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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: March 15, 1977

Project Title: Propagation of Noise from Electric Transformers

Project No: E-25-672

Project Director: Dr. W. James Hadden, Jr.

Sponsor: General Electric Company; Rome, Ga. 30161

Agreement Period: From 1/15/77 Until 1/14/78

Type Agreement: Purchase Order No. 086-554405-000, dated 3/1/77

Amount: $22,230

Reports Required: Monthly Progress Reports; Final Report

Sponsor Contact Person (s):

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Contractual Matters
(thru OCA)

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Rome, Ga. 30161

NOTE: CONTINUATION OF E-25-656

Defense Priority Rating: none

Assigned to: Mechanical Engineering (School/Laboratory)

COPIES TO:

Project Director
Division Chief (EES)
School/Laboratory Director
Dean/Director—EES
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Procurement Office
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Project File (OCA)
Project Code (GTRI)
Other

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AH

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: November 16, 1978

Project Title: Propagation of Noise from Electric Transformers

Project No: E-25-672

Project Director: Dr. W. James Hadden, Jr.

Sponsor: General Electric Company; Rome, GA 30161

Effective Termination Date: 1/14/78

Clearance of Accounting Charges: 1/14/78

Grant/Contract Closeout Actions Remaining:

X Final Invoice ~~and Closing Documents~~
_ Final Fiscal Report
_ Final Report of Inventions
_ Govt. Property Inventory & Related Certificate
_ Classified Material Certificate
_ Other ____________

Assigned to: Mechanical Engineering (School/Laboratory)

COPIES TO:

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Library, Technical Reports Section
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Other ____________

CA–4 (3/76)

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Vol. 62, Supplement No. 1, Fall 1977

The 94th Meeting of the Acoustical Society of America

Carillon Hotel • Miami Beach, Florida • 12–16 December 1977

THURSDAY, 15 DECEMBER 1977 CYPRESS ROOM, 9:00 A.M.

Session X. Noise IV: Mechanical Noise Control

PREDICTION OF FAR FIELD ELECTRIC TRANSFORMER NOISE FROM SURFACE ACCELERATION MEASUREMENTS

by

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Presented at the 94th ASA Meeting on Mechanical Noise Control

Miami, Florida

December 15, 1977

ABSTRACT

This paper describes the application of an approximate Green's Function and the Combined Helmholtz Integral Equation Formulation (CHIEF) [H. A. Schenck, J. Acoust. Soc. Am. 44, 41-58(1968)] to the prediction of noise radiated from machinery with relatively smooth casings under steady running conditions. Experiments were conducted for a fluid-filled boxlike structure with pure-tone excitation in which surface accelerations and far field sound pressure levels were measured. It is found that the use of a modified geometrical theory of diffraction led to better agreement between sound pressure levels in the far field predicted from measured surface accelerations and the measured sound pressure levels than was obtained by using the CHIEF algorithm. Probable reasons for this discrepancies are discussed.

INTRODUCTION

Many times different type of noise sources have to be installed close to residential areas or other buildings regularly used by human beings. Since such noise may be found objectionable, the sound radiation from a closed vibrating surface is a problem of considerable practical interest. Recently we have been concerned with predicting radiation patterns in the far field, from vibration measurements made at the source.

EXPERIMENTAL ARRANGEMENTS

We have considered a metallic boxlike structure as our source as shown in Slide 1. The box was almost filled with water. Two underwater speakers were excited at a pure-tone frequency of 265 Hz. Each side of the box may be conceptually divided into several elements. Acceleration measurements were taken on these elements all around the surface.

Slide 2 shows one of the typical surfaces of the boxlike structure. This shows the dimension of one of the sides. The cross marks on the slide are the points where the magnitudes of acceleration were measured with an accelerometer. The phase for each point was measured relative to a reference point denoted by the encircled cross on the slide.

Slide 3 shows the vibration distribution of a typical surface due to the excitation of the underwater speakers. Here, positive means the surface is coming out in that region.

MATHEMATICAL FORMULATION OF THE RADIATION PROBLEM

Now let us look at the mathematical formulation for our problem. The equation that one has to solve for the far field pressure is the Helmholtz equation (Slide 4)

$$\nabla^2 p + k^2 p = 0$$

where p: acoustic pressure

k: wave number ω/c

ω: angular frequency

c: speed of sound

The solution for the radiation pattern at Q due to the source at P is given by

$$p(\vec{r}) = \frac{1}{4\pi} \iint_{S_0} \left[p(\vec{r}_0)\, \nabla G(\vec{r},\vec{r}_0) - G(\vec{r},\vec{r}_0)\, \nabla p(\vec{r}_0) \right] \cdot \hat{n}_{out}(\vec{r}_0)\, dS_0$$

where $G(r,r_0)$: Green's function

S_0 : vibrating surface

$\vec{r}_0$: point on the surface (source point)

$\vec{r}$: point outside the surface (field point)

$\hat{n}_{out}$: unit normal pointing out of the vibrating surface.

The appropriate boundary condition over the surface S_0 which relates the outward normal gradient of pressure to the normal velocity and hence the normal acceleration is (Slide 5)

$$-\nabla p(\bar{r}_o).\bar{n}_{out} = -i\rho_o \omega v_n(\bar{r}_o)$$
$$= \rho_o a_n(\bar{r}_o)$$

where ρ_o is the density of air.

Substituting this in the expression for far field pressure (Slide 4) one gets

$$p(\bar{r}) = \frac{1}{4\pi}\iint_{S_o}\left[p(\bar{r}_o)\nabla G(\bar{r},\bar{r}_o).\bar{n}_{out}(\bar{r}_o) + G(\bar{r},\bar{r}_o)\rho_o a_n(\bar{r}_o)\right]dS_o$$

This equation is known as Helmholtz Integral Equation. If the field point $(\bar{r})$ is outside the surface S_o, the factor is $\frac{1}{4\pi}$. If the field point $(\bar{r})$ is on the surface S_o, the factor is $\frac{1}{2\pi}$. This equation is known as Surface Helmholtz Integral Equation. If the field point $(\bar{r})$ is inside the surface S_o the factor is zero. This equation is known as Internal Helmholtz Integral Equation.

At this point if one knows the normal surface acceleration and the surface pressure one can compute the far field pressure.

METHODS OF SOLUTION

This is the Combined Helmholtz Integral Equation Formulation (CHIEF) (Slide 6). It is based on the simple type of Green's function $\frac{e^{ikR}}{R}$ and Surface and Internal Helmholtz Integral Equation Formulation. This has been discussed in details by Harry A. Schenck in his paper: "Improved Integral Formulation for Acoustic Radiation Problems", J. Acoust. Soc. Am. 44, 41-58 (1968).

In this method the integral equation is replaced by an overdetermined system of linear equations where one specifies the surface acceleration and computes the surface pressure. Then one computes the far field pressure from the Helmholtz Integral Equation.

This method has a limitation that $kd \ll 1$. where d is a characteristic length for the vibration of the surface. In our measurements kd was not sufficiently small because of limitations imposed by the available computer storage capacity. The method CHIEF did not work very well for our case.

So let us look for some other simple approach (Slide 7) which describes all situations and also includes all revelant effects. One such method is an alternative approximation of the Green's function. It is based on a good approximation of Green's function such that $\nabla G(\bar{r},\bar{r}_o)=0$. on the surface. The expression for the pressure is now given by

$$p(\bar{r}) = \frac{1}{4\pi}\iint_{S_o} G(\bar{r},\bar{r}_o)\rho_o a_n(\bar{r}_o)\, dS_o$$

We shall combine this approximate Green's function with the assumption that sound diffracted around more than one corner of the box makes a negligible contribution to the pressure at the receiver location.

For a source on the surface of the wedge as shown here (Slide 8), the pressure at any point can be due to incident or diffracted waves. Depending on the position of the receiver it will receive the incident or the diffracted wave or both.

The effect of the diffracted term has been discussed in details by Allan D. Pierce in his paper: "Diffraction of Sound Around Corners and Over Wide Barriers", J. Acoust. Soc. Am. 55, 941-955 (1974). We can look at our vibrating tank as a 90° wedge. The Green's function for the diffraction term for the configuration shown in Slide 8 is given by

$$G(\bar{r},\bar{r}_0) = 2\left(\frac{e^{ikL}}{L}\right)\frac{e^{i\pi/4}}{\sqrt{2}}\left[f|x| - i\,g|x|\right]$$

where L : distance from the source to the corner to the receiver.

f(x),g(x): auxiliary Fresnel functions.

The Green's function for the incident term is given by $\frac{e^{ikR}}{R}$, where R is the distance between the source and the receiver.

Our next slides (Slides 9 and 10) show the four different approximations of the Green's function depending on the source and receiver position.

I. No corner visible

The receiver does not see the source.

$G(\bar{r},\bar{r}_0)=0.$

II. One corner visible, second really invisible $x \gg 1$

This means r_0 is very very large and λ (wave length) is small.

$$G(\bar{r},\bar{r}_0) = \frac{e^{ikL}}{L}\,\frac{e^{i\pi/4}}{\sqrt{2}}\,\frac{1}{\pi x}$$

III. One cornervisible, second possibly visible

Only one diffraction term is present

$$G(\bar{r},\bar{r}_0) = \frac{e^{ikL}}{L}$$

IV. Both corners visible

~~Both incident and diffraction terms are present~~.
Only incident term is considered.

$$G(\bar{r},\bar{r}_0) = 2\,\frac{e^{ikL}}{L}$$

Now we are in a position to find the far field pressure for our boxlike structure. Slide 11 shows that there are sources P_1, P_2, P_3, P_4 on each side of the tank. The receiver is at Q. The receiver will see the source P_1 on side 1. The Green's function for side 1 is $2\,\frac{e^{ikL_1}}{L_1}$. The receiver does not see the source P_3 on side 3. So the Green's function for side 3 is 0. The sources at sides 2 and 4 will contribute to the diffracted term only. The green's function for sides 2 is $\frac{e^{ikL_2}}{L_2}$ and for side 4 is $\frac{e^{ikL_4}}{L_4}$

So the far field pressure at Q is

$$p(\bar{r}) = \frac{\rho_0}{4\pi}\iint_{S_0}\left(2\,\frac{e^{ikL_1}}{L_1} + \frac{e^{ikL_2}}{L_2} + \frac{e^{ikL_4}}{L_4}\right)a_n(\bar{r}_0)\,dS_0$$

The sound pressure level is given by

$$\mathrm{SPL} = 10\log_{10}\frac{\langle p^2(\bar{r})\rangle}{(p_{ref}^2)}$$

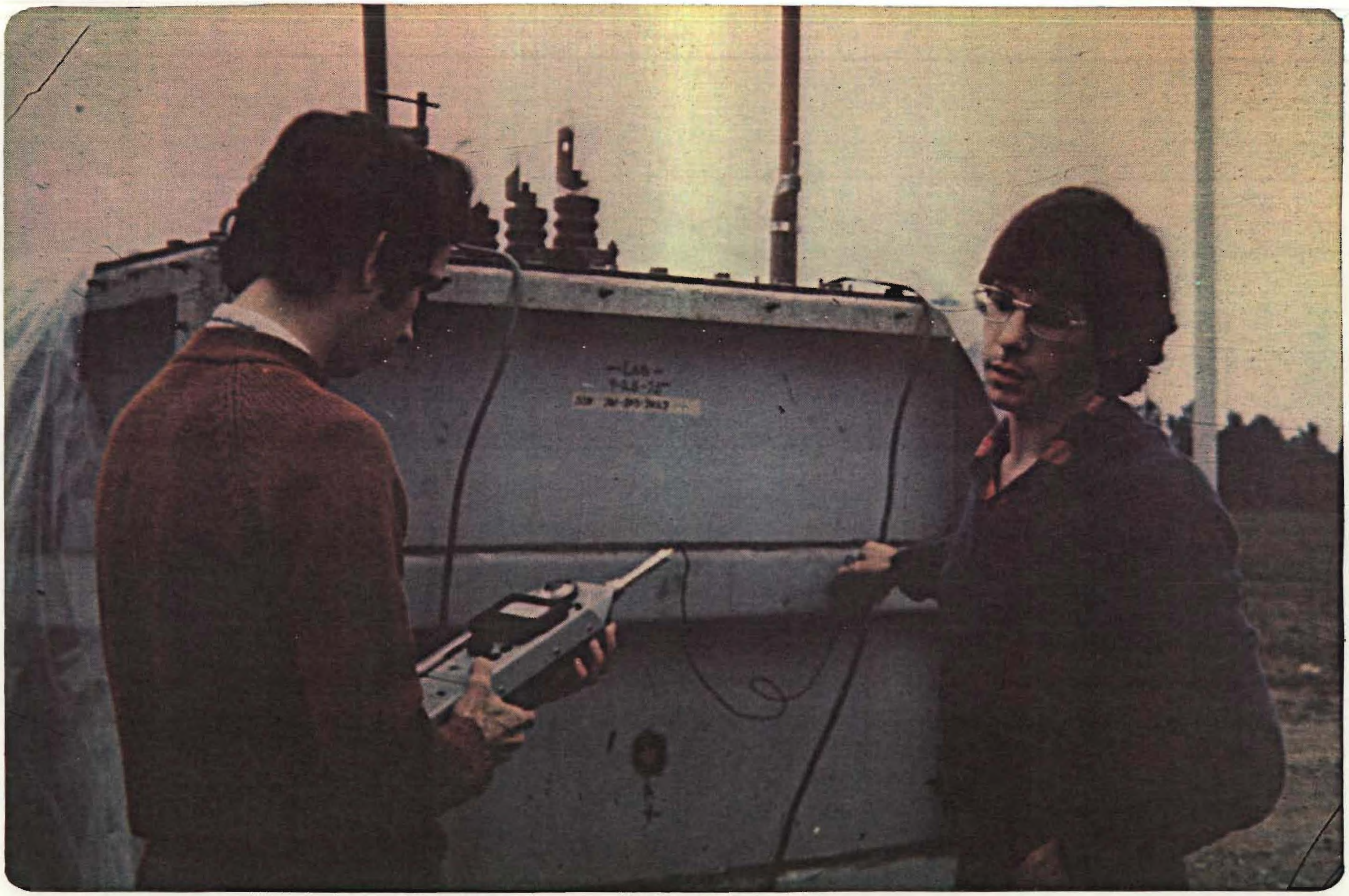
$$= 10\log_{10}\frac{\frac{1}{2}\,|p(\bar{r})|^2}{p_{ref}^2}$$

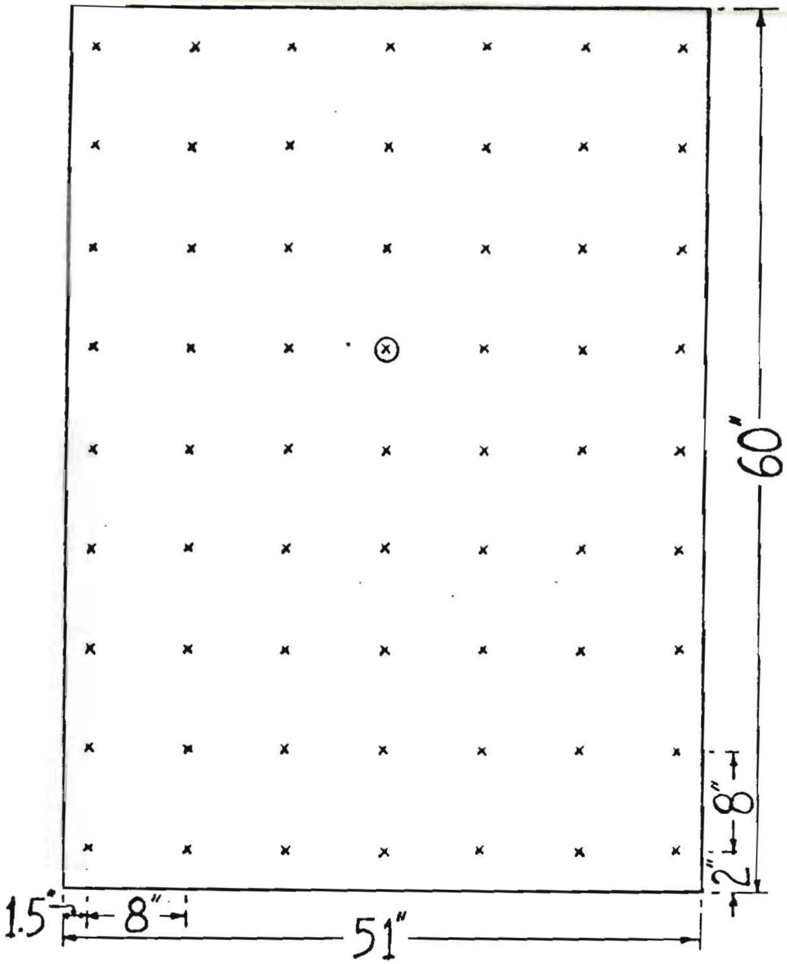
RESULTS AND CONCLUSION

The results obtained by measuring sound pressure level agree closely with the predicted sound pressure level obtained by the Green's function approximation. The CHIEF prediction is in general much higher than the measured sound pressure level. The reason for this is that CHIEF is valid for kd$\ll$1 and in our case this restriction could not be met (Slide 12).

Table. Measured and Predicted Sound Pressure Level

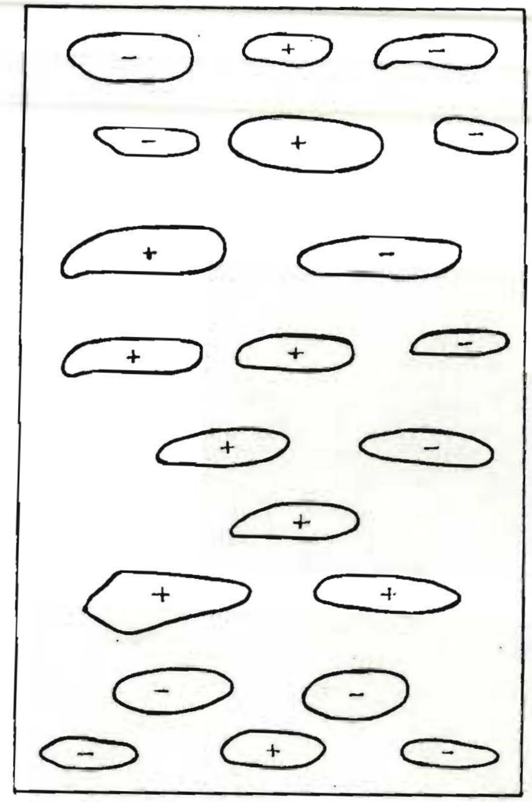
Distance from the Center of Tank in ft.	θ in degree	0	45	90	135	180	225	270	315
	Measured SPL	57.3	53.3	57.0	56.6	57.4	49.9	49.5	51.0
20	Approx. Green's Func.	58.4	52.4	53.9	56.5	55.8	56.2	54.1	50.5
	CHIEF	50.6	51.0	59.3	61.0	47.3	52.3	62.3	62.3
	Measured Spl	49.6	47.1	51.9	50.8	50.8	45.8	48.8	48.9
40	Approx. Green's Func.	52.6	45.1	50.4	50.4	49.5	52.0	51.5	48.4
	CHIEF	49.1	47.2	52.2	53.0	45.9	50.4	55.5	53.0
	Measured SPL	42.5	42.7	45.9	45.0	45.8	36.2	41.3	45.1
80	Approx. Green's Func.	46.3	38.9	44.8	44.3	43.3	46.1	46.1	43.2
	CHIEF	27.3	36.4	50.1	52.1	40.8	42.6	54.0	52.8





Acceleration Measurements on a Typical Surface

Slide 2



Vibration Distribution of a Typical Surface

Slide 3

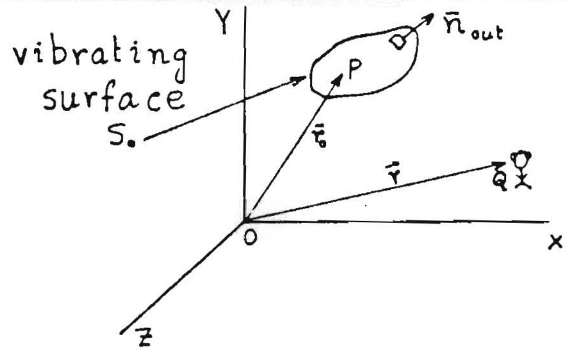
Helmholtz Integral Equation

Helmholtz Equation

$$\boxed{\nabla^2 p + k^2 p = 0}$$

Pressure at field point $\bar{r}$

$$\boxed{p(\bar{r}) = \frac{1}{4\pi} \iint_{S_0} \left[p(\bar{r}_0)\, \nabla G(\bar{r}, \bar{r}_0) - G(\bar{r}, \bar{r}_0)\, \nabla p(\bar{r}_0) \right] . \, \bar{n}_{out}(\bar{r}_0)\, ds_0}$$



Relation between normal surface acceleration and normal gradient of pressure

$$\rho_0\, a_n(\bar{r}_0) = -\nabla p . \, \bar{n}_{out}(\bar{r}_0)$$

Pressure at $\bar{r}$,

$$\boxed{p(\bar{r}) = \frac{1}{4\pi} \iint_{S_0} \left[p(\bar{r}_0)\, \nabla G(\bar{r}, \bar{r}_0) . \, \bar{n}_{out}(\bar{r}_0) + G(\bar{r}, \bar{r}_0)\, \rho_0\, a_n(\bar{r}_0) \right] ds_0}$$

Helmholtz Integral Equation

Methods of Solution

Method # 1

Combined Helmholtz Integral Equation Formulation (CHIEF)

Based on simplest type of Green's function e^{ikR}/R

What is the working method ?

Any limitations ? $kd \ll 1$

Try some other simple method

Too much CHIEF but not enough

GREEN'S FUNCTION

Method # 2

Approx. of Green's Function

Based on good approx. of Green's Function

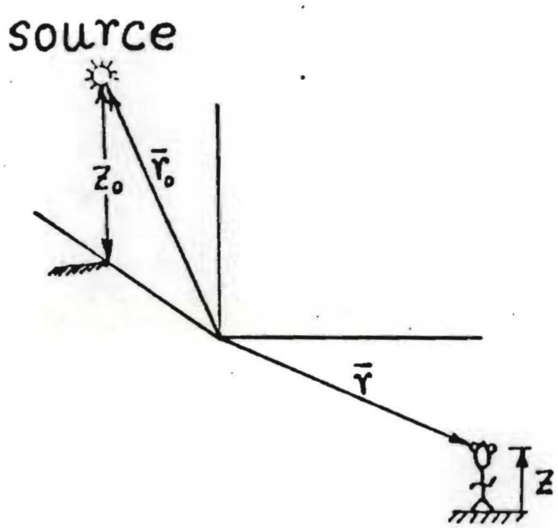
$$\nabla G(\bar{r}, \bar{r}_o) . \bar{n}_{out} = 0$$

on the surface

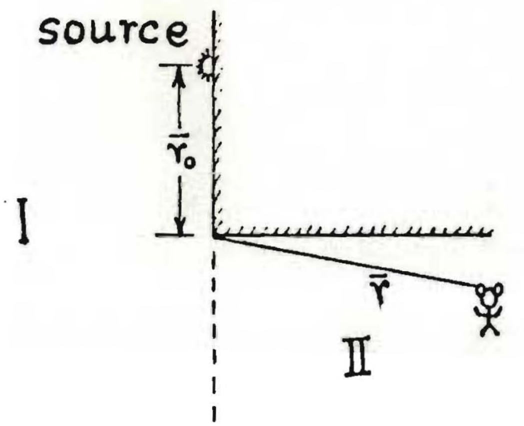
Pressure at $\bar{r}$

$$\boxed{p(\bar{r}) = \frac{1}{4\pi} \iint_{S_o} G(\bar{r}, \bar{r}_o) \rho_o a_n(\bar{r}_o) \, ds_o}$$

Geometry for 90° Wedge



Looking from top



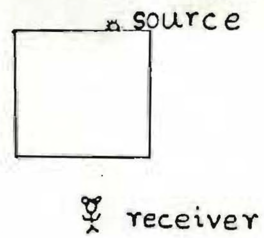
Green's function for diffraction term

$$\boxed{G(\bar{r},\bar{r}_0) = 2\left(e^{ikL}/L\right)\left(e^{i\pi/4}/\sqrt{2}\right)\left[f|x| - i\,g|x|\right]}$$

$f(x)$, $g(x)$: auxiliary Fresnel function

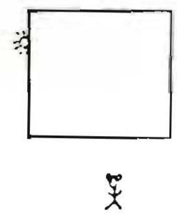
Four Different Approximatins of Green's Function

I No corner visible



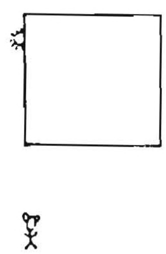
$$G(\bar{r},\bar{r}_0) = 0$$

II One corner visible, second really invisible



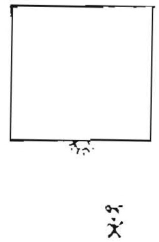
$$G(\bar{r},\bar{r}_0) = \frac{e^{ikL}}{L} \; \frac{e^{i\pi/4}}{\sqrt{2}} \; \frac{2}{\pi X}$$

III One corner visible, second possibly visible



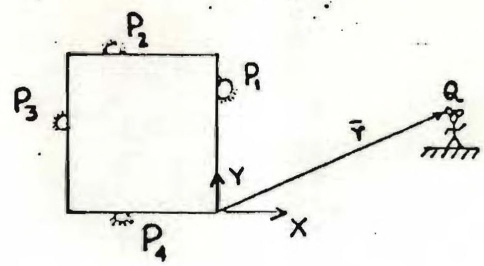
$$G(\bar{r},\bar{r}_0) = e^{ikL}/L$$

IV Both corners visible



$$G(\bar{r},\bar{r}_0) = 2\left(e^{ikL}/L\right)$$

Far Field Sol'n for the Vibrating Tank



Pressure at Q

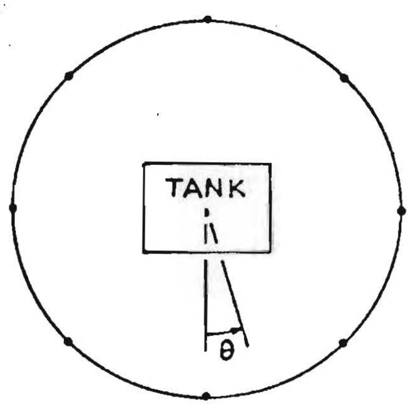
$$p(\bar{r}) = \frac{\rho_0}{4\pi} \iint_{S_0} G(\bar{r}, \bar{r}_0)\, a_n(\bar{r}_0)\, ds_0$$

$$G = \underset{\Downarrow}{G_1} + \underset{\Downarrow}{G_2} + \underset{\Downarrow}{G_3} + \underset{\Downarrow}{G_4}$$

$$2\left(e^{ikL_1}/L_1\right) \quad \left(e^{ikL_2}/L_2\right) \quad (0) \quad \left(e^{ikL_4}/L_4\right)$$

$$\boxed{\text{SPL at } Q = 10 \log_{10} \frac{\langle p^2(r) \rangle}{(p^2_{ref})}}$$

Slide 11



Measured and Predicted SPL at 20 ft. from the center of Tank

θ in degree	0	45	90	135	180	225	270	315
Measured SPL	57.3	53.3	57.0	56.6	57.4	49.9	49.5	51.0
Approx. Green's fnc	58.4	52.4	53.9	56.5	55.8	56.2	54.1	50.5
CHIEF	50.6	51.0	59.3	61.0	47.3	52.3	62.3	62.3