - 2\eta\frac{\partial}{\partial\eta}P_n^m(\eta) - \frac{m^2}{1-\eta^2}P_n^m(\eta) = -\lambda_n P_n^m(\eta), \tag{37}$$

where

$$\lambda_n = n(n+1). \tag{38}$$

and by substitution of (36) and (37) into (40) using (39), one is left with the algebraic equation related F_{nm} to w_{nm}:

$$\left\{\frac{(\Omega^2+1-\nu)\,[\Omega^2-2\,(1+\nu)]}{\Omega^2-(1-\nu^2)} - \lambda_n\right\} w_{nm} = \frac{-a^2}{hC_p^2\rho_s[\Omega^2-(1-\nu^2)]}[\Omega^2+1-\nu-\lambda_n]F_{nm} \quad . \tag{39}$$

In analogy with mechanical impedance [Ref. 13], the modal mechanical impedance, Z_n, can be defined as:

$$Z_n = \frac{F_{nm}}{i\omega w_{nm}}, \tag{40}$$

where the time dependence is given by $e^{-i\omega t}$.

It is then possible to write Equation (40) with modal mechanical impedance, as

$$Z_n = i\frac{hC_p\rho_s}{a\Omega}\left\{\frac{[\Omega^2-2(1+\upsilon)](\Omega^2+1-\upsilon-\lambda_n)-\lambda_n(1+\upsilon)^2}{\Omega^2+1-\upsilon-\lambda_n}\right\}. \tag{41}$$

Now, for the scattering problem, the pressure directed radially inward will be the sum of the incidental spherical wave and the outgoing spherical wave.

$$F_{nm} = -\left\{j_n(ka)I_{nm} + h_n^{(2)}(ka)R_{nm}\right\}, \tag{42}$$

where the term $j_n(ka)I_{nm}$ refers the incident spherical wave, p^i, and the term $h_n^{(2)}(ka)R_{nm}$ is the scattered spherical wave, p^s. The constants I_{nm} and R_{nm} are amplitudes of incident and scattered waves respectively.

$$p^i = \Sigma_{nm} I_{nm}\, j_n(kr)P_n^m(\eta)e^{im\phi}, \tag{43}$$

$$p^s = \Sigma_{nm} R_{nm} h_n^{(2)}(kr)P_n^m(\eta)e^{im\phi}, \tag{44}$$

$$w = \Sigma_{nm} w_{nm} P_n^m(\eta) e^{im\phi}. \tag{45}$$

Equations (43), (44), and (45) express the pressures and radial displacements in terms of spherical harmonics.

Applying Equation (42) in Equation (40) yields

$$I_{nm}\, j_n(ka) + R_{nm} h_n^{(2)}(ka) = -i\omega Z_n w_{nm}. \tag{46}$$

Furthermore, applying Euler's Equation [Ref. 13] at the surface of sphere,

$$\frac{\partial p}{\partial r}\rfloor_{r=a} = -\rho_f \frac{\partial^2 w}{\partial t^2}\rfloor_{r=a}. \tag{47}$$

where, ρ_f is the density of the fluid.

The pressure at surface, p, is the sum of the incident pressure, p^i, and the scattered pressure, p^s, as in

$$p = p^i + p^s. \tag{48}$$

Now, applying Equations (43), (44), (45) and (46) on (47),

$$I_{nm}\, j'_n(ka) + R_{nm} h_n^{(2)\prime}(ka) = \omega \rho_f C_f w_{nm}. \tag{49}$$

where $j_n'(ka)$ and $h_n^{(2)\prime}(ka)$ are the first derivatives of the spherical Bessel and Hankel functions.

From Equation (49),

$$w_{nm} = \frac{1}{\omega\rho_f C_f}\left\{I_{nm}\, j_n'(ka) + R_{nm} h_n^{(2)\prime}(ka)\right\}. \tag{50}$$

Now, Equation (50) can be utilized in Equation (46), yielding

$$\rho_f C_f \,[I_{nm}\, j_n(ka) + R_{nm} h_n^{(2)}(ka)] = -iZ_n[I_{nm}\, j_n'(ka) + R_{nm} h_n^{(2)\prime}(ka)]. \tag{51}$$

Finally, we have an equation for calculation of the constant term R_{nm},

$$R_{nm} = -\left\{\frac{iZ_n j_n'(ka) + \rho_f C_f\, j_n(ka)}{iZ_n h_n^{(2)\prime}(ka) + \rho_f C_f\, h_n^{(2)}(ka)}\right\} I_{nm} \quad . \tag{52}$$

The values of R_{nm} for each n and m will be the diagonal elements of the T-matrix of the thin spherical shell; each I_{nm} equals one.

2. Thinness Criteria

The theory of thin elastic shells is based upon the postulate that shells are thin. No exact definition of thinness is available, however.

From Junger & Feit [Ref. 14] we have a definition of "thick" plates, expressed as

$$h > \frac{\lambda_s}{20}, \tag{53}$$

where λ_s is the shear wavelength. An ad hoc treatment to account for thick shells that takes into account bending stresses introduces the parameter β, which is a function of the thickness, h, and the middle surface of the shell, a_m, as in

$$\beta^2 = \frac{h^2}{12a_m^2}. \tag{54}$$

A rule of thumb suggested by Kraus [Ref. 15], is that the thickness should be less than one tenth of the radius of curvature of the reference surface, i.e., $\beta^2 < 1/1200$.

On the other hand, when Kraus examines the dynamic analysis of shells [Ref. 15], he affirms that the theory based upon Love's postulate gives a reliable result in the range

$$0 < \Omega < \Omega_s, \tag{55}$$

where Ω_s is the dimensionless frequency of the first thickness shear mode:

$$\Omega_S = \frac{\omega_S a_m}{C_T}, \tag{56}$$

where

$$\omega_s = \frac{\pi C_T}{h}, \tag{57}$$

and

$$C_T = \left(\frac{E}{2(1+\upsilon)\rho_s}\right)^{\frac{1}{2}}. \tag{58}$$

Applying Equation (27) and (29) in Equation (55) yields

$$0 < \sqrt{\frac{\rho_s(1-\upsilon^2)}{E}}\,\omega a_m < \frac{1}{10}\sqrt{\frac{\rho_s(1-\upsilon^2)}{E}}\,\omega_s a_m. \tag{59}$$

Now, after simplifying Equation (59) and substituting Equation (57),

$$0 < \omega < \frac{2\pi C_T}{20h}, \tag{60}$$

which can be rewritten as

$$h < 0.05\lambda_s, \tag{61}$$

and is exactly the same definition offered by Junger & Feit [Ref. 14] listed in Equation (53).

At this point, the thinness criterion for applying the theory of thin elastic shell can be considered to be the expression in Equation (61). This criterion is obeyed in all subsequent calculations.

III. SPHERICAL THREE-DIMENSIONAL MODEL

A. INTRODUCTION

In order to apply the T-matrix method to modeling a dense sonar array, the radiated and scattered pressure from an individual transducer must be calculated. Using finite element analysis, the pressure scattered from a transducer due to an incident spherical harmonic wave can be computed very accurately. To employ the Finite Element Code ATILA, a three-dimensional model of an elastic spherical shell is used.

B. THE MODEL

A 0.5 m outer radius, one centimeter-thick spherical steel shell in water is modeled. An ATILA model is realized using 3D elastic elements, 3D fluid elements, 2D solid-fluid interface elements, and 2D radiation surface elements. The thickness was chosen in an attempt to comply with aspect ratio constraints [Ref. 2] for elements used by ATILA, and to be within the theoretical conditions of thinness (Chapter II).

In order to calculate the limit of thickness to which we can apply the theory of thin elastic shells (Chapter II), the following parameters of the model (for steel) are applied in Equation (58)

$E = 0.125x10^{12}$ (Young's modulus)

$\rho_s = 7500 \, Kg/m^3$, and

$\upsilon = 0.33$ (Poisson's ratio).

The value of C_T is then 3282.83 m/sec^2, which for a chosen operating frequency of 474 Hz (corresponding to ka=1) results in an upper limit for the shell thickness of 0.346 m, and therefore a thickness of one centimeter is verifiably inside the limit.

The complete ATILA code for the elastic shell is presented in Appendix B. Note that, to write an ATILA code for a piezoelectric sphere, the same model can be used as for the elastic sphere. In this instance, the ATILA code can handle the piezoelectric sphere by changing the elements from elastic to piezoelectric type.

The model is composed of 2746 nodes and 288 elements. The mesh is shown in Figures 5 and 6.

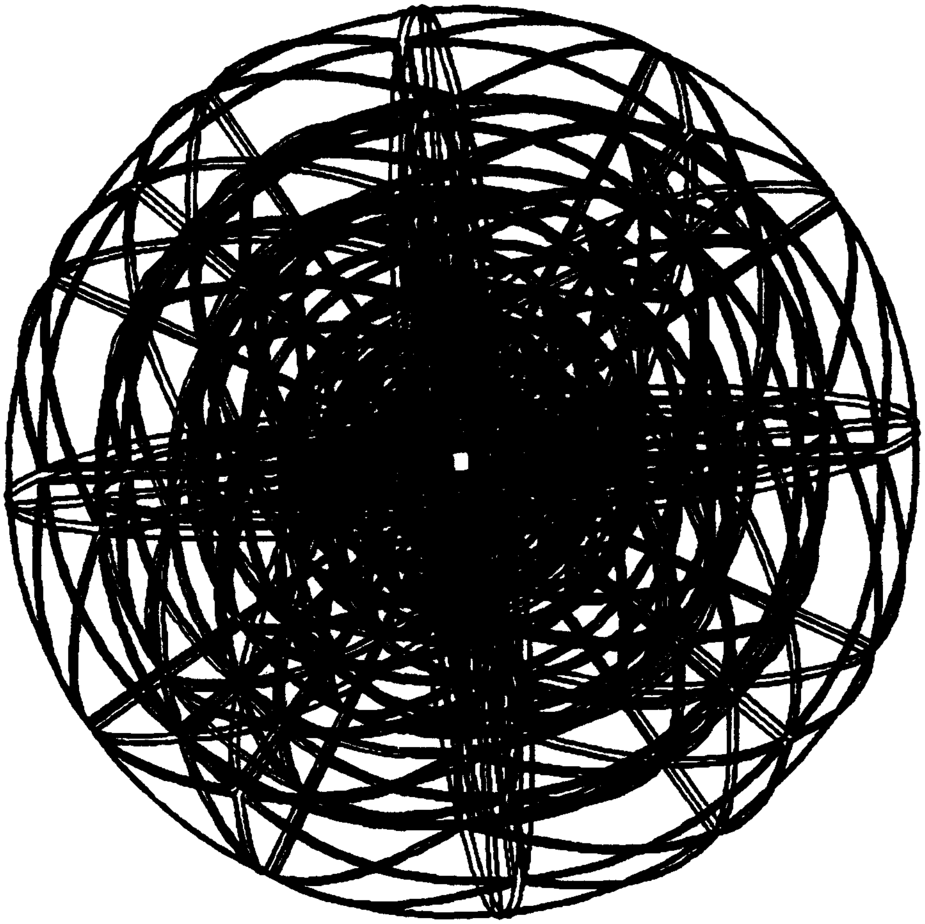

Figure 5. The Model, as Seen from the Side.

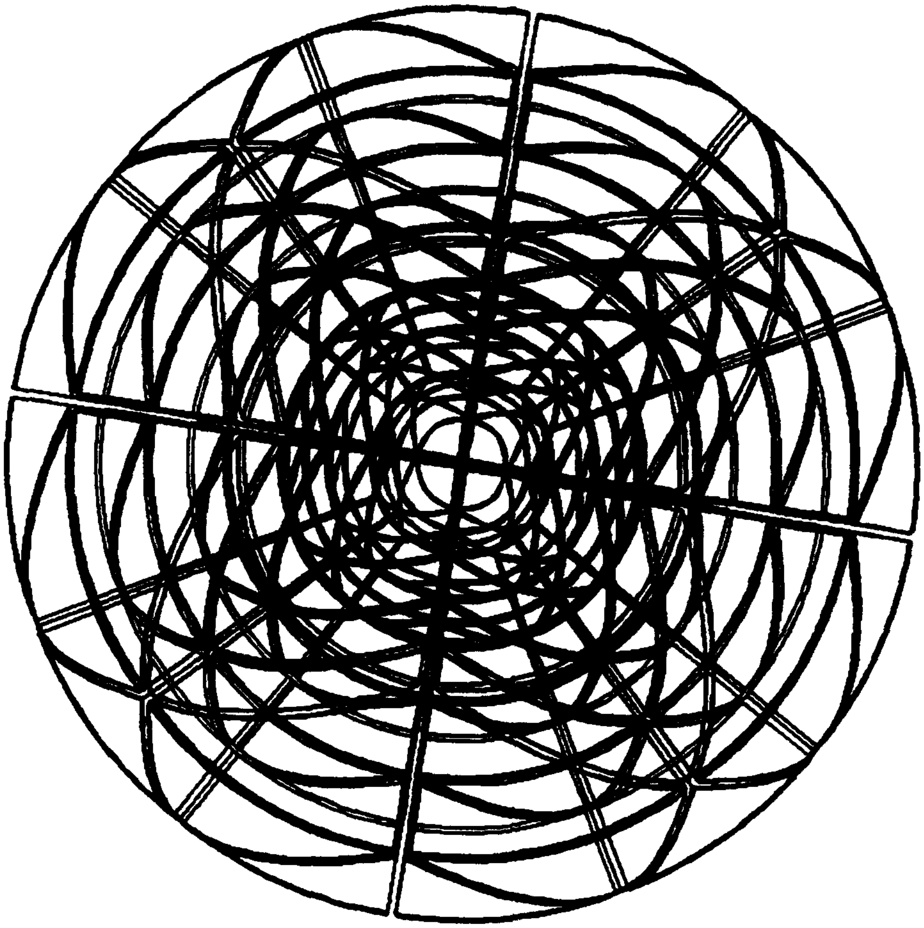

Figure 6. The Model, as Seen from Above.

The material properties of the shell are listed on the first page of Appendix B. The format is described in the ATILA user's manual [Ref. 2].

The elements used in the model followed the pattern from the manual [Ref. 2], and are presented in Table 1.

TABLE I. ATILA ELEMENTS		
Region	**Element**	**Geometry**
Elastic shell	SHEL06C	6-node triangular
Interface solid - fluid	TRIA12I	12-node triangular
Fluid	PRIS15F	15-node triangular prism
Radiation Surface	TRIA06R	6-node triangular

IV. RESULTS

A. THE T-MATRIX ELEMENTS AND THE ATILA CODE.

The definition of the T-matrix adopted in this work relates outgoing spherical waves (i.e. Hankel functions) to incident standing waves (i.e., spherical Bessel functions). However, using ATILA, calculation of the coefficients of the scattered pressure for each harmonic, $\{P^S\}$, requires that the incident wave [Appendix A] be an incoming traveling wave rather than a standing wave.

To use the results of the ATILA code in calculations, Equation (46) and its respective derivative, Equation (49) is adapted to

$$\overline{I_{nm}}\, h_n^{(1)}(ka)+\overline{R_{nm}}\, h_n^{(2)}(ka) = -i\omega Z_n\, \overline{W_{nm}}, \qquad (62)$$

and its first derivative,

$$\overline{I_{nm}}\, h_n^{(1)\prime}(ka)+\overline{R_{nm}}\, h_n^{(2)\prime}(ka) = \omega\rho_f C_f\, \overline{W_{nm}}. \qquad (63)$$

The coefficients $\overline{R_{nm}}$ are the amplitudes of the scattered wave components and the coefficients $\overline{W_{nm}}$ are the amplitudes of the components of the radial displacement coefficients for an incoming wave with coefficients $\overline{I_{nm}}$.

Equation (52) (Chapter II) is used to calculate the R_{nm} coefficients from an incident standing wave, from where the T-Matrix elements are obtained. For incident incoming traveling waves, the R_{nm} elements can be calculated as follows.

From Equation (62) and (63),

$$\overline{R_{nm}} = -\left\{ \frac{iZ_n h_n^{(1)'}(ka) + \rho_f C_f h_n^{(1)}(ka)}{iZ_n h_n^{(2)'}(ka) + \rho_f C_f h_n^{(2)}(ka)} \right\} \overline{I}_{nm}. \tag{64}$$

We can relate R_{nm} and $\overline{R_{nm}}$. We, first ,define :

$$X_{nm} = -\left\{ \frac{iZ_n(i\, y_n'(ka)) + \rho_f C_f (i\, y_n(ka))}{iZ_n h_n^{(2)'}(ka) + \rho_f C_f h_n^{(2)'}(ka)} \right\} I_{nm}, \tag{65}$$

where $y_n(ka)$ is the spherical Bessel function of the second kind.

Applying Equation (65) on Equations (52) and (64), respectively :

$$R_{nm} - X_{nm} = -1 \tag{66}$$

and

$$\overline{R_{nm}} - X_{nm} = R_{nm} \tag{67}$$

Solving Equations (66) and (67) in terms of R_{nm}:

$$R_{nm} = \tfrac{1}{2}\{\overline{R_{nm}} - 1\} \tag{68}$$

Equation (68) is used to calculate the R_{nm} coefficients, and hence the T-Matrix elements for incident standing waves, from the $\overline{R_{nm}}$ coefficients calculated when ATILA code uses incoming incident waves to compute the scattered pressure.

The goal of this research is to compare the T-Matrix elements computed by scattered field pressure from the ATILA code with those determined by theoretical means (Appendix C).

The T-Matrix for an elastic spherical shell is a diagonal matrix where the non-zero elements equal the R_{nm} coefficients, for $I_{nm} = \overline{I_{nm}} = 1$. In this research, calculations of $\overline{R_{nm}}$ were performed up to the harmonic of second order, and the T-Matrix has the following format:

$$\begin{pmatrix} R_{00} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_{1-1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_{10} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{2-2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_{2-1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & R_{20} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_{21} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_{22} \end{pmatrix}$$

In the T-matrix, for instance, the element R_{2-1} corresponds to the spherical harmonic with n equal to two and m equal to negative one. The

T-Matrix elements were theoretically computed using thin shell theory (Appendix C) and the results are presented in Table II.

TABLE II. THE ANALYTIC DIAGONAL ENTRIES OF THE T-MATRIX				
ELEMENT	REAL PART	IMAG PART	MAGNITUDE	PHASE (DEGREES)
$T_{11} = R_{00}$	-1.3465E-02	1.1525E-01	1.1604E-01	9.6663E+01
$T_{22} = R_{1-1}$	-6.0255E-03	7.7390E-02	7.7624E-02	9.4452E+01
$T_{33} = R_{10}$	-6.0255E-03	7.7390E-02	7.7624E-02	9.4452E+01
$T_{44} = R_{11}$	-6.0255E-03	7.7390E-02	7.7624E-02	9.4452E+01
$T_{55} = R_{2-2}$	-6.1773E-04	-2.4847E-02	2.4854E-02	-9.1424E+01
$T_{66} = R_{2-1}$	-6.1773E-04	-2.4847E-02	2.4854E-02	-9.1424E+01
$T_{77} = R_{20}$	-6.1773E-04	-2.4847E-02	2.4854E-02	-9.1424E+01
$T_{88} = R_{21}$	-6.1773E-04	-2.4847E-02	2.4854E-02	-9.1424E+01
$T_{99} = R_{22}$	-6.1773E-04	-2.4847E-02	2.4854E-02	-9.1424E+01

Incident waves of the form

$$P_{inc}(r, \theta, \phi) = h_n^{(1)}(kr) P_n^m(\cos\theta) e^{im\phi} e^{iwt}$$

[Appendix A] for particular values of *n* and *m* were applied to the finite-element model spherical shell using the ATILA code and the resulting scattered pressures were calculated . For each incident wave of a particular spherical harmonic component (one *n* and *m*), the resulting reflection coefficients for all the spherical harmonic components (all *n* and *m*) were calculated from nodal values of the scattered pressure on the shell surface by a least-squares fitting procedure employing singular value decomposition

[Appendix C]. The results for the diagonal elements of the T-matrix are given in Table III. The last two columns of Table III give the error in the ATILA results for the diagonal components compared to the theoretical results of Table II.

TABLE III. THE ATILA DIAGONAL T-MATRIX ELEMENTS

ELEMENT	REAL PART	IMAG PART	MAGNITUDE	PHASE (DEGREES)	MAG. ERROR (PERCENT)	PHASE ERROR (DEGREES)
T_{11}	-1.2624E-02	1.1429E-01	1.1498E-01	9.6303E+01	-0.91	-0.36
T_{22}	-6.8902E-03	8.2376E-02	8.2664E-02	9.4781E+01	6.49	0.33
T_{33}	-5.7422E-03	8.3113E-02	8.3311E-02	9.3952E+01	7.33	-0.5
T_{44}	-6.8668E-03	8.2363E-02	8.2649E-02	9.4766E+01	6.47	0.31
T_{55}	-2.8487E-03	-1.5203E-02	1.5468E-02	-1.0061E+02	-37.8	-9.19
T_{66}	-2.7899E-03	-1.5159E-02	1.5413E-02	-1.0043E+02	-38	-9.01
T_{77}	-2.4889E-03	-1.5287E-02	1.5489E-02	-9.9247E+01	-37.7	-7.82
T_{88}	-2.7847E-03	-1.5164E-02	1.5418E-02	-1.0041E+02	-38	-8.99
T_{99}	-2.8227E-03	-1.5182E-02	1.5443E-02	-1.0053E+02	-37.9	-9.11

The T-matrix for a spherically symmetric scattered should be diagonal, that is, there should be only one spherical harmonic component of the scattered wave for a single-component incident wave, and it should be the same component as the incident wave. Nonzero off-diagonal components computed for the T-matrix of the spherical elastic shell can be termed "leakage" (in some abstract sense). The existence of leakage indicates a weakness in the model.

Nonzero off-diagonal components of the T-matrix which were greater than 10^{-14} of the diagonal element were found for a few of the ATILA results. These are given in Table IV below.

TABLE IV. SIGNIFICANT OFF-DIAGONAL T-MATRIX ELEMENTS

element	real	imag	mag	phase	mag T_{ij} rel to T_{ii}	phase T_{ij} rel to T_{ii}
T_{71}	-7.6679E-04	5.3764E-04	9.3650E-04	1.4496E+02	8.14E-03	48.7
T_{62}	2.2172E-05	7.2191E-06	2.3318E-05	1.8035E+01	2.82E-04	-76.7
T_{84}	-8.9863E-06	-3.8094E-07	8.9944E-06	-1.7757E+02	1.09E-04	-272.3
T_{95}	1.6194E-05	1.4535E-05	2.1761E-05	4.1911E+01	1.41E-03	142.5
T_{26}	-1.1214E-05	4.1657E-08	1.1214E-05	1.7979E+02	7.28E-04	280.2
T_{17}	5.5328E-03	-4.3539E-03	7.0405E-03	-3.8200E+01	4.55E-01	61
T_{48}	3.5575E-05	3.6843E-05	5.1215E-05	4.6003E+01	3.32E-03	146.4
T_{59}	9.8906E-03	7.9364E-03	1.2681E-02	3.8744E+01	8.21E-01	139.3

It is seen that there is significant leakage from the 2,0 to the 0,0 component T_{17}, and from the 2,2 to the 2,-2 component T_{59}, for the finite-element model employed. This could indicate that either the mesh is too coarse, particularly that of the shell, or that the radius of the radiation damping elements which terminate the fluid mesh is too small. These possibilities remain to be investigated.

B. THE ACOUSTIC IMPEDANCE

To further validate the three-dimensional model used in the ATILA code, the acoustic impedance computed analytically and with ATILA output were also compared. The theoretical acoustic impedance, for each harmonic, is given by Equation (42).

On the other hand, output from ATILA can be used to determine the impedance from Equation (41), where F_{nm} will be the total field pressure. Total pressures are output from ATILA when the pressure command in ATILA code (Appendix B) is "PRESSURE TOTAL" [Reference 2]. The terms W_{nm} are also computed from the ATILA output. Averaged values of F_{nm} and W_{nm} were used to compute an approximation to the acoustic impedance of each harmonic. The results are presented in Table VI.

TABLE V. RESULTS OF ACOUSTIC IMPEDANCE

Theoretical Values	From ATILA	Error and Number of Points
Z_0=0.00-i 0.8396E+07	Z_0=0.5804E+03-i 0.82305E+07	2% and 146
Z_1=0.00+i 0.6945E+06	Z_1=0.26659E+04+i 0.60223E+06	13% and 138

V. CONCLUSIONS

The transition matrix, or "T-matrix", relating the scattered and incident acoustic waves for a thin elastic spherical shell in a free-field environment has been evaluated using the ATILA finite-element code. A three-dimensional finite-element model of a 0.5-m outer radius, 1-cm thick spherical steel shell surrounded by water was developed [Appendix A]. In this model the spherical shell surface is divided into seventy-two approximately equal area triangular regions. The ATILA code was used to calculate the scattered pressure over the surface of the shell for incident waves represented as products of radial Hankel functions and spherical harmonics. This was done for all components through the second order in the Hankel function. The chosen driving frequency was 474 Hz, corresponding to a value of ka=1, where k is the wavenumber of sound in water and a is the radius of the shell. The ATILA results were compared with the results of analytical thin shell theory. For the diagonal elements of the T-matrix , the two results were found to agree within one, seven, and thirty-eight percent, respectively, for the zeroth, first, and second order components. The ATILA results also produce a few nonzero off-diagonal T-matrix elements which do not appear in the theoretical results, and which should not be present according to symmetry considerations. The reason for the appearance of nonzero off-diagonal elements in the ATILA results is not known at this time and warrants further investigation. Also computed for each harmonic component was the modal acoustical impedance of the shell. These results agreed with the results of thin shell theory within two percent for the zeroth order component and thirteen percent for the first order components.

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APPENDIX A

```
      FUNCTION INCPRE(X,Y,Z,K)
*------------------------------------------------------------
* PROGRAM BY ARTHUR LOBO DA COSTA RUIZ  12/23/93
*------------------------------------------------------------
* FUNCTION:
* COMPUTES THE INCIDENT SPHERICAL HARMONIC PRESSURE AT THE POINT
* (X,Y,Z),FOR THE WAVENUMBER K
*
* VARIABLES INPUT:
*            X,Y,Z: CARTESIAN COORDINATES OF THE POINT
*                K: WAVENUMBER
*
* VARIABLES OUTPUT:
*            RADIUS :R IN METERS
*            PHI IN DEGREE (HORIZONTAL ANGLE)
*            THETA IN RADIANS (AZIMUTAL ANGLE)
*            INCPRE : PRESSURE AT POINT IN PASCAL
*------------------------------------------------------------
     DOUBLE PRECISION K,X,Y,Z,R,PHI,THETA,KR
      REAL*8 PMN(-2:2,0:2),LOUT
      INTEGER N,M,NMAX
      COMPLEX*16 INCPRE,H(0:2),HOUT
*
* N AND M ARE ORDERS FOR HANKEL AND LEGENDRE FUNCTIONS
*
      N=0
      M=0
*
*     HOUT AND LOUT ARE HANKEL AND LEGENDRE OUTPUTS
*     REF TO N AND M
*
      NMAX=2
*
* TRANSFORM CARTESIAN COORDINATES (X,Y,Z)
*        INTO SPHERICAL COORDINATES
* R(RADIUS), PHI(AZIMUTAL ANGLE) AND THETA(POLAR ANGLE)
*
      R=DSQRT(X*X+Y*Y+Z*Z)
      PHI=DATAN2D(Y,X)
      IF((X.EQ.0).AND.(Y.EQ.0)) PHI=0.0D0
      THETA=DACOS(Z/R)
      KR=K*R
*
* NMAX IS THE MAXIMUM NUMBER OF HARMONICS
```

```
*
      CALL HANKEL(KR,NMAX,H)
*
* SUBROUTINE HANKEL RETURNS SPHERICAL HANKEL
*                FUNCTIONS JN AND I YN
*
      CALL LEGNDR(THETA,NMAX,PMN)
      LOUT=PMN(M,N)
*
* SUBROUTINE LEGNDR RETURNS ASSOCIATE LEGENDRE FUNTION
*
      INCPRE=H(N)*LOUT*DCMPLX(DCOSD(M*PHI),DSIND(M*PHI))
      IF ((R.LE.0.501).AND.(R.GT.0.499)) THEN
*     PRINT *,"X,Y,Z =",X,Y,Z
*     PRINT *,"PHI,THETA =",PHI,THETA
*     PRINT *,"K,R,KR =",K,R,KR
*     PRINT *,"REAL HANKEL =",HOUT
*     PRINT *,"LEGENDRE =",LOUT
      PRINT *,INCPRE
*     PRINT *,"****************"
      ELSE
       CONTINUE
      ENDIF
      RETURN
      END
C *************************************************************
C
      SUBROUTINE HANKEL(X,NMAX,H)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMPLEX*16 H(0:NMAX)
C
C  GIVEN THE VARIABLE X, AND THE MAXIMUM ORDER NMAX,
C    THIS ROUTINE GENERATES THE SPHERICAL HANKEL FUNCTION HN
C    FOR ALL N FROM 0 TO NMAX (INCLUSIVE)
C  INPUT:
C    X = DOUBLE PREC. VARIABLE (RADIUS)
C    NMAX = INTEGER MAXIMUM ORDER OF BESSEL FUNCTIONS DESIRED
C  OUTPUT:
C    H(N) = ARRAY OF SPHERICAL HANKEL FUNCTIONS HN(X), WHERE
C        HN = JN + I YN C C  THIS ROUTINE IS BASED ON THE RECURSION FORMULAE
C    FROM ABRAMOWITZ & STEGUN: 10.1.10 & 10.1.15, PP.438-9
C    THE F' S ARE THE COEFFICIENTS OF ORDER N & -(N+1),
C    THE FO' S ARE OLD F' S, FOR RECURSION
C
      IF ( X .LE. 0.0D0 ) THEN
        H(0) = DCMPLX(1.0D0,-1.0D35)
        DO 2 N = 1, NMAX
          H(N) = CMPLX(0.0D0,-1.0D35)
    2   CONTINUE
        RETURN
      END IF
```

```
      SX = DSIN(X)
      CX = DCOS(X)
      XINV = 1.0D0/X
      M1N = -1.0D0
      FN = XINV
      FMN = 0.0D0
      FNO = FMN
      FMNO = FN
      DO 4 N = 0, NMAX
      H(N) = CMPLX( FN*SX + M1N*FMN*CX, -FN*CX + M1N*FMN*SX )
      T1 = (2*N+1)*XINV
      T2 = T1*FN - FNO
      FNO = FN
      FN = T2
      T2 = -T1*FMN - FMNO
      FMNO = FMN
      FMN = T2
      M1N = -M1N
    4 CONTINUE
      RETURN
      END
C
C ****************************************************************
C
      SUBROUTINE LEGNDR(THETA,NMAX,PMN)
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8  PMN(-NMAX:NMAX,0:NMAX)
C
C GIVEN THE VARIABLE THETA, AND THE MAXIMUM ORDER NMAX,
C   THIS ROUTINE GENERATES THE ASSOC. LEGENDRE FUNCTIONS PMN
C   OF THE ARGUMENT COS(THETA)  (THETA MUST BE BETWEEN 0 & PI)
C   FOR ALL N FROM 0 TO NMAX (INCLUSIVE)
C   AND FOR ALL M FROM -N TO N (SOME OTHERS SET TO ZERO)
C INPUT:
C   THETA = VARIABLE (POLAR ANGLE), MUST BE BETWEEN 0 & PI (INCL.)
C   NMAX = INTEGER MAXIMUM ORDER OF LEGENDRE FUNCTIONS DESIRED
C OUTPUT:
C   PMN = DOUBLE PREC. ARRAY, CONTAINS ASSOC. LEGENDRE FNS
C
C THIS ROUTINE IS BASED ON THE RECURSION FORMULAE
C   FROM ABRAMOWITZ & STEGUN
C
      X = DCOS(THETA)
      SINTHT = DSIN(THETA)
      IF ( SINTHT .GT. 0. ) THEN
        SININV = 1.0D0/SINTHT
      ELSE
        SININV = 0.0D0
      END IF
C SET VALUES FOR N = 0, 1  (NMAX MUST BE AT LEAST 1)
      PMN(0,0) = 1.0D0
```

```
      PMN(1,0) = 0.0D0
      PMN(-1,0) = 0.0D0
      PMN(0,1) = X
      PMN(1,1) = -SINTHT
      PMN(-1,1) = SINTHT*0.5D0
C  IN LOOP, TNP1 = 2*N+1, TNP2FC = (2*N+2)!, M1N = (-1)**(N+1)
      TNP1 = 1.0D0
      TNP2FC = 2.0D0
      M1N = -1.0D0
      DO 4 N = 1, NMAX-1
        TNP1 = TNP1 + 2.0D0
        TNP2FC = TNP2FC * TNP1 * (TNP1+1)
        M1N = -M1N
        DO 3 M = -N, N
          PMN(M,N+1) = (TNP1*X*PMN(M,N) - (N+M)*PMN(M,N-1))/(N-M+1)
    3   CONTINUE
        PMN(N+1,N) = 0.0D0
        PMN(-N-1,N) = 0.0D0
        PMN(N+1,N+1) = (X*PMN(N,N+1) - TNP1*PMN(N,N)) * SININV
        PMN(-N-1,N+1) = M1N*PMN(N+1,N+1)/TNP2FC
4 CONTINUE
C     DO 120 N=0,NMAX
C     DO 120 M=-N,N
C120  WRITE(6,130) N,M,PMN(M,N)
C130  FORMAT(1X,'  N= ',I4,1X,'  M= ',I4,1X,'  PMN= ',F13.6)
      RETURN
      END
```

APPENDIX B

```
*****************************************************
* ATILA MODEL ESHELL4:  3-D ELASTIC SPHERICAL SHELL, 1 CM THICK
* AUTHOR:  BAKER        SHELL RADIUS 0.5 M, MADE OF NEW CURVED SHELL ELEMENTS
*   DATE:  MAR 1994     FLUID RADIUS 2.5 M
*                      EACH OCTANT DIVIDED INTO 9 REGIONS
*                      2 FLUID LAYERS, EACH 0.25 M THICK,
*                      3 FLUID LAYERS, EACH 0.5 M THICK
*****************************************************
PRINTING = 2
RADIATION DIPOLAR
ANALYSIS HARMONIC
MATERIAL
 25CD4SH    * PROPERTIES FOR CURVED COMPOSITE SHELL ELEMENTS
0.215E+12  0.330E+00  0.750E+04  0.000E+00  0.000E+00  0.000E+00 &
0.215E+12  0.330E+00  0.750E+04  0.000E+00  1.0        0.000E+00
LCPDDC = 6
NLOAD = 1
FREQUENCY  474.
GEOMETRY
   1
  2.5     * RADIUS OF RADIATION BOUNDARY = 2.5 M
   2
  1  0  0.01    * THICKNESS OF SHELL = 1 CM
PRESSURE SCATTERED
SKYLINE REAL
PRECISION DOUBLE
NEWAXES SPHERICAL
  0  0  0  0  0  0
NODES
* 0001 *  0.490  000  000.0
* 0002 *  0.490  015  000.0
* 0003 *  0.490  015  090.0
* 0004 *  0.490  015  180.0
* 0005 *  0.490  015  270.0
* 0006 *  0.490  030  000.0
* 0007 *  0.490  030  045.0
* 0008 *  0.490  030  090.0
* 0009 *  0.490  030  135.0
* 0010 *  0.490  030  180.0
* 0011 *  0.490  030  225.0
* 0012 *  0.490  030  270.0
* 0013 *  0.490  030  315.0
* 0014 *  0.490  045  000.0
* 0015 *  0.490  045  030.0
```

```
* 0016 * 0.490 045 060.0
* 0017 * 0.490 045 090.0
* 0018 * 0.490 045 120.0
* 0019 * 0.490 045 150.0
* 0020 * 0.490 045 180.0
* 0021 * 0.490 045 210.0
* 0022 * 0.490 045 240.0
* 0023 * 0.490 045 270.0
* 0024 * 0.490 045 300.0
* 0025 * 0.490 045 330.0
* 0026 * 0.490 060 000.0
* 0027 * 0.490 060 022.5
* 0028 * 0.490 060 045.0
* 0029 * 0.490 060 067.5
* 0030 * 0.490 060 090.0
* 0031 * 0.490 060 112.5
* 0032 * 0.490 060 135.0
* 0033 * 0.490 060 157.5
* 0034 * 0.490 060 180.0
* 0035 * 0.490 060 202.5
* 0036 * 0.490 060 225.0
* 0037 * 0.490 060 247.5
* 0038 * 0.490 060 270.0
* 0039 * 0.490 060 292.5
* 0040 * 0.490 060 315.0
* 0041 * 0.490 060 337.5
* 0042 * 0.490 075 000.0
* 0043 * 0.490 075 018.0
* 0044 * 0.490 075 036.0
* 0045 * 0.490 075 054.0
* 0046 * 0.490 075 072.0
* 0047 * 0.490 075 090.0
* 0048 * 0.490 075 108.0
* 0049 * 0.490 075 126.0
* 0050 * 0.490 075 144.0
* 0051 * 0.490 075 162.0
* 0052 * 0.490 075 180.0
* 0053 * 0.490 075 198.0
* 0054 * 0.490 075 216.0
* 0055 * 0.490 075 234.0
* 0056 * 0.490 075 252.0
* 0057 * 0.490 075 270.0
* 0058 * 0.490 075 288.0
* 0059 * 0.490 075 306.0
* 0060 * 0.490 075 324.0
* 0061 * 0.490 075 342.0
* 0062 * 0.490 090 000.0
* 0063 * 0.490 090 015.0
* 0064 * 0.490 090 030.0
* 0065 * 0.490 090 045.0
* 0066 * 0.490 090 060.0
```

```
* 0067 * 0.490 090 075.0
* 0068 * 0.490 090 090.0
* 0069 * 0.490 090 105.0
* 0070 * 0.490 090 120.0
* 0071 * 0.490 090 135.0
* 0072 * 0.490 090 150.0
* 0073 * 0.490 090 165.0
* 0074 * 0.490 090 180.0
* 0075 * 0.490 090 195.0
* 0076 * 0.490 090 210.0
* 0077 * 0.490 090 225.0
* 0078 * 0.490 090 240.0
* 0079 * 0.490 090 255.0
* 0080 * 0.490 090 270.0
* 0081 * 0.490 090 285.0
* 0082 * 0.490 090 300.0
* 0083 * 0.490 090 315.0
* 0084 * 0.490 090 330.0
* 0085 * 0.490 090 345.0
* 0086 * 0.490 105 000.0
* 0087 * 0.490 105 018.0
* 0088 * 0.490 105 036.0
* 0089 * 0.490 105 054.0
* 0090 * 0.490 105 072.0
* 0091 * 0.490 105 090.0
* 0092 * 0.490 105 108.0
* 0093 * 0.490 105 126.0
* 0094 * 0.490 105 144.0
* 0095 * 0.490 105 162.0
* 0096 * 0.490 105 180.0
* 0097 * 0.490 105 198.0
* 0098 * 0.490 105 216.0
* 0099 * 0.490 105 234.0
* 0100 * 0.490 105 252.0
* 0101 * 0.490 105 270.0
* 0102 * 0.490 105 288.0
* 0103 * 0.490 105 306.0
* 0104 * 0.490 105 324.0
* 0105 * 0.490 105 342.0
* 0106 * 0.490 120 000.0
* 0107 * 0.490 120 022.5
* 0108 * 0.490 120 045.0
* 0109 * 0.490 120 067.5
* 0110 * 0.490 120 090.0
* 0111 * 0.490 120 112.5
* 0112 * 0.490 120 135.0
* 0113 * 0.490 120 157.5
* 0114 * 0.490 120 180.0
* 0115 * 0.490 120 202.5
* 0116 * 0.490 120 225.0
* 0117 * 0.490 120 247.5
```

```
* 0118 *  0.490  120  270.0
* 0119 *  0.490  120  292.5
* 0120 *  0.490  120  315.0
* 0121 *  0.490  120  337.5
* 0122 *  0.490  135  000.0
* 0123 *  0.490  135  030.0
* 0124 *  0.490  135  060.0
* 0125 *  0.490  135  090.0
* 0126 *  0.490  135  120.0
* 0127 *  0.490  135  150.0
* 0128 *  0.490  135  180.0
* 0129 *  0.490  135  210.0
* 0130 *  0.490  135  240.0
* 0131 *  0.490  135  270.0
* 0132 *  0.490  135  300.0
* 0133 *  0.490  135  330.0
* 0134 *  0.490  150  000.0
* 0135 *  0.490  150  045.0
* 0136 *  0.490  150  090.0
* 0137 *  0.490  150  135.0
* 0138 *  0.490  150  180.0
* 0139 *  0.490  150  225.0
* 0140 *  0.490  150  270.0
* 0141 *  0.490  150  315.0
* 0142 *  0.490  165  000.0
* 0143 *  0.490  165  090.0
* 0144 *  0.490  165  180.0
* 0145 *  0.490  165  270.0
* 0146 *  0.490  180  000.0
* 0147 *  0.000  000  000.0
* 0148 *  0.000  000  000.0
* 0149 *  0.000  000  000.0
* 0150 *  0.000  000  000.0
* 0151 *  0.000  000  000.0
* 0152 *  0.000  000  000.0
* 0153 *  0.000  000  000.0
* 0154 *  0.000  000  000.0
* 0155 *  0.000  000  000.0
* 0156 *  0.000  000  000.0
* 0157 *  0.000  000  000.0
* 0158 *  0.000  000  000.0
* 0159 *  0.000  000  000.0
* 0160 *  0.000  000  000.0
* 0161 *  0.000  000  000.0
* 0162 *  0.000  000  000.0
* 0163 *  0.000  000  000.0
* 0164 *  0.000  000  000.0
* 0165 *  0.000  000  000.0
* 0166 *  0.000  000  000.0
* 0167 *  0.000  000  000.0
* 0168 *  0.000  000  000.0
```

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* 0169 * 0.000 000 000.0
* 0170 * 0.000 000 000.0
* 0171 * 0.000 000 000.0
* 0172 * 0.000 000 000.0
* 0173 * 0.000 000 000.0
* 0174 * 0.000 000 000.0
* 0175 * 0.000 000 000.0
* 0176 * 0.000 000 000.0
* 0177 * 0.000 000 000.0
* 0178 * 0.000 000 000.0
* 0179 * 0.000 000 000.0
* 0180 * 0.000 000 000.0
* 0181 * 0.000 000 000.0
* 0182 * 0.000 000 000.0
* 0183 * 0.000 000 000.0
* 0184 * 0.000 000 000.0
* 0185 * 0.000 000 000.0
* 0186 * 0.000 000 000.0
* 0187 * 0.000 000 000.0
* 0188 * 0.000 000 000.0
* 0189 * 0.000 000 000.0
* 0190 * 0.000 000 000.0
* 0191 * 0.000 000 000.0
* 0192 * 0.000 000 000.0
* 0193 * 0.000 000 000.0
* 0194 * 0.000 000 000.0
* 0195 * 0.000 000 000.0
* 0196 * 0.000 000 000.0
* 0197 * 0.000 000 000.0
* 0198 * 0.000 000 000.0
* 0199 * 0.000 000 000.0
* 0200 * 0.000 000 000.0
* 0201 * 0.495 000 000.0
* 0202 * 0.495 015 000.0
* 0203 * 0.495 015 090.0
* 0204 * 0.495 015 180.0
* 0205 * 0.495 015 270.0
* 0206 * 0.495 030 000.0
* 0207 * 0.495 030 045.0
* 0208 * 0.495 030 090.0
* 0209 * 0.495 030 135.0
* 0210 * 0.495 030 180.0
* 0211 * 0.495 030 225.0
* 0212 * 0.495 030 270.0
* 0213 * 0.495 030 315.0
* 0214 * 0.495 045 000.0
* 0215 * 0.495 045 030.0
* 0216 * 0.495 045 060.0
* 0217 * 0.495 045 090.0
* 0218 * 0.495 045 120.0
* 0219 * 0.495 045 150.0
```

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* 0220 * 0.495 045 180.0
* 0221 * 0.495 045 210.0
* 0222 * 0.495 045 240.0
* 0223 * 0.495 045 270.0
* 0224 * 0.495 045 300.0
* 0225 * 0.495 045 330.0
* 0226 * 0.495 060 000.0
* 0227 * 0.495 060 022.5
* 0228 * 0.495 060 045.0
* 0229 * 0.495 060 067.5
* 0230 * 0.495 060 090.0
* 0231 * 0.495 060 112.5
* 0232 * 0.495 060 135.0
* 0233 * 0.495 060 157.5
* 0234 * 0.495 060 180.0
* 0235 * 0.495 060 202.5
* 0236 * 0.495 060 225.0
* 0237 * 0.495 060 247.5
* 0238 * 0.495 060 270.0
* 0239 * 0.495 060 292.5
* 0240 * 0.495 060 315.0
* 0241 * 0.495 060 337.5
* 0242 * 0.495 075 000.0
* 0243 * 0.495 075 018.0
* 0244 * 0.495 075 036.0
* 0245 * 0.495 075 054.0
* 0246 * 0.495 075 072.0
* 0247 * 0.495 075 090.0
* 0248 * 0.495 075 108.0
* 0249 * 0.495 075 126.0
* 0250 * 0.495 075 144.0
* 0251 * 0.495 075 162.0
* 0252 * 0.495 075 180.0
* 0253 * 0.495 075 198.0
* 0254 * 0.495 075 216.0
* 0255 * 0.495 075 234.0
* 0256 * 0.495 075 252.0
* 0257 * 0.495 075 270.0
* 0258 * 0.495 075 288.0
* 0259 * 0.495 075 306.0
* 0260 * 0.495 075 324.0
* 0261 * 0.495 075 342.0
* 0262 * 0.495 090 000.0
* 0263 * 0.495 090 015.0
* 0264 * 0.495 090 030.0
* 0265 * 0.495 090 045.0
* 0266 * 0.495 090 060.0
* 0267 * 0.495 090 075.0
* 0268 * 0.495 090 090.0
* 0269 * 0.495 090 105.0
* 0270 * 0.495 090 120.0
```

```
* 0271 * 0.495 090 135.0
* 0272 * 0.495 090 150.0
* 0273 * 0.495 090 165.0
* 0274 * 0.495 090 180.0
* 0275 * 0.495 090 195.0
* 0276 * 0.495 090 210.0
* 0277 * 0.495 090 225.0
* 0278 * 0.495 090 240.0
* 0279 * 0.495 090 255.0
* 0280 * 0.495 090 270.0
* 0281 * 0.495 090 285.0
* 0282 * 0.495 090 300.0
* 0283 * 0.495 090 315.0
* 0284 * 0.495 090 330.0
* 0285 * 0.495 090 345.0
* 0286 * 0.495 105 000.0
* 0287 * 0.495 105 018.0
* 0288 * 0.495 105 036.0
* 0289 * 0.495 105 054.0
* 0290 * 0.495 105 072.0
* 0291 * 0.495 105 090.0
* 0292 * 0.495 105 108.0
* 0293 * 0.495 105 126.0
* 0294 * 0.495 105 144.0
* 0295 * 0.495 105 162.0
* 0296 * 0.495 105 180.0
* 0297 * 0.495 105 198.0
* 0298 * 0.495 105 216.0
* 0299 * 0.495 105 234.0
* 0300 * 0.495 105 252.0
* 0301 * 0.495 105 270.0
* 0302 * 0.495 105 288.0
* 0303 * 0.495 105 306.0
* 0304 * 0.495 105 324.0
* 0305 * 0.495 105 342.0
* 0306 * 0.495 120 000.0
* 0307 * 0.495 120 022.5
* 0308 * 0.495 120 045.0
* 0309 * 0.495 120 067.5
* 0310 * 0.495 120 090.0
* 0311 * 0.495 120 112.5
* 0312 * 0.495 120 135.0
* 0313 * 0.495 120 157.5
* 0314 * 0.495 120 180.0
* 0315 * 0.495 120 202.5
* 0316 * 0.495 120 225.0
* 0317 * 0.495 120 247.5
* 0318 * 0.495 120 270.0
* 0319 * 0.495 120 292.5
* 0320 * 0.495 120 315.0
* 0321 * 0.495 120 337.5
```

```
* 0322 * 0.495 135 000.0
* 0323 * 0.495 135 030.0
* 0324 * 0.495 135 060.0
* 0325 * 0.495 135 090.0
* 0326 * 0.495 135 120.0
* 0327 * 0.495 135 150.0
* 0328 * 0.495 135 180.0
* 0329 * 0.495 135 210.0
* 0330 * 0.495 135 240.0
* 0331 * 0.495 135 270.0
* 0332 * 0.495 135 300.0
* 0333 * 0.495 135 330.0
* 0334 * 0.495 150 000.0
* 0335 * 0.495 150 045.0
* 0336 * 0.495 150 090.0
* 0337 * 0.495 150 135.0
* 0338 * 0.495 150 180.0
* 0339 * 0.495 150 225.0
* 0340 * 0.495 150 270.0
* 0341 * 0.495 150 315.0
* 0342 * 0.495 165 000.0
* 0343 * 0.495 165 090.0
* 0344 * 0.495 165 180.0
* 0345 * 0.495 165 270.0
* 0346 * 0.495 180 000.0
* 0347 * 0.000 000 000.0
* 0348 * 0.000 000 000.0
* 0349 * 0.000 000 000.0
* 0350 * 0.000 000 000.0
* 0351 * 0.000 000 000.0
* 0352 * 0.000 000 000.0
* 0353 * 0.000 000 000.0
* 0354 * 0.000 000 000.0
* 0355 * 0.000 000 000.0
* 0356 * 0.000 000 000.0
* 0357 * 0.000 000 000.0
* 0358 * 0.000 000 000.0
* 0359 * 0.000 000 000.0
* 0360 * 0.000 000 000.0
* 0361 * 0.000 000 000.0
* 0362 * 0.000 000 000.0
* 0363 * 0.000 000 000.0
* 0364 * 0.000 000 000.0
* 0365 * 0.000 000 000.0
* 0366 * 0.000 000 000.0
* 0367 * 0.000 000 000.0
* 0368 * 0.000 000 000.0
* 0369 * 0.000 000 000.0
* 0370 * 0.000 000 000.0
* 0371 * 0.000 000 000.0
* 0372 * 0.000 000 000.0
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* 0373 * 0.000 000 000.0
* 0374 * 0.000 000 000.0
* 0375 * 0.000 000 000.0
* 0376 * 0.000 000 000.0
* 0377 * 0.000 000 000.0
* 0378 * 0.000 000 000.0
* 0379 * 0.000 000 000.0
* 0380 * 0.000 000 000.0
* 0381 * 0.000 000 000.0
* 0382 * 0.000 000 000.0
* 0383 * 0.000 000 000.0
* 0384 * 0.000 000 000.0
* 0385 * 0.000 000 000.0
* 0386 * 0.000 000 000.0
* 0387 * 0.000 000 000.0
* 0388 * 0.000 000 000.0
* 0389 * 0.000 000 000.0
* 0390 * 0.000 000 000.0
* 0391 * 0.000 000 000.0
* 0392 * 0.000 000 000.0
* 0393 * 0.000 000 000.0
* 0394 * 0.000 000 000.0
* 0395 * 0.000 000 000.0
* 0396 * 0.000 000 000.0
* 0397 * 0.000 000 000.0
* 0398 * 0.000 000 000.0
* 0399 * 0.000 000 000.0
* 0400 * 0.000 000 000.0
* 0401 * 0.500 000 000.0
* 0402 * 0.500 015 000.0
* 0403 * 0.500 015 090.0
* 0404 * 0.500 015 180.0
* 0405 * 0.500 015 270.0
* 0406 * 0.500 030 000.0
* 0407 * 0.500 030 045.0
* 0408 * 0.500 030 090.0
* 0409 * 0.500 030 135.0
* 0410 * 0.500 030 180.0
* 0411 * 0.500 030 225.0
* 0412 * 0.500 030 270.0
* 0413 * 0.500 030 315.0
* 0414 * 0.500 045 000.0
* 0415 * 0.500 045 030.0
* 0416 * 0.500 045 060.0
* 0417 * 0.500 045 090.0
* 0418 * 0.500 045 120.0
* 0419 * 0.500 045 150.0
* 0420 * 0.500 045 180.0
* 0421 * 0.500 045 210.0
* 0422 * 0.500 045 240.0
* 0423 * 0.500 045 270.0
```

```
* 0424 * 0.500 045 300.0
* 0425 * 0.500 045 330.0
* 0426 * 0.500 060 000.0
* 0427 * 0.500 060 022.5
* 0428 * 0.500 060 045.0
* 0429 * 0.500 060 067.5
* 0430 * 0.500 060 090.0
* 0431 * 0.500 060 112.5
* 0432 * 0.500 060 135.0
* 0433 * 0.500 060 157.5
* 0434 * 0.500 060 180.0
* 0435 * 0.500 060 202.5
* 0436 * 0.500 060 225.0
* 0437 * 0.500 060 247.5
* 0438 * 0.500 060 270.0
* 0439 * 0.500 060 292.5
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* 0441 * 0.500 060 337.5
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* 0443 * 0.500 075 018.0
* 0444 * 0.500 075 036.0
* 0445 * 0.500 075 054.0
* 0446 * 0.500 075 072.0
* 0447 * 0.500 075 090.0
* 0448 * 0.500 075 108.0
* 0449 * 0.500 075 126.0
* 0450 * 0.500 075 144.0
* 0451 * 0.500 075 162.0
* 0452 * 0.500 075 180.0
* 0453 * 0.500 075 198.0
* 0454 * 0.500 075 216.0
* 0455 * 0.500 075 234.0
* 0456 * 0.500 075 252.0
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* 0458 * 0.500 075 288.0
* 0459 * 0.500 075 306.0
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* 0461 * 0.500 075 342.0
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* 0604 * 0.500 015 180.0
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* 0622 * 0.500 045 240.0
* 0623 * 0.500 045 270.0
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* 0637 * 0.500 060 247.5
* 0638 * 0.500 060 270.0
* 0639 * 0.500 060 292.5
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* 0645 * 0.500 075 054.0
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* 0652 * 0.500 075 180.0
* 0653 * 0.500 075 198.0
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* 0657 * 0.500 075 270.0
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* 0738 * 0.500 150 180.0
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* 0808 * 0.625 030 090.0
* 0809 * 0.625 030 135.0
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* 0811 * 0.625 030 225.0
* 0812 * 0.625 030 270.0
* 0813 * 0.625 030 315.0
* 0814 * 0.625 045 000.0
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* 0817 * 0.625 045 090.0
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* 0819 * 0.625 045 150.0
* 0820 * 0.625 045 180.0
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* 0822 * 0.625 045 240.0
* 0823 * 0.625 045 270.0
* 0824 * 0.625 045 300.0
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* 0837 * 0.625 060 247.5
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* 0839 * 0.625 060 292.5
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* 0854 * 0.625 075 216.0
* 0855 * 0.625 075 234.0
* 0856 * 0.625 075 252.0
* 0857 * 0.625 075 270.0
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* 0860 * 0.625 075 324.0
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* 0894 * 0.625 105 144.0
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* 0920 * 0.625 120 315.0
* 0921 * 0.625 120 337.5
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* 1019 * 0.750 045 150.0
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* 1023 * 0.750 045 270.0
* 1024 * 0.750 045 300.0
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* 1034 * 0.750 060 180.0
* 1035 * 0.750 060 202.5
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* 1057 * 0.750 075 270.0
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* 1061 * 0.750 075 342.0
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* 1117 * 0.750 120 247.5
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* 1129 * 0.750 135 210.0
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* 1132 * 0.750 135 300.0
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* 1137 * 0.750 150 135.0
```

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* 1234 * 0.875 060 180.0
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* 1239 * 0.875 060 292.5
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* 1252 * 0.875 075 180.0
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* 1256 * 0.875 075 252.0
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* 1258 * 0.875 075 288.0
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* 1260 * 0.875 075 324.0
* 1261 * 0.875 075 342.0
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* 1303 * 0.875 105 306.0
* 1304 * 0.875 105 324.0
* 1305 * 0.875 105 342.0
* 1306 * 0.875 120 000.0
* 1307 * 0.875 120 022.5
* 1308 * 0.875 120 045.0
* 1309 * 0.875 120 067.5
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* 1313 * 0.875 120 157.5
* 1314 * 0.875 120 180.0
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* 1316 * 0.875 120 225.0
* 1317 * 0.875 120 247.5
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* 1325 * 0.875 135 090.0
* 1326 * 0.875 135 120.0
* 1327 * 0.875 135 150.0
* 1328 * 0.875 135 180.0
* 1329 * 0.875 135 210.0
* 1330 * 0.875 135 240.0
* 1331 * 0.875 135 270.0
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* 1333 * 0.875 135 330.0
* 1334 * 0.875 150 000.0
* 1335 * 0.875 150 045.0
* 1336 * 0.875 150 090.0
* 1337 * 0.875 150 135.0
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* 1391 * 0.000 000 000.0
* 1392 * 0.000 000 000.0
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* 1405 * 1.000 015 270.0
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* 1409 * 1.000 030 135.0
* 1410 * 1.000 030 180.0
* 1411 * 1.000 030 225.0
* 1412 * 1.000 030 270.0
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* 1415 * 1.000 045 030.0
* 1416 * 1.000 045 060.0
* 1417 * 1.000 045 090.0
* 1418 * 1.000 045 120.0
* 1419 * 1.000 045 150.0
* 1420 * 1.000 045 180.0
* 1421 * 1.000 045 210.0
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* 1433 * 1.000 060 157.5
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* 1437 * 1.000 060 247.5
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* 1500 *  1.000  105  252.0
* 1501 *  1.000  105  270.0
* 1502 *  1.000  105  288.0
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* 1725 * 1.250 135 090.0
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* 1727 * 1.250 135 150.0
* 1728 * 1.250 135 180.0
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* 1731 * 1.250 135 270.0
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* 1733 * 1.250 135 330.0
* 1734 * 1.250 150 000.0
* 1735 * 1.250 150 045.0
* 1736 * 1.250 150 090.0
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* 1738 * 1.250 150 180.0
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* 1740 * 1.250 150 270.0
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* 1833 * 1.500 060 157.5
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* 1838 * 1.500 060 270.0
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* 1861 * 1.500 075 342.0
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* 1875 * 1.500 090 195.0
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* 1877 * 1.500 090 225.0
* 1878 * 1.500 090 240.0
* 1879 * 1.500 090 255.0
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* 1888 * 1.500 105 036.0
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* 1893 * 1.500 105 126.0
* 1894 * 1.500 105 144.0
* 1895 * 1.500 105 162.0
* 1896 * 1.500 105 180.0
* 1897 * 1.500 105 198.0
* 1898 * 1.500 105 216.0
* 1899 * 1.500 105 234.0
* 1900 * 1.500 105 252.0
* 1901 * 1.500 105 270.0
* 1902 * 1.500 105 288.0
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* 1904 * 1.500 105 324.0
* 1905 * 1.500 105 342.0
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* 1908 * 1.500 120 045.0
* 1909 * 1.500 120 067.5
* 1910 * 1.500 120 090.0
* 1911 * 1.500 120 112.5
* 1912 * 1.500 120 135.0
* 1913 * 1.500 120 157.5
* 1914 * 1.500 120 180.0
* 1915 * 1.500 120 202.5
* 1916 * 1.500 120 225.0
* 1917 * 1.500 120 247.5
* 1918 * 1.500 120 270.0
* 1919 * 1.500 120 292.5
* 1920 * 1.500 120 315.0
* 1921 * 1.500 120 337.5
* 1922 * 1.500 135 000.0
* 1923 * 1.500 135 030.0
* 1924 * 1.500 135 060.0
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* 1928 * 1.500 135 180.0
* 1929 * 1.500 135 210.0
* 1930 * 1.500 135 240.0
* 1931 * 1.500 135 270.0
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* 1933 * 1.500 135 330.0
* 1934 * 1.500 150 000.0
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* 1936 * 1.500 150 090.0
* 1937 * 1.500 150 135.0
* 1938 * 1.500 150 180.0
* 1939 * 1.500 150 225.0
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* 1944 * 1.500 165 180.0
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* 1953 * 0.000 000 000.0
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* 2145 * 1.750 165 270.0
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2708 2734 2736 2723 2735 2724
2736 2710 2708 2725 2709 2724
2736 2712 2710 2726 2711 2725
2712 2736 2738 2726 2737 2727
2738 2714 2712 2728 2713 2727
2738 2716 2714 2729 2715 2728
2716 2738 2740 2729 2739 2730
2740 2718 2716 2731 2717 2730
2740 2720 2718 2732 2719 2731
2720 2740 2734 2732 2741 2733
2734 2706 2720 2722 2721 2733
2746 2736 2734 2743 2735 2742
2746 2738 2736 2744 2737 2743
2746 2740 2738 2745 2739 2744
2746 2734 2740 2742 2741 2745
```

END

APPENDIX C.

```
      PROGRAM BNDMAT
      CALL SVDSUB
      STOP
      END
C
C ****************************************************************
C
      SUBROUTINE SVDSUB
C **********************************************************
      PARAMETER (NHARM=2,MSPHER=3,
     1 IBLOCK=(NHARM+1)**2,NPOINT=146)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMPLEX*16 CZERO,CONE,CI,HRADB(0:NHARM),MATINF(NPOINT,IBLOCK),
     1 WK(NPOINT),SIG(IBLOCK),EXTRA(IBLOCK),VM(IBLOCK,IBLOCK),
     2 UM(NPOINT,NPOINT),UIINV(IBLOCK,NPOINT),PHIFAC,PDATA(NPOINT),
     3 ACHK(IBLOCK),RES(NPOINT),MATCHK(NPOINT,IBLOCK),HRADR(0:NHARM),
     4 CTEM1,ZZCHK
      REAL*8 KK,KA,PMX(-NHARM:NHARM,0:NHARM),KR
      COMMON/COM0/CZERO,CONE,CI,ORIGIN(0:MSPHER,3)
C **********************************************************
      PI=4.0D0*DATAN(1.0D0)
C
C THIS ROUTINE INITIALIZES ARRAYS FOR THE MAIN ROUTINE
C   SPECIFICALLY, IT:
C     SETS COMPLEX CONSTANTS FOR 0, 1, AND I
C     COMPUTES HANKEL & BESSEL FUNCTIONS (& DERIVATIVES) FOR RADIUS
C
C INPUT:
C   KK = WAVENUMBER
C   RADSPH = RADIUS OF SPHERE
C   CFLD=FLUID WAVE SPEED  1524 METERS/SEC
C   FLDDEN=FLUID DENSITY 1000 KG/METER**3
C   RHOC = RHO*C, RADIATION IMPEDANCE OF MEDIUM
C   X,Y,Z = COORDINATES FOR EACH SPHERE
C   NPOINT = NUMBER OF DATA POINTS USED IN THE CALCULATION
C
C SET COMPLEX CONSTANTS
      CZERO = DCMPLX(0.0D0,0.0D0)
      CONE  = DCMPLX(1.0D0,0.0D0)
      CI    = DCMPLX(0.0D0,1.0D0)
C  INPUT THE EXCITATION MODE MMI AND NNI
      MMI=0
      NNI=2
      III=NNI*NNI+NNI+MMI+1
```

```
C  INPUT WAVENUMBER, SPHERE RADIUS, AND MEDIUM' S DENSITY*SOUND SPEED
      RADSPH=0.5D0
      CFLD=1492.94D0
      HERTZ=474.0D0
      KK = 2*PI*HERTZ/CFLD
      FLDDEN=1000.0D0
      RHOC=CFLD*FLDDEN
      KA = KK*RADSPH
      WRITE(6,21) KK,RADSPH,RHOC
 21   FORMAT(5X,'  K= ' ,1E10.4,'   A= ' ,E10.4,'   RHO*C =' ,E10.4)
      CALL HANKEL(KA,NHARM,HRADB)
*********************
C THE DATA FILE MUST RESIDE IN UNIT 12 TO DO THE FOLLOWING
      DO 10 I=1,NPOINT
      READ(12,15) X,Y,Z,PDATA(I)
 15   FORMAT(E11.3,E12.3,E12.3,E13.3,E12.3)
      IF(I.EQ.1) THEN
         RBND=DSQRT(X**2+Y**2+Z**2)
         KR=KK*RBND
          PRINT *,KR
         CALL HANKEL(KR,NHARM,HRADR)
      ENDIF
      THETX=DATAN2(DSQRT(X**2+Y**2),Z)
      CALL LEGNDR(THETX,NHARM,PMX)
      PHIX=DATAN2(Y,X)
C  THE FOLLOWING IS TO CHECK  OUTPUTS FROM ATILA N=1, M=-1
C
C        ZZCHK=DCMPLX( 0.97307D0, 0.23051D0)*DCONJG(HRADR(0))
C        ZZCHK=DCMPLX(0.98795D0, 0.15478D0)*DCONJG(HRADR(NNI))*
C      1  PMX(MMI,NNI)*DCMPLX(DCOS(MMI*PHIX),DSIN(MMI*PHIX))
      ZZCHK=DCMPLX(0.99876D0,-0.049693D0)*DCONJG(HRADR(NNI))*
     1  PMX(MMI,NNI)*DCMPLX(DCOS(MMI*PHIX),DSIN(MMI*PHIX))
C
C
C       PDATA(I)=ZZCHK
      PHASED=DATAN2(DIMAG(PDATA(I)),DREAL(PDATA(I)))
      PHASEA=DATAN2(DIMAG(ZZCHK),DREAL(ZZCHK))
C
      WRITE(6,16) X,Y,Z,PDATA(I),CDABS(PDATA(I)),
     1 ZZCHK,CDABS(ZZCHK)
      ZZCHK=ZZCHK-PDATA(I)
      WRITE(6,617) ZZCHK,CDABS(ZZCHK)
617   FORMAT(13X,2E17.5,E17.5)
      WRITE(6,616) PHASED,PHASEA,PHASEA-PHASED
616   FORMAT(7X,3E17.6)
 16   FORMAT(2X,6E12.3,/,38X,3E12.3)
      WRITE(25,125) PHIX,PHASED
 125  FORMAT(2X,2F13.5)
      DO 10 N=0,NHARM
      DO 10 M=-N,N
      PHIFAC=DCMPLX(DCOS(M*PHIX),DSIN(M*PHIX))
```

```
   JJ=N*N+N+M+1
   MATINF(I,JJ)=DCONJG(HRADR(N))*PMX(M,N)*PHIFAC
   MATCHK(I,JJ)=MATINF(I,JJ)
 10 CONTINUE
   CALL ZSVDC(MATINF,NPOINT,NPOINT,IBLOCK,SIG,EXTRA,UM,NPOINT,VM,
  1 IBLOCK,WK,21,INFOX)
   WRITE(6,30) (SIG(I),I=1,IBLOCK)
 30 FORMAT(1X,2E20.5)
   DO 40 I=1,IBLOCK
   DO 40 J=1,NPOINT
   UIINV(I,J)=CZERO
   DO 40 K=1,IBLOCK
   IF(CDABS(SIG(K)).LT.10E-8) GO TO 40
   UIINV(I,J)=UIINV(I,J)+VM(I,K)*DCONJG(UM(J,K))/SIG(K)
 40 CONTINUE
   DO 50 I=1,IBLOCK
   ACHK(I)=CZERO
   DO 50 K=1,NPOINT
   ACHK(I)=ACHK(I)+UIINV(I,K)*PDATA(K)
 50 CONTINUE
   WRITE(6,160)
 160 FORMAT(1X,' THE FOLLOWING ARE THE UNMODIFIED T MATRIX ELEMENTS' ,/,
  1 1X,' OR THE VALUES OF THE RADIATED PRESSURES' )
   DO 55 N=0,NHARM
   DO 55 M=-N,N
   I=N*N+N+M+1
   CTEM1=ACHK(I)
 55 WRITE(6,60) I,CTEM1,CDABS(CTEM1)
 60 FORMAT(1X,I3,1X,3E20.5)
   WRITE(6,161)
 161 FORMAT(1X,' THE FOLLOWING ARE THE TRUE T MATRIX ELEMENTS' )
C III IS THE EXCITATION MODE EG FOR M=0,N=0 III=1
   DO 155 N=0,NHARM
   DO 155 M=-N,N
   I=N*N+N+M+1
   IF((N.EQ.NNI).AND.(M.EQ.MMI)) THEN
     CTEM1=0.5D0*(ACHK(I)-1.0D0)
   ELSE
     CTEM1=ACHK(I)
   ENDIF
155 WRITE(6,60) I,CTEM1,CDABS(CTEM1)
C  WANT TO GET A HANDLE ON THE RELATIVE ERROR INVOLVED IN THE SVD CALC
   DO 70 J=1,NPOINT
   RES(J)=DCMPLX(0.0D0,0.0D0)
   DO 80 I=1,IBLOCK  80 RES(J)=RES(J)+MATCHK(J,I)*ACHK(I)
   RES(J)=RES(J)-PDATA(J)
 70 CONTINUE
   DO 100 I=1,NPOINT
   RESM=RESM+RES(I)*DCONJG(RES(I))
   DATAM=DATAM+PDATA(I)*CONJG(PDATA(I))
100 CONTINUE
```

```
   RELERR=RESM/DATAM
   WRITE(6,110) RESM,DATAM,RELERR
110 FORMAT(1X,' MAGNITUDE OF RESIDUAL = ' , E15.6,/,1X,
  1        ' MAGNITUDE OF DATA = ' , E15.6,/,1X,
  2        ' RELATIVE ERROR IN THE CALCULATION = ' , E15.6)
   RETURN
   END
C
C *************************************************************
C
   SUBROUTINE HANKEL(X,NMAX,H)
   IMPLICIT REAL*8 (A-H,O-Z)
   COMPLEX*16 H(0:NMAX)
C
C GIVEN THE VARIABLE X, AND THE MAXIMUM ORDER NMAX,
C   THIS ROUTINE GENERATES THE SPHERICAL HANKEL FUNCTION HN
C   FOR ALL N FROM 0 TO NMAX (INCLUSIVE)
C INPUT:
C   X = DOUBLE PREC. VARIABLE (RADIUS)
C   NMAX = INTEGER MAXIMUM ORDER OF BESSEL FUNCTIONS DESIRED
C OUTPUT:
C   H(N) = ARRAY OF SPHERICAL HANKEL FUNCTIONS HN(X), WHERE
C        HN = JN + I YN
C
C THIS ROUTINE IS BASED ON THE RECURSION FORMULAE
C   FROM ABRAMOWITZ & STEGUN: 10.1.10 & 10.1.15, PP.438-9
C   THE F' S ARE THE COEFFICIENTS OF ORDER N & -(N+1),
C   THE FO' S ARE OLD F' S, FOR RECURSION
C
   IF ( X .LE. 0.0D0 ) THEN
     H(0) = DCMPLX(1.0D0,-1.0D35)
     DO 2 N = 1, NMAX
        H(N) = CMPLX(0.0D0,-1.0D35)
  2  CONTINUE
     RETURN
   END IF
   SX = DSIN(X)
   CX = DCOS(X)
   XINV = 1.0D0/X
   M1N = -1.0D0
   FN = XINV
   FMN = 0.0D0
   FNO = FMN
   FMNO = FN
   DO 4 N = 0, NMAX
   H(N) = CMPLX( FN*SX + M1N*FMN*CX, -FN*CX + M1N*FMN*SX )
   T1 = (2*N+1)*XINV
   T2 = T1*FN - FNO
   FNO = FN
   FN = T2
   T2 = -T1*FMN - FMNO
```

```
      FMNO = FMN
      FMN = T2
      M1N = -M1N
    4 CONTINUE
      RETURN
      END
C
C ******************************************************************
C
      SUBROUTINE LEGNDR(THETA,NMAX,PMN)
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8  PMN(-NMAX:NMAX,0:NMAX)
C
C GIVEN THE VARIABLE THETA, AND THE MAXIMUM ORDER NMAX,
C   THIS ROUTINE GENERATES THE ASSOC. LEGENDRE FUNCTIONS PMN
C   OF THE ARGUMENT COS(THETA)  (THETA MUST BE BETWEEN 0 & PI)
C   FOR ALL N FROM 0 TO NMAX (INCLUSIVE)
C   AND FOR ALL M FROM -N TO N (SOME OTHERS SET TO ZERO)
C INPUT:
C   THETA = VARIABLE (POLAR ANGLE), MUST BE BETWEEN 0 & PI (INCL.)
C   NMAX = INTEGER MAXIMUM ORDER OF LEGENDRE FUNCTIONS DESIRED
C OUTPUT:
C   PMN = DOUBLE PREC. ARRAY, CONTAINS ASSOC. LEGENDRE FNS
C
C THIS ROUTINE IS BASED ON THE RECURSION FORMULAE
C   FROM ABRAMOWITZ & STEGUN
C
      X = DCOS(THETA)
      SINTHT = DSIN(THETA)
      IF ( SINTHT .GT. 0. ) THEN
        SININV = 1.0D0/SINTHT
      ELSE
        SININV = 0.0D0
      END IF
C SET VALUES FOR N = 0, 1  (NMAX MUST BE AT LEAST 1)
      PMN(0,0) = 1.0D0
      PMN(1,0) = 0.0D0
      PMN(-1,0) = 0.0D0
      PMN(0,1) = X
      PMN(1,1) = -SINTHT
      PMN(-1,1) = SINTHT*0.5D0
C IN LOOP, TNP1 = 2*N+1, TNP2FC = (2*N+2)!, M1N = (-1)**(N+1)
      TNP1 = 1.0D0
      TNP2FC = 2.0D0
      M1N = -1.0D0
      DO 4 N = 1, NMAX-1
        TNP1 = TNP1 + 2.0D0
        TNP2FC = TNP2FC * TNP1 * (TNP1+1)
        M1N = -M1N
        DO 3 M = -N, N
          PMN(M,N+1) = (TNP1*X*PMN(M,N) - (N+M)*PMN(M,N-1))/(N-M+1)
```

```
  3  CONTINUE
     PMN(N+1,N) = 0.0D0
     PMN(-N-1,N) = 0.0D0
     PMN(N+1,N+1) = (X*PMN(N,N+1) - TNP1*PMN(N,N)) * SININV
     PMN(-N-1,N+1) = M1N*PMN(N+1,N+1)/TNP2FC
  4 CONTINUE
C    DO 120 N=0,NMAX
C    DO 120 M=-N,N
C120  WRITE(6,130) N,M,PMN(M,N)
C130  FORMAT(1X,'  N= ',I4,1X,'  M= ',I4,1X,'  PMN= ',F13.6)
    RETURN
    END
```

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