CALCULATING FAR-FIELD RADIATED SOUND PRESSURE LEVELS FROM NASTRAN OUTPUT

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SUMMARY

FAFRAP is a computer program which calculates far-field radiated sound pressure levels from quantities computed by a NASTRAN direct frequency response analysis of an arbitrarily shaped structure. Fluid loading on the structure can be computed directly by NASTRAN or an added-mass approximation to fluid loading on the structure can be used. Output from FAFRAP includes tables of radiated sound pressure levels and several types of graphic output. FAFRAP results for monopole and dipole sources compare closely with an explicit calculation of the radiated sound pressure level for those sources.

INTRODUCTION

FAFRAP computes far-field radiated sound pressure levels using the Helmholtz exterior integral equation by numerically integrating fluid pressures and normal velocities over the fluid-structure interface of a finite element model. The numerical integration requires the XYZ coordinates, unit normal vector, tributary area, fluid pressure, and outward normal velocity for every grid point on the fluid-structure interface. ALTER statements in a NASTRAN direct frequency response analysis are used to obtain these quantities. Fluid pressures at the fluid-structure interface are computed directly by NASTRAN if an explicit fluid finite element mesh is used. Alternatively, FAFRAP will calculate fluid pressures if an added-mass approximation to fluid loading is used.

THEORY

Consider the arbitrarily shaped body in figure 1. Let $\underline{z}$ be the position vector to an exterior fluid point P, and $z = |\underline{z}|$. Let $\underline{x}$ be the position vector to a point on the fluid-structure interface (with $x = |\underline{x}|$), let $\underline{r} = \underline{z} - \underline{x}$ (with $r = |\underline{r}|$), and let $\underline{n}$ be the unit outward normal at the location $\underline{x}$. The time-harmonic ($e^{i\omega t}$) pressure at $\underline{z}$ is given by the Helmholtz integral (ref. 1)

$$p(\underline{z}) = \int_S [i\omega\rho\, v_n(\underline{x}) + (ik + 1/r)p(\underline{x})\cos\beta\ ](e^{-ikr}/4\pi r)\, dS \qquad (1)$$

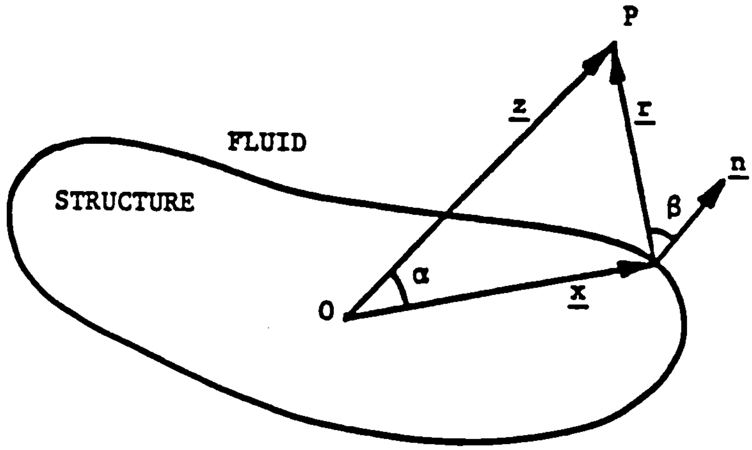

Figure 1. Geometry for Far-Field Radiated Sound Pressure Level Computations

where $v_n(\underline{x})$ and $p(\underline{x})$ are the complex normal surface velocity and complex surface pressure, respectively, and $k = \omega/c$, where ω = circular frequency, and c = speed of sound in the fluid.

Equation (1) can be simplified if only far-field locations are of interest. As $|\underline{z}| \to \infty$, $ik + 1/r \to ik$, and from the law of cosines, $r \to z - x \cos\alpha$. Therefore, at far-field locations

$$p(\underline{z}) \cong (ik\ e^{-ikz}/4\pi z) \int_S [\rho c v_n(\underline{x}) + p(\underline{x}) \cos\beta\ ] e^{ikx \cos\alpha}\ dS \qquad (2)$$

where $\cos\beta \cong (\underline{z}/|\underline{z}|)\cdot \underline{n}$.

One convention for presenting far-field pressures is as "sound pressure level (RMS) in dB relative to 1 μPa at 1 yard." Sound pressure levels (SPL) due to an excitation force applied as amplitude rather than RMS is obtained from eq. (2) by substituting z = 36 inches and by multiplying by the conversion factor 1 psi = 6.895×10^9 μPa to convert pressure $p(\underline{z})$ from pounds per square inch (psi) to micropascals (μPa). Therefore, for $|\underline{z}|$ = 36 inches

$$SPL = 20 \log ((6.895 \times 10^9\ p(\underline{z}))/\sqrt{2}) \qquad (3)$$

FLUID LOADING

Fluid pressures on the fluid-structure interface can be computed by NASTRAN if an explicit fluid finite element mesh is used. The finite element method that models the exterior surrounding fluid out to a predetermined distance is described by Everstine (refs. 2,3). This method uses, as the fundemental unknowns, the structural displacements and a velocity potential in the fluid. The outer boundary is terminated with nonreflective (wave-absorbing) boundary conditions, which assume that the outgoing waves are locally planar.

This approach to fluid loading results in an accurate model of the fluid mass at the expense of a much larger model due to the increased number of degrees of freedom introduced in modeling the fluid region.

An alternative to using an explicit fluid finite element mesh is to use an appropriate added-mass approximation to fluid loading. The added-mass is applied to the grid points on the fluid-structure interface. For example, at low frequencies for a conical section, the effect of the fluid pressure is that of a mass-like impedance. Junger and Feit (ref. 4) show this impedance to be

$$z = -i\omega m_a \tag{4}$$

where the effective added mass per unit area is

$$m_a = \rho_f R(n/(n^2+1)) \tag{5}$$

where ρ_f = fluid mass density, R = radius of conical section, and n = circumferential harmonic number.

IMPLEMENTATION

The numerical integration of eq. (2) requires, for each grid point on the fluid-structure interface, the XYZ coordinates, unit normal vector, tributary area, fluid pressure, and outward normal velocity. All of these quantities can be obtained directly from NASTRAN using the OUTPUT2 utility module. The following ALTER statements will output the required data blocks on to the NASTRAN UT1 file.

```
$ FAFRAP ALTER STATEMENTS, RIGID FORMAT 8, APR 84 VERSION
ALTER 21,21 $
GP3 GEOM3,EQEXIN,GEOM2/SLT,GPTT/S,N,NOGRAV/NEVER=1 $
ALTER 55 $
SSG1 SLT,BGPDT,CSTM,SIL,EST,MPT,GPTT,EDT,,CASECC,DIT/
     PG/LUSET/NSKIP
SDR2 CASECC,CSTM,MPT,DIT,EQEXIN,SIL,GPTT,EDT,BGPDT,,,,
     EST,XYCDB,PG/OPG1,,,,,/*STATICS*/S,N,NOSORT2/-1/
     S,N,STRNFLG $
ALTER 137 $
OUTPUT2 PG,BGPDT,EQEXIN,FRL,UPVC $
ENDALTER $
```

These ALTER statements allow a static unit pressure load to be applied to the structure during the dynamic frequency response analysis. The unit pressure load is applied to the fluid-structure interface of the finite element model. The components of the load vector created by the static pressure load are used by FAFRAP to compute the unit normal vector and tributary area of the grid points on the fluid-structure interface. The following is a list of the quantities in the data blocks written with the OUTPUT2 statement.

PG - load vector components
BGPDT - XYZ coordinates
EQEXIN - internal to external grid point numbering equivalencing
FRL - frequency response list
UPVC - grid point displacements

The displacements are converted to velocities by the relationship $v = i\omega u$, where u is displacement and v is velocity. If an explicit fluid finite element mesh has been used, then the pressure at a fluid grid point on the fluid-structure interface is evaluated as the time derivative of the velocity potential (ref. 2). If an added-mass approach to fluid loading is used, FAFRAP calculates pressure from the displacement.

Several user-defined input parameters to FAFRAP control the number of far-field locations at which to calculate an SPL and the different types of output.

OUTPUT

Several types of output are available from FAFRAP. There are tables of computed values and three types of graphics output. Table 1 lists the SPL at far-field locations. The headings COLAT and LON refer to colatitudinal and longitudinal far-field locations, respectively. These tables are printed for each subcase and frequency. Table 2 lists phasor sum, RMS velocity, maximum SPL and where it occurs, maximum SPL in a horizontal plane and where it occurs, and radiated power for each subcase. Equations 6 and 7 define the phasor sum and RMS velocity, respectively,

$$\text{phasor sum} = \sum_i (v_{n,i} A_i) \;/\; A \tag{6}$$

$$\text{RMS velocity} = \sum_i \sqrt{(|v_{n,i}|^2 A_i) \;/\; A} \tag{7}$$

where the summation is for all i grid points on the fluid-structure interface. Radiated power represents a summation of all pressure intensities in the far-field.

A separate plotting program, FAFPLOT, was written to display SPL's in any of the three principal planes for any subcase or frequency. Figure 2 is an example of a polar plot of SPL generated by FAFPLOT. The two numbers in the lower left-hand corner refer to the subcase and frequency defined for that plot. The polar plot is useful in evaluating the sound pressure pattern generated by the structure.

Log-log plots can be generated for plots of pressure, velocity, or impedance at a grid point on the fluid-structure interface versus frequency. An example of this type of plot is shown in figure 3. The log-log plots are useful in evaluating the response of specific points on the fluid-structure interface for different load cases.

PATRAN (ref. 5) can also be used to display all of the SPL's in the far-field for one subcase and frequency as a color contour plot (fig. 4). This type of plot gives a good view of the overall radiated sound pressure pattern.

COMPARISON TO ANALYTICAL SOLUTION

Analytical solutions exist for the pressure fields produced by two simple radiators, the monopole and dipole sources. The equations defining the pressure fields generated by these sources were used to validate the results of FAFRAP. A NASTRAN analysis was performed for each of the sources to provide the necessary input for FAFRAP. The equations defining the pressure fields for a monopole and dipole source can be found in equations 4.15 and 4.75 respectively, of Ross (ref. 6). After converting the equations to provide results in the correct units, the difference between the far-field radiated SPL calculated by FAFRAP and the values obtained from the equations was less than one percent.

REFERENCES

1. Lamb H., Hydrodynamics, sixth edition, Dover Publications, New York, 1945, p. 498.

2. Everstine, G.C., "A Symmetric Potential Formulation for Fluid-Structure Interaction," Journal of Sound and Vibration, Vol. 79, pp. 157-160, November 1981.

3. Everstine, G.C., F.M. Henderson, and R.R. Lipman, "Finite Element Prediction of Acoustic Scattering and Radiation From Submerged Elastic Structures," Twelfth NASTRAN User's Colloquium, NASA CP-2328, National Aeronautics and Space Administration, Washington, D.C., pp. 192-209, May 1984.

4. Junger, M.C. and D. Feit, Sound, Structures, and Their Interaction, The MIT Press, Cambridge, Massachussets, 1972, pp. 208,266.

5. PATRAN User's Guide, PDA Engineering Software Products Division, Santa Ana, California, 1984.

6. Ross, D., Mechanics of Underwater Noise, Pergamon Press, New York, 1976, pp. 61,77.

EXAMPLE OF FAFRAP OUTPUT
01/16/86 12.24.57.

SUBCASE 1, FREQUENCY = 55.[illegible]

COLAT	LON	SPL (DB)	PHASE
.0	.0	92.651	112.3
18.0	.0	103.330	94.1
18.0	18.0	103.633	98.1
18.0	36.0	103.340	92.5
18.0	54.0	102.431	97.7
18.0	72.0	100.827	104.0
18.0	90.0	98.385	113.1
18.0	108.0	94.970	128.9
18.0	126.0	91.329	160.6
18.0	144.0	91.027	205.0
18.0	162.0	93.[illegible]	231.3
18.0	180.0	94.582	243.7
18.0	198.0	94.643	2[illegible].4
18.0	216.0	93.916	255.4
18.0	234.0	90.897	261.3
18.0	252.0	83.256	2[illegible].7
18.0	270.0	64.366	46.2
18.0	288.0	93.425	65.8
18.0	306.0	97.934	72.6
18.0	324.0	100.682	76.6
18.0	342.0	102.387	80.3
36.0	.0	105.197	43.9
36.0	18.0	105.413	49.[illegible]
36.0	36.0	104.992	55.5
36.0	54.0	103.894	63.9
36.0	72.0	102.072	76.2
36.0	90.0	99.767	96.1
36.0	108.0	98.232	126.2
36.0	126.0	98.649	154.9
36.0	144.0	99.7[illegible]3	171.3
36.0	162.0	100.232	1[illegible]1.4
36.0	180.0	100.032	1[illegible]6.3
36.0	198.0	99.111	189.[illegible]
36.0	216.0	97.342	190.7
36.0	234.0	94.142	191.2
36.0	252.0	86.9[illegible]8	1[illegible].1
36.0	270.0	83.829	45.9
36.0	288.0	94.850	32.7
36.0	306.0	99.726	33.3
36.0	324.0	102.592	35.9
36.0	342.0	104.306	39.5

Table 1. Sound Pressure Levels in the Far-Field

EXAMPLE OF FAFRAP OUTPUT
[illegible]1/16/86 12.24.37.

SC	FREQ	PHASOR SM	RMS VEL	MAX SPL	COLAT	LON	MIN SPL	COLAT	LON	POWER
1	50.0	1.120E-08	4.689E-06	95.595	144.	198.	91.41[illegible]	36.	90.	3.31[illegible]E-03
1	51.0	1.282E-08	5.236E-06	97.6[illegible]6	144.	198.	92.[illegible]4	36.	90.	4.64[illegible]E-03
1	52.0	1.491E-08	5.926E-06	99.446	144.	198.	94.273	36.	90.	6.577E-03
1	53.0	1.776E-08	6.781E-06	10[illegible].[illegible]7	144.	198.	95.[illegible]	36.	90.	9.[illegible]7E-03
1	54.0	2.159E-08	7.964E-06	103.[illegible]1	144.	198.	97.792	36.	90.	1.45[illegible]E-02
1	55.0	2.731E-08	9.425E-06	105.484	144.	198.	99.707	36.	90.	2.313E-02
1	56.0	3.639E-08	1.159E-05	107.939	144.	198.	102.[illegible]7	36.	90.	3.9[illegible]E-02
1	57.0	5.231E-08	1.491E-05	110.6[illegible]4	144.	198.	104.626	36.	90.	7.3[illegible]E-02
1	58.0	8.340E-08	2.043E-05	114.294	144.	198.	[illegible]7.[illegible]4	144.	[illegible]7[illegible].	1.[illegible]E-01
1	59.0	1.4[illegible]E-07	3.033E-05	118.5[illegible]7	144.	198.	11[illegible].95[illegible]	36.	90.	3.9[illegible]E-01
1	60.0	1.621E-07	4.266E-05	121.721	144.	198.	11[illegible].[illegible]4[illegible]	36.	90.	7.[illegible]7E-01
1	61.0	8.572E-08	3.651E-05	120.121	144.	198.	114.453	36.	90.	5.4[illegible]3E-01
1	62.0	2.819E-08	2.644E-05	116.841	144.	198.	11[illegible].453	36.	90.	2.3[illegible]E-01
1	63.0	1.377E-08	1.672E-05	114.458	144.	198.	[illegible]7.[illegible]	36.	90.	1.4[illegible]5E-01
1	64.0	1.367E-08	1.428E-05	112.659	144.	198.	[illegible]	36.	90.	9.75[illegible]E-02
1	65.0	1.105E-08	1.151E-05	111.292	144.	198.	1[illegible]4.5[illegible]7	36.	90.	7.14[illegible]E-02
1	66.0	1.044E-08	9.644E-06	110.210	144.	198.	103.4[illegible]	36.	90.	5.6[illegible]4[illegible]E-02
1	67.0	9.603E-09	8.306E-06	109.331	144.	198.	102.525	36.	90.	4.61[illegible]E-02
1	68.0	9.183E-09	7.301E-06	1[illegible]8.6[illegible]	144.	198.	[illegible].757	36.	90.	3.9[illegible]E-02
1	69.0	8.6[illegible]7E-09	6.521E-06	107.984	144.	198.	101.2[illegible]	36.	90.	3.44[illegible]E-02
1	70.0	8.084E-09	5.897E-06	107.434	144.	198.	[illegible].54[illegible]	36.	90.	3.[illegible]E-02

Table 2. Summary of FAFRAP Results

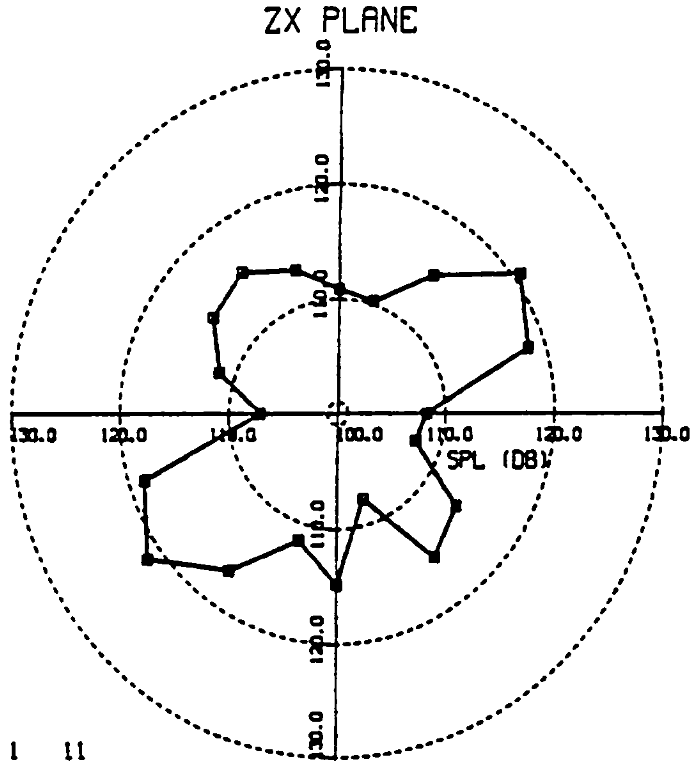

Figure 2. Polar Plot of Sound Pressure Levels in the Far-Field

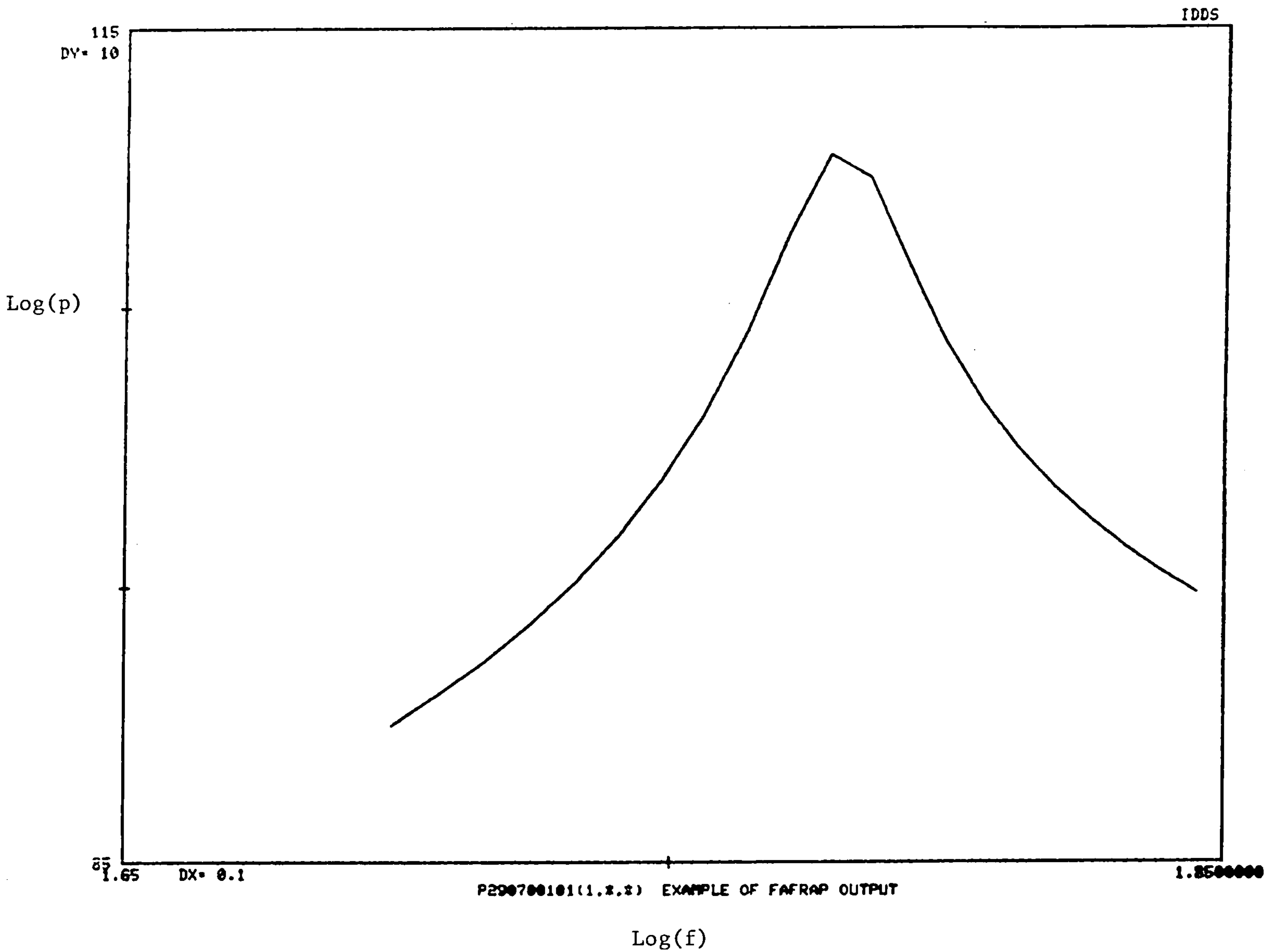

Figure 3. Log-log Plot of Pressure Versus Frequency at a Grid Point

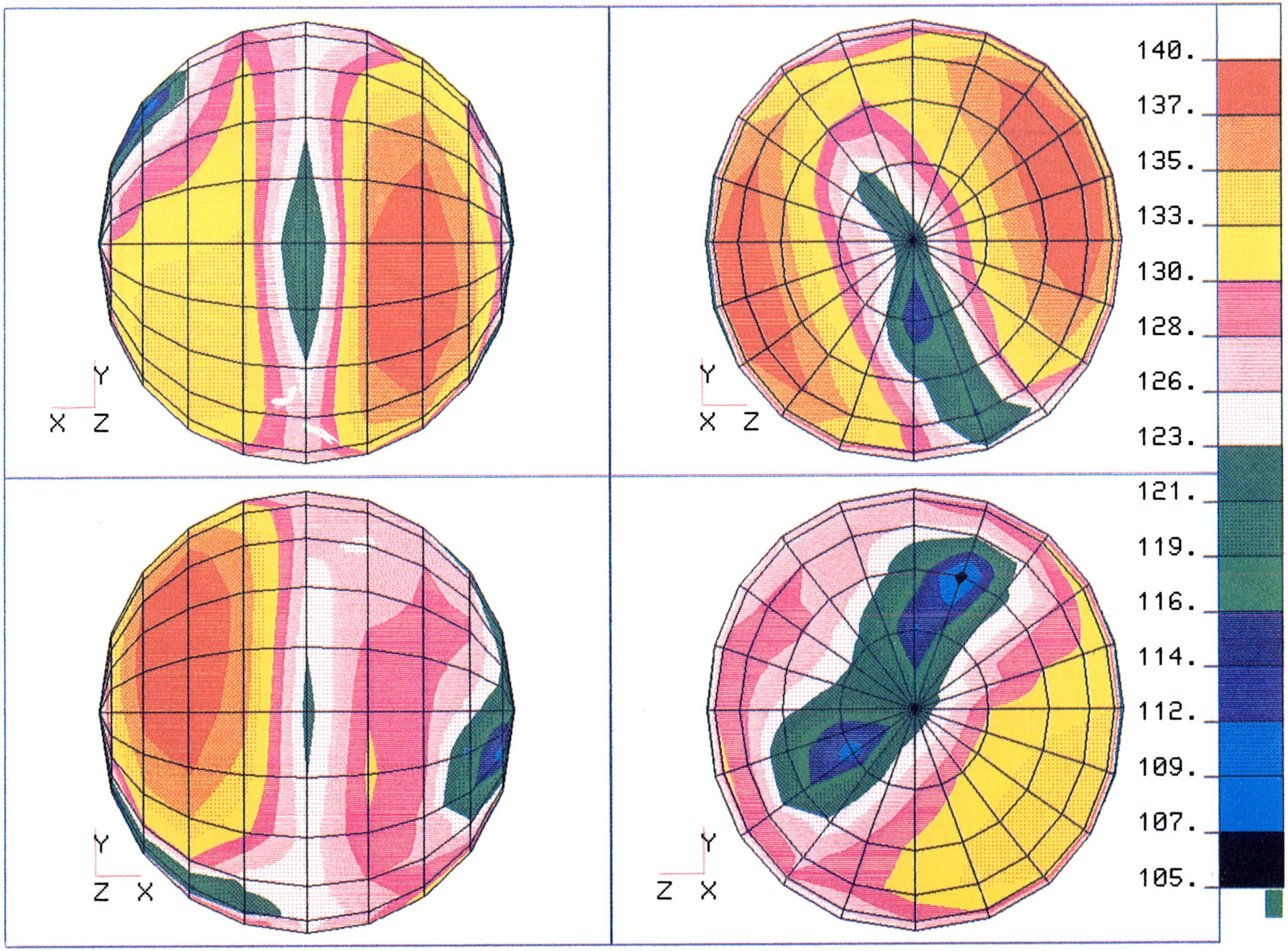

Figure 4. Contour Plot of Sound Pressure Levels in the Far-Field