HYDRO

Version 4.1

User's Guide

<u>ABSTRACT</u>

HYDRO is a computer program that develops models of sloshing incompressible fluid in NASTRAN. The user prepares the fluid model in any preprocessor and writes it out as a NASTRAN deck. HYDRO reads this deck and prepares a series of two or more NASTRAN input decks that generate a model of the fluid. The model represents either fully enclosed fluids, or fluids with free surfaces. For fluids with free surfaces, the surfaces can move relative to inertial space or to any grid on the structure. In either case, fluid slosh modes are calculated. A no-slosh option is also provided that correctly removes the sloshing weight of the fluid from the model. The no-slosh option can either be run in standard mode, where the fluid mass matrix is added to the structure before calculating modes, or in a õfastö mode, where the fluid mass is added after calculation of empty modes. Most options also allow for the recovery of fluid pressures anywhere on the exterior surface of the fluid. This can be particularly useful for launch vehicle Pogo analysis. In all cases, the fluid model is designed to be coupled with a NASTRAN structural model to calculate the coupled fluid/structural response. Applications include fuel and water storage tanks, rocket fuel tanks, and automotive and motorcycle fuel tanks.

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Abbreviations

ATA	ATA Engineering, Inc.
DOF	Degrees of freedom
DMAP	Direct matrix abstraction program
GUI	Graphical user interface
HFEM	Hydroelastic finite element model
HYDRO	Hydroelastic modeling and analysis procedure
Iódeas	Integrated Design Engineering Analysis System
NASTRAN	NASA Structural Analysis Program
SOL	NASTRAN solution sequence (rigid format)

Scalar Variables

β	Bulk Modulus
g	Gravity
ρ	Density

Matrices

A	Area
F	Force
G	Transformation
K	Stiffness
M	Mass
p	Pressure
u	Displacement
$\ddot{u}$	Acceleration
ϕ	Normal mode shapes
Φ	Unit rigid body mode shapes

Superscripts

f	Fluid
n	Normal displacements at the free surface
s	Structure

Subscripts

a	A-set (analysis DOF)
g	G-set (all DOF)
m	M-set (MPC)
n	Normal DOF (free surface)
o	O-set (omitted DOF)
r	R-set (SUPORT DOF)

1. **INTRODUCTION**

HYDRO is a procedure for developing hydroelastic finite element models of incompressible fluids in NASTRAN[1]. Typical hydroelastic models include liquid fuel rockets, fuel storage tanks, and other fluid-filled tanks, as shown in Figure 1-1.
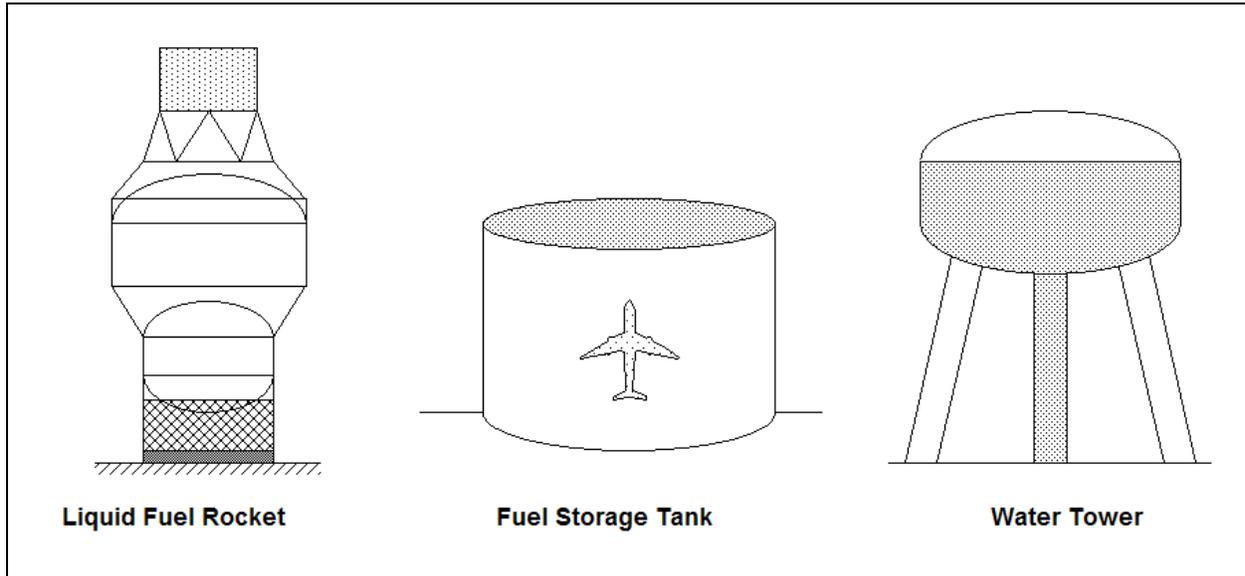
Figure 1-1. Hydroelastic models are used to model fluid in thin-walled tanks.

HYDRO was originally developed for modeling the Titan IV/Centaur upper stage and has since been used on a large number of different rockets as well as motorcycle fuel tanks. HYDRO offers many advantages for static, modal, and transient analysis of hydroelastic models when compared with other options in NASTRAN:

- The HYDRO mathematical formulation produces symmetric matrices instead of unsymmetric matrices developed by many methods including the NASTRAN axisymmetric approach.

- The HYDRO solution is compatible with standard symmetric matrix multiplication, decomposition, forward-backward substitution, and real eigensolver methods. Important postprocessing operations (modal effective mass, rigid body mass from rigid body modes, effective rigid body mass, etc.) can be readily performed using the symmetric matrices.

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[1] Both MSC and NX Nastran are supported.

- Mass of the elements connected to the axis of an axisymmetric model is correctly included by the HYDRO procedure, unlike the limitation of the NASTRAN axisymmetric method.

- The geometry of the fluid is arbitrary in HYDRO. The geometry is not limited to axisymmetric systems. Annular fluid volumes and more complex shapes can be easily and accurately processed.

- The coupled hydroelastic model may be restrained or free-free. HYDRO does not introduce artificial grounding that would prevent rigid body motion.

- HYDRO is compatible with NASTRAN superelement technology. The fluid superelement may be introduced at any level in the superelement tree. Both standard bulk data and external superelements are supported.

- Multiple fluid models can be included in a single model. Each fluid model is represented by a superelement. There is no limit on the number of fluid superelements that can be included in a model[2].

- Fluid incompressibility is explicitly enforced by a multipoint constraint (MPC) equation. No compressibility assumptions or approximations are required.

- HYDRO can be used to recover pressure anywhere on the exterior surface of the fluid. This is particularly important when doing a Pogo analysis.

- The fluid model can include a free surface or can be completely enclosed by a wetted surface. If the fluid model has a free surface, slosh modes are calculated to identify slosh frequencies and effective mass, or an alternative no-slosh model can be used.

- The fluid free surface reference plane can be fixed or can be relative to a local acceleration vector.

- Unimportant slosh modes can be easily eliminated from the fluid superelement to improve efficiency and avoid large numbers of unneeded system modes.

- The hydroelastic mode shapes can be easily plotted using I-deas, Femap, or any other NASTRAN postprocessor. A special õdisplayö model can plot the modes of both the structure and free surface.

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[2] The õfastö no-slosh option does not use superelements and is currently limited to a single fluid model, though this can span multiple tanks.

- HYDRO has been proven to provide accurate results if the fluid element mesh is sufficiently refined.

- HYDRO includes a õfastö option that uses the empty modes of the structure to reduce the mass matrix, allowing the user to solve very large fluid structure interaction problems.

- While HYDRO does require the execution of a sequence of NASTRAN runs, this process is automated using an intuitive graphical user interface (GUI).

The overall procedure for developing and using a hydroelastic model is a three-step process, as shown in Figure 1-2. The first step is to create the hydroelastic finite element model (HFEM). The HFEM includes solid elements for the fluid and shell elements representing the wetted structure and fluid free surface. There are several requirements for the HFEM that must be satisfied to provide correct fluid properties and to ensure compatibility between the fluid and structural models.

```
┌─────────────────────────────┐
│   Hydroelastic Finite       │
│   Element Model             │
│   (I-deas, FEMAP, etc.)     │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│   Generate Hydroelastic     │
│   Superelement              │
│   (HYDRO/Nastran)           │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│   Coupled                   │
│   Fluid/Structure Model     │
│   (Nastran)                 │
└─────────────────────────────┘
```
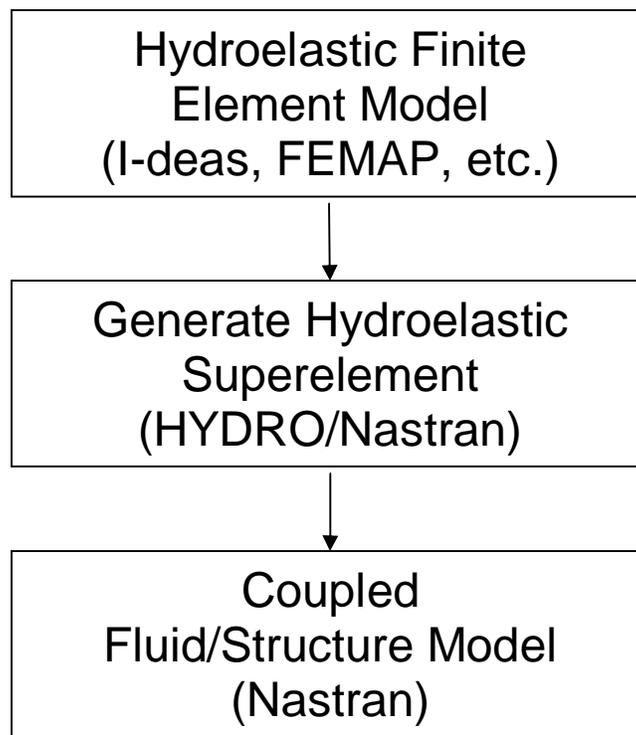
Figure 1-2. A hydroelastic model is developed in a three-step process.

The second step in developing a hydroelastic model is to create the fluid superelement. This is done using NASTRAN[3] and the HYDRO program. HYDRO reads the FEM in NASTRAN format and writes a series of two or more NASTRAN input decks. The output from this series of

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[3] Both MSC and NX Nastran are supported.

runs is either a NASTRAN superelement of the fluid model or matrices that can be used to represent the fluid mass.

The final step in the HYDRO procedure is to couple the fluid superelement to the structural model. This step is performed using standard superelement methods, or through the use of a DMAP alter, if using the "fast" method. If desired, multiple fluid components can be defined and assembled into a single model.

The theory for the hydroelastic analysis of incompressible fluids is presented in Chapter 2. This chapter describes the derivation of the fluid equations of motion and the procedures to couple the fluid model to the structural model. Additional references are included in Appendix A.

Chapter 3 describes the implementation of the HYDRO procedures, with all steps described.

Two complete sample problems are presented in Chapter 4. This chapter illustrates the development of the hydroelastic finite element model, execution of the HYDRO program, running the NASTRAN hydroelastic runs, and coupling the fluid superelement to a structural model.

Chapters 5 and 6 describe accuracy checks and error messages. The accuracy checks should be performed by the user to verify that the fluid superelement was properly defined and that all operations were performed satisfactorily. The error messages provide more-complete descriptions of errors from HYDRO or NASTRAN, along with suggestions for correcting the errors.

2. **THEORY**

The fundamental assumption for a hydroelastic model is that the fluid dynamics can be represented by potential flow. This is valid for a fluid which is inviscid (viscosity effects negligible), irrotational (zero vorticity), and undergoing small amplitude oscillations (linear small motion theory).

The fluid degrees of freedom (DOF) are pressures. Since the structure is represented by displacement DOF (translations and rotations at the grid points), special techniques are needed to couple the fluid pressure model to the structural displacement model. This is accomplished by õarea matricesö that convert fluid pressures to corresponding structural forces.

If the fluid is not completely contained by a structure, the fluid will have a free surface. For this configuration, the fluid will have õsloshö modes that can be extremely important for both the fluid dynamic characteristics and the coupled fluid/structure modes.

For a wide range of problems, the compressibility of the fluid is negligible in comparison to the structural flexibility. For these problems, the fluid can be assumed to be incompressible. This greatly simplifies the fluid equations of motion and also results in a symmetric formulation for the coupled fluid/structure system.

The final result of a hydroelastic model depends on the option chosen. For a fully enclosed fluid or a fluid using the no-slosh option, it is a fully coupled mass matrix; for a fluid with a sloshing free surface it is a Craig-Bampton [1] superelement that defines the mass and dynamic characteristics of the fluid; and for the "fast" no-slosh option it is two matrices that can used to represent the fluid mass matrix in the coupled run. A multipoint constraint equation is also defined to enforce the incompressibility relationship for all but the no-slosh options.

2.1. **Fluid Equations of Motion**

The fluid equations of motion presented in this section follow the derivation presented by Herting, Hoesly, and Herendeen in [2]. The equations of motion for an irrotational fluid can be developed in the form of energy integrals using principles of variational calculus [3]:

$$\delta\left[\int_{V}\left(\frac{1}{2\beta}\dot{p}^2+\frac{1}{2\rho}\nabla p\cdot\nabla p\right)dV\right]-\int_{S}\delta p\left(\frac{1}{\rho}\nabla p\right)d\vec{S} \qquad (1)$$

where:

p = pressure
$\dot{p}$ = time derivative of pressure
β = bulk modulus
ρ = mass density
V = volume
$d\vec{S}$ = incremental surface vector (outward)
∇ = vector gradient operator
δ = variational operator

Equation (1) can be greatly simplified if the fluid is assumed to be incompressible. This is an accurate assumption if the frequencies of the fluid acoustic modes are much greater than the frequencies of the fluid/structure modes of interest. For an incompressible fluid, the bulk modulus is assumed to be infinite, and the $\dot{p}^2$ term in (1) is zero. On the exterior surface of the fluid, the pressure gradient may be replaced with the acceleration vector, $\ddot{u}$, using the momentum equation

$$\nabla p = -\rho\vec{\ddot{u}} \tag{2}$$

Equation (1) can be rewritten for an incompressible fluid using (2) and eliminating the $\dot{p}^2$ term:

$$\delta\left[\int_v \left(\frac{1}{2\rho}\nabla p \cdot \nabla p\right)dV\right] - \int_s \delta p\vec{\ddot{u}} \cdot d\vec{S} = 0 \tag{3}$$

or

$$\delta U + \delta W = 0 \tag{4}$$

The continuum equation (3) can be discretized using the finite element method. The fluid volume is divided into a number of solid finite elements. At each grid point, there is one DOF representing the pressure at that location in the fluid. Typically, linear finite elements are used which assume linear variation of pressure between grid points. Sufficient elements must be defined such that linear pressure variation accurately represents the fluid behavior. A typical fluid finite element model is shown in Figure 2-1.
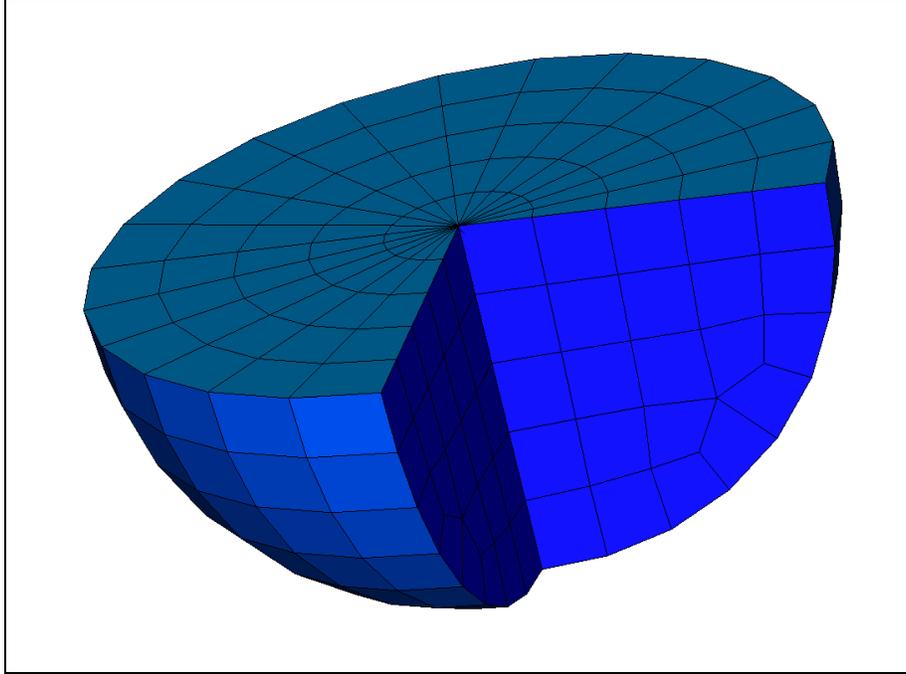
Figure 2-1. Fluid is modeled with linear solid elements.

The continuum equation (3) can be written in matrix form for a finite element model:

$$\left[K^f\right]\{p\}+\left[B\right]\{\ddot{u}\}=0 \tag{5}$$

where

$$B_{ij}=\frac{\partial}{\partial p_i \partial u_j}\int_s p\vec{u}\cdot d\vec{S} \tag{6}$$

$$K_{ij}^f=\frac{\partial}{\partial p_i \partial p_j}\int_v \frac{1}{2\rho}\nabla p\cdot\nabla p dV \tag{7}$$

There is an analogy between the incompressible fluid equations of motion and those for heat transfer analysis as shown by Coppolino [4]. The analogy between the fluid and heat transfer is summarized in Table 2-1.

Table 2-1. Analogy between fluid and heat transfer variables.

FLUID MODEL		HEAT TRANSFER MODEL	
Variable	Symbol	Variable	Symbol
Pressure	p	Temperature	T
Outward normal acceleration	$\ddot{\vec{u}}$	Outward normal flux/area	f_n inverse
Mass density	ρ	Inverse thermal conductivity	$1/K_t$
Incompressible	$\beta = \infty$	No heat capacity	$C_p = 0$

Therefore, a fluid model can be defined using standard heat transfer modeling and analysis procedures with the appropriate analogy for the material properties.

The fluid model can be mathematically reduced to those grid points that are on the exterior of the fluid, as shown in Figure 2-2.
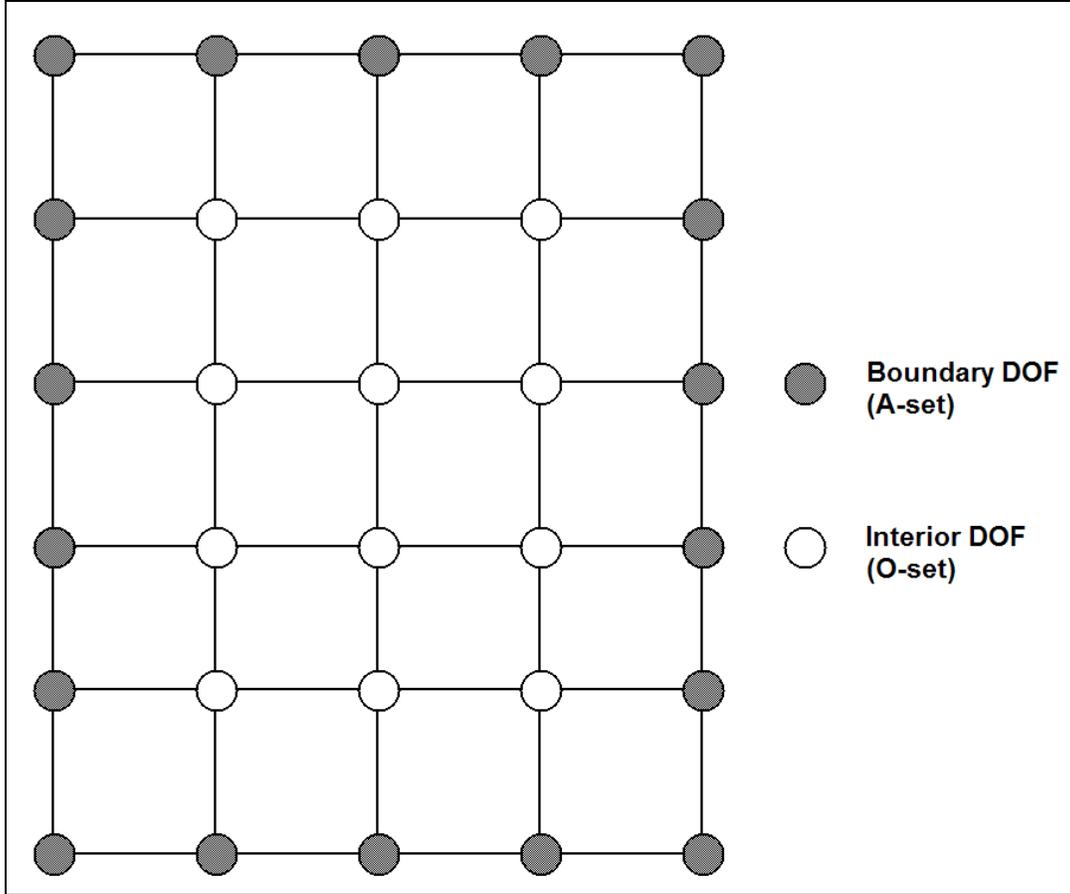
Figure 2-2. The finite element model of an incompressible fluid can be mathematically reduced to the boundary grids with no loss of accuracy.

The reduction from all pressure DOF to the exterior DOF is performed using the same equations as Guyan reduction [5] for a structural model. First, partition the fluid stiffness matrix into interior and boundary terms:

$$[K^f] = \begin{bmatrix} K^f_{oo} & K^f_{oa} \\ K^f_{ao} & \overline{K}^f_{aa} \end{bmatrix}$$

(8)

Calculate unit pressure shapes:

$$[G^f_{oa}] = -[K^f_{oo}]^{-1}[K^f_{oa}]$$

(9)

Form the reduced fluid stiffness matrix:

$$[K^f_{aa}] = -[\overline{K}^f_{aa}] + [K^f_{ao}][G^f_{oa}]$$

(10)

For an incompressible fluid, the reduction is **<u>exact</u>**. The reduction to the fluid exterior DOF provides a substantial decrease in the fluid matrix size and the analysis costs for developing the fluid model.

HYDRO provides two options for representing a fluid free surface. In the standard option, the fluid free surface mass is retained in order to calculate slosh modes, and the boundary of the fluid therefore consists of both the wetted structural surface and the free surface. The second case is a no-slosh option, where the slosh modes are not explicitly calculated, though the sloshing mass is correctly removed from the problem. In this case, the fluid free surface pressure DOF are set to zero (SPCed) and are not included in the A-set. The no-slosh solution also has a õfastö option where the fluid mass matrix is never explicitly calculated. This is described in Section 2.9.

2.2.   **<u>Area Matrices</u>**

The fluid model is represented by pressure degrees of freedom. However, a structural model is represented by displacements (translations and rotations) at the structural grid points. Special procedures are needed to connect the fluid and structure models since they have different types of DOF.

The pressure and displacement DOF are coupled using õarea matrices.ö An area matrix converts the pressure at a fluid DOF to an equivalent set of forces on the structural DOF, as shown in Figure 2-3.

UNIT PRESSURE


```
CQUAD4,101,100,11,12,22,21
CQUAD4,102,100,12,13,23,22
CQUAD4,103,100,21,22,32,31
CQUAD4,104,100,22,23,33,32
$
$ Load case 22 - unit pressure at grid 22
$
PLOAD4,22,101,0.,0.,1.,0.
PLOAD4,22,102,0.,0.,0.,1.
PLOAD4,22,103,0.,1.,0.,0.
PLOAD4,22,104,1.,0.,0.,0.
```
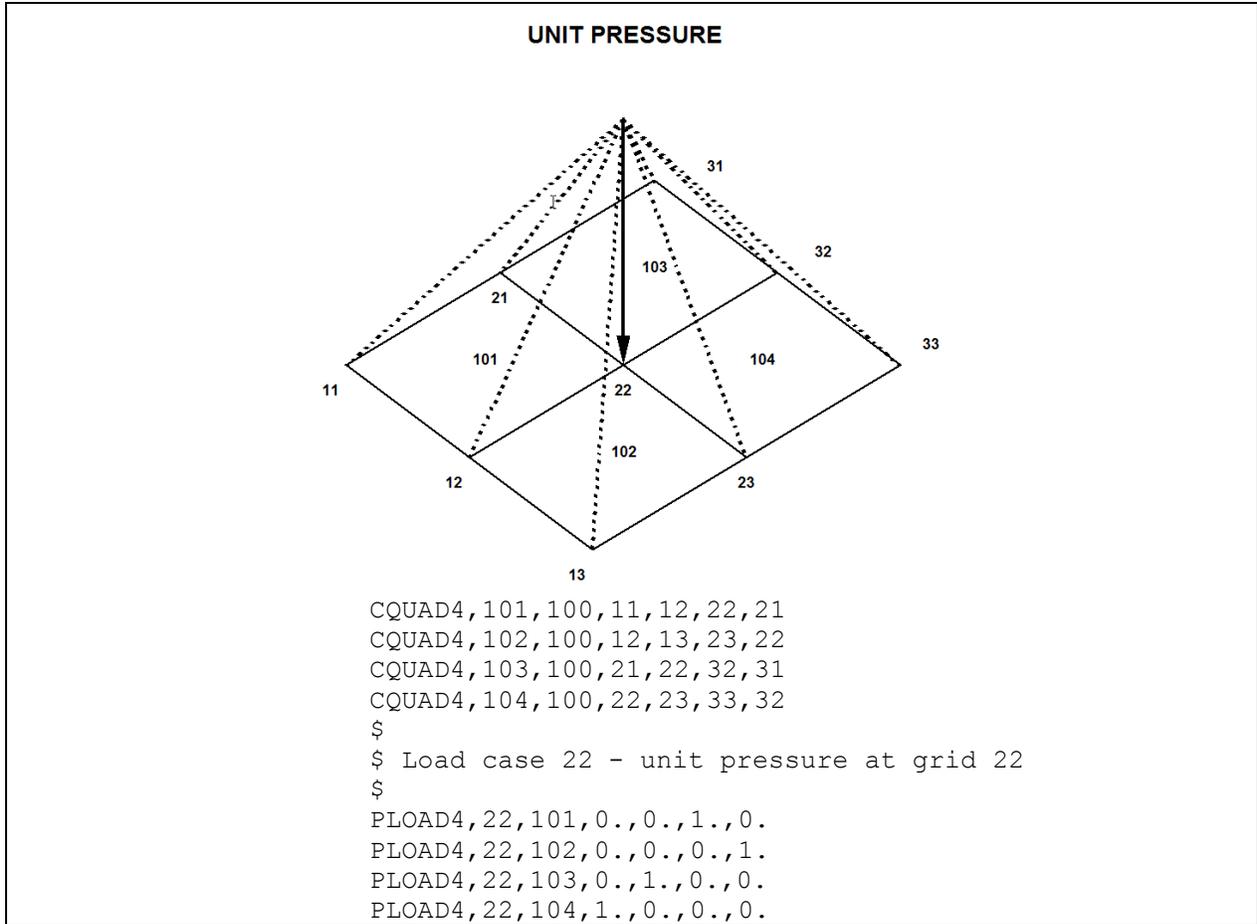
Figure 2-3. A column of the area matrix contains the structural forces
caused by a unit pressure at a fluid boundary grid.

There will be one column in the area matrix corresponding to each exterior fluid DOF. The structural forces exerted by the fluid on the structure can be written as:

$$\{F_g\} = [A_{ga}]\{p_a\} \tag{11}$$

where

$$A_{ij} = \frac{\partial}{\partial u_i \partial p_j} \int_s p\vec{u} \cdot d\vec{S} \tag{12}$$

Comparing (6) and (13), it can be seen that:

$$[A] = [B]^T \tag{13}$$

The area matrices are generated by the HYDRO procedure using PLOAD4 cards. For each exterior fluid DOF, the appropriate wetted structure and free surface elements are identified. A PLOAD4 card is written for each element with a unit pressure at the fluid grid and zero pressure

at all other grids. This process defines linearly varying pressure fields that are compatible with the linear fluid elements. Typical PLOAD4 statements are shown in Figure 2-3.

2.3. **Fluid Mass**

After generating the area matrices, the fluid stiffness matrix generated as described in Section 2.1 can be converted to an equivalent mass matrix at the wetted structure and free surface degrees of freedom. The equation of motion for the structure as forced by the fluid pressures can be written as:

$$[M^s_{gg}]\{\ddot{u}_g\} + [K^s_{gg}]\{u_g\} - [A_{ga}]\{p_a\} = \{0\} \tag{14}$$

The pressure in (14) can be obtained by inserting (13) into (5) and solving for p_a:

$$[K^f_{aa}]\{p_a\} + [A_{ga}]^T\{\ddot{u}_g\} = 0 \tag{15}$$

$$\{p_a\} = -[K^f_{aa}]^{-1}[A_{ga}]^T\{\ddot{u}_g\} \tag{16}$$

Unfortunately, in the standard free-surface option, $[K^f_{aa}]$ is singular and cannot be directly inverted. $[K^f_{aa}]$ contains one rigid body mode corresponding to uniform exterior pressure causing no potential in the fluid. This situation is similar to uniform displacements in a structure causing no internal strain energy. When using either of the no-slosh options, the pressure DOF on the entire free surface of the fluid are restrained, so this is not an issue.

To invert $[K^f_{aa}]$, one pressure DOF must be selected as a reference, and all other fluid DOF are expressed relative to the reference grid [4]. Next rewrite (16) into reference and complementary partitions as follows:

$$\begin{bmatrix} K^f_{rr} & K^f_{rl} \\ K^f_{lr} & K^f_{ll} \end{bmatrix} \begin{Bmatrix} p_r \\ p_l \end{Bmatrix} = -\begin{bmatrix} A_{gr}^T \\ A_{gl}^T \end{bmatrix} \{\ddot{u}_g\} \tag{17}$$

The reference pressure p_r can be subtracted from the pressure term in (17). This is equivalent to subtracting a rigid body displacement shape from a set of displacements without changing the structural strain energy.

$$\begin{bmatrix} K^f_{rr} & K^f_{rl} \\ K^f_{lr} & K^f_{ll} \end{bmatrix} \begin{Bmatrix} 0 \\ p_l' \end{Bmatrix} = -\begin{bmatrix} A_{gr}^T \\ A_{gl}^T \end{bmatrix} \{\ddot{u}_g\} \tag{18}$$

The upper and lower partitions of (18) can be written as:

$$[K^f_{rl}]\{p_l'\} = -[A_{gr}]^T\{\ddot{u}_g\} \tag{19}$$

$$\left[K_{ll}^{f}\right]\left\{p_{l}^{\,\prime}\right\}=-\left[A_{gl}\right]^{T}\left\{\ddot{u}_{g}\right\} \tag{20}$$

And the lower partition (20) can be solved for pressure as:

$$\left\{p_{l}^{\,\prime}\right\}=-\left[K_{ll}^{f}\right]^{-1}\left[A_{gl}\right]^{T}\left\{\ddot{u}_{g}\right\} \tag{21}$$

Note that (21) can be used to recover pressures anywhere on the surface of the fluid relative to the reference pressure, as a function of the structural accelerations. A partition of this matrix is used when the user requests pressure output from HYDRO.

The complete pressure vector (relative to the reference pressure) is:

$$\left\{p_{a}^{\,\prime}\right\}=\left\{\begin{matrix}0\\p_{l}^{\,\prime}\end{matrix}\right\} \tag{22}$$

Next, (22) can be substituted into (14):

$$\left[M_{gg}^{s}\right]\left\{\ddot{u}_{g}\right\}+\left[K_{gg}^{s}\right]\left\{u_{g}\right\}-\left[A_{gr}\quad A_{gl}\right]\left\{\begin{matrix}0\\p_{l}^{\,\prime}\end{matrix}\right\}=\left\{0\right\} \tag{23}$$

Or, this can be expressed as:

$$\left[M_{gg}^{s}\right]\left\{\ddot{u}_{g}\right\}+\left[K_{gg}^{s}\right]\left\{u_{g}\right\}-\left[A_{gl}\right]\left\{p_{l}^{\,\prime}\right\}=\left\{0\right\} \tag{24}$$

Equation (21) can be substituted into (24):

$$\left(\left[M_{gg}^{s}\right]+\left[A_{gl}\right]\left[K_{ll}^{f}\right]^{-1}\left[A_{gl}\right]^{T}\right)\left\{\ddot{u}_{g}\right\}+\left[K_{gg}^{s}\right]\left\{u_{g}\right\}=\left\{0\right\} \tag{25}$$

or

$$\left(\left[M_{gg}^{s}\right]+\left[M_{gg}^{f}\right]\right)\left\{\ddot{u}_{g}\right\}+\left[K_{gg}^{s}\right]\left\{u_{g}\right\}=\left\{0\right\} \tag{26}$$

where

$$\left[M_{gg}^{f}\right]=\left[A_{gl}\right]\left[K_{ll}^{f}\right]^{-1}\left[A_{gl}\right]^{T} \tag{27}$$

M_{gg}^{f} represents the fluid mass transformed to the wetted structure and free surface degrees of freedom. Note that there is no fluid stiffness term in (26). This is correct since fluid has no stiffness.

In the case of a õno-sloshö surface, the fluid stiffness matrix $\left[K_{aa}^{f}\right]$ is not singular and no R-set is introduced into the problem. Otherwise, the calculation of the fluid mass is identical. In the õno-sloshö case, the fluid mass perpendicular to the surface will be equal to the full fluid mass.

However, in the plane of the surface, the õno-sloshö fluid mass does not include the lateral mass of the fluid slosh modes. Since the fluid slosh modes are almost always at a much lower frequency than the structural modes, the õno-sloshö fluid surface option provides an excellent approximation of the effect of the fluid on the structure without introducing a large number of slosh modes to the problem. This can be used to simplify the problem.

In the "fast" version of the no-slosh fluid surface, the mass matrix is never calculated. Instead, the $\left[K_{ll}^f\right]^{-1}$ and $\lfloor A_{gl}\rfloor$ matrices are output and read directly into the coupled fluid/structure solution where they are used to construct a mass matrix in modal rather than physical coordinates.

2.4. **Incompressibility**

The fluid mass matrix was obtained using the lower partition of (18). An important additional result is obtained from the upper partition of (18). Inserting (21) into (19) results in the following expression:

$$-\left[K_{rl}^f\right]\left[K_{ll}^f\right]^{-1}\left[A_{gl}\right]^T\left\{\ddot{u}_g\right\}=-\left[A_{gr}\right]^T\left\{\ddot{u}_g\right\} \tag{28}$$

Equation (28) can be rearranged as follows:

$$\left(\left[A_{gr}\right]^T-\left[K_{rl}^f\right]\left[K_{ll}^f\right]^{-1}\left[A_{gl}\right]^T\right)\left\{\ddot{u}_g\right\}=0 \tag{29}$$

Equation (30) is very important because it defines the volume relationship for an incompressible fluid (i.e., constant volume). This relationship has one row and õgö columns that can be defined in NASTRAN as a multipoint constraint equation. A side effect of the MPC for incompressibility is that all structural and free surface DOF will be coupled, resulting in poor matrix bandwidth and high matrix density for the final Craig-Bampton fluid model and any downstream superelements. This is a computational challenge for both conventional bandwidth-oriented matrix solvers and modern sparse matrix algorithms.

Incompressibility equations are not required when using the õno-sloshö fluid surface option.

2.5. **Free Surface Stiffness**

If the fluid has a free surface and is in a gravity field, the fluid will have slosh modes caused by õgravity stiffness.ö Slosh modes occur in both axial and lateral directions, as illustrated in Figure 2-4. In theory, there exist an infinite number of axial and lateral slosh modes similar to those shown in Figure 2-5. In a finite element model, the number of slosh modes is limited by the finite

element mesh. In addition, the accuracy of the calculated slosh modes is controlled by the fluid mesh refinement (see Section 5.1 for additional comments on accuracy).
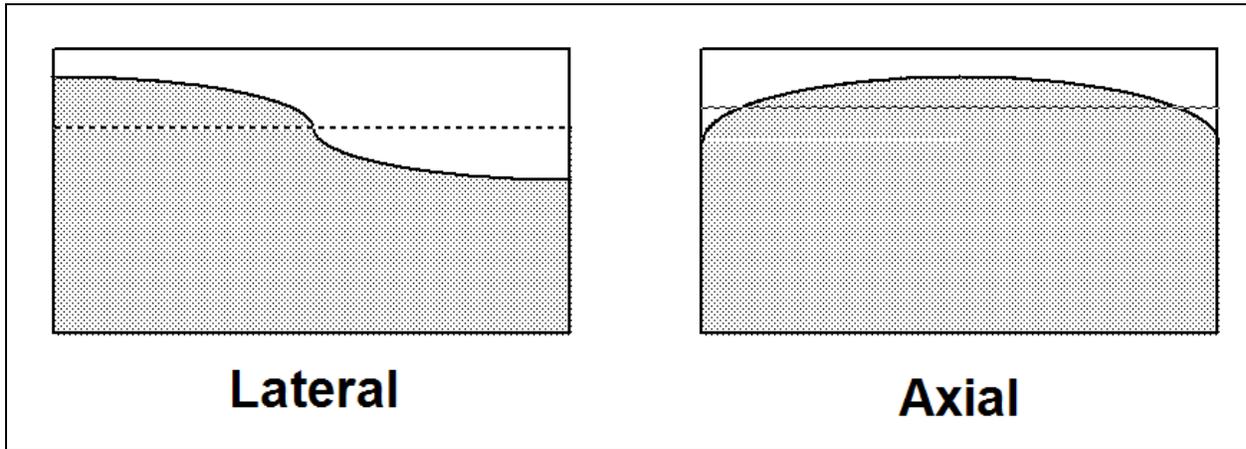
Figure 2-4. Lateral and axial slosh modes occur when the fluid
has a free surface and is in a gravity field.
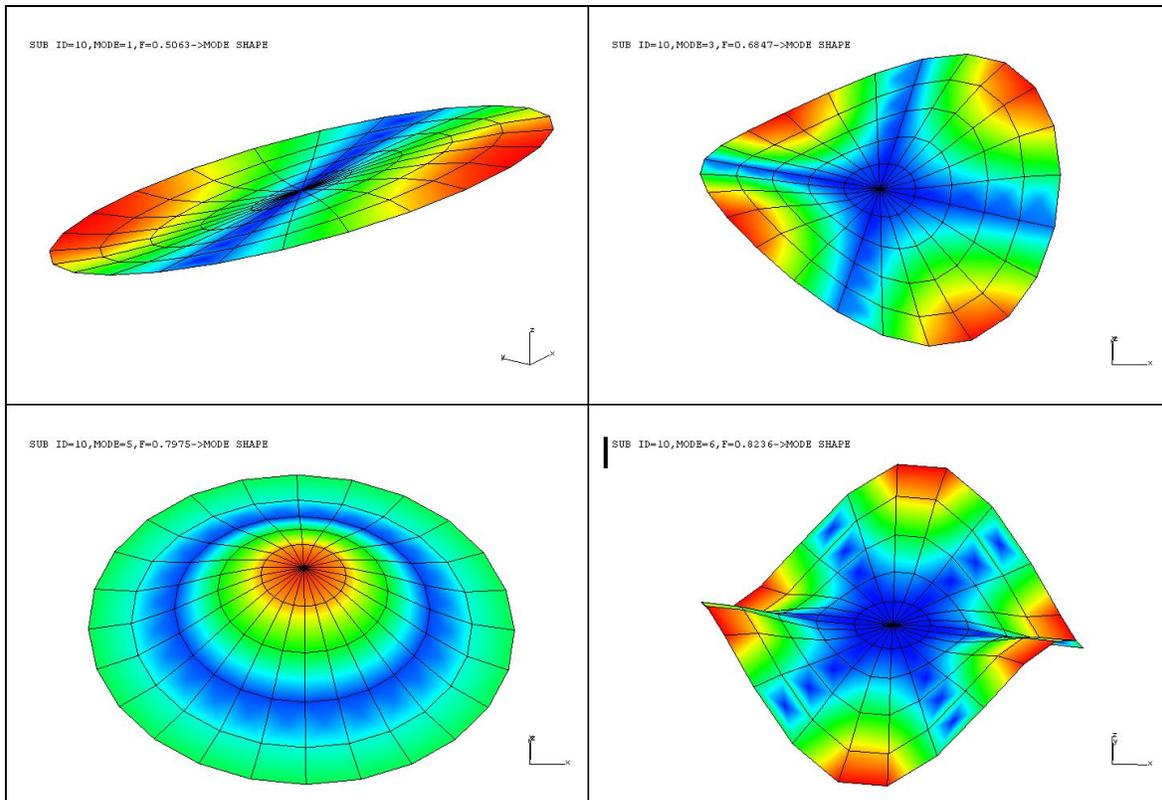
Figure 2-5. Large numbers of axial and lateral slosh modes
will exist when the fluid has a free surface.

If the fluid is in a gravity field and is disturbed from its undeformed position, there is a pressure in the fluid caused by displacement relative to the original position:

$$\{p_n\} = \rho g\{u_n\} \tag{30}$$

Both sides of (31) can be pre-multiplied by a special area matrix which includes columns only for the boundary pressure DOF at the free surface:

$$[A_{nn}]\{p_n\} = \rho g[A_{nn}]\{u_n\} \tag{31}$$

Equation (31) can be written in terms of a free surface stiffness matrix:

$$-[A_{nn}]\{p_n\} + [K_{nn}^n]\{u_n\} = 0 \tag{32}$$

where

$$[K_{nn}^n] = \rho g[A_{nn}] \tag{33}$$

A_{nn} is a special area matrix that includes only terms for the free surface. In general, similar terms would appear at all structural wetted surface DOF. However, studies [5] have shown that the gravity stiffness terms are usually several orders of magnitude less than the structural stiffness terms. Therefore, the gravity stiffness terms at the structural wetted surface are neglected. The free surface area matrix is calculated using the same methodology described in Section 2.2 but is limited to columns corresponding to pressure grids at the free surface.

No free surface stiffness is generated for either the õno-sloshö option or when the fluid is fully enclosed.

2.6. **Relative Free Surface**

The equations for the free surface stiffness developed in Section 2.5 make the stiffness relative to inertial space. This is correct when the tank is fixed in space, but is not correct when the tank is fixed to a moving body such as a rocket. In this case, the free surface stiffness should be relative to the steady state acceleration which is oriented along the thrust vector. HYDRO offers the option of making the free surface stiffness relative to a grid that can be connected to any DOF on the model. In this case, the fluid free surface stiffness is modified as follows:

$$[K_{NN}^n] = \begin{bmatrix} I_{nn} \\ \Phi_{RB} \end{bmatrix} [K_{nn}^n] [I_{nn} \quad \Phi_{RB}^T] \tag{34}$$

where

Φ_{RB} - 6 rigid body vectors partitioned to the free surface DOF.

This is the same approach that NASTRAN takes to convert grounded stiffness or flexibility terms for a GENEL element to an element that is ungrounded relative to 6 dependent DOF.

The relative option also corrects for an error in the pitch and yaw mass moments of inertia that arises when using the õfixedö surface option. The error results because the constraint shapes used to reduce the mass matrix can only represent axial motion of the free surface. Adding the relative grid allows the constraint shapes to represent all rigid body motion of the free surface, capturing the correct mass properties. The error in the fixed option is negligible in most cases, but the user should always compare the G-set and A-set mass properties written by the WEIGHTCHECK in the _SUP run to check that errors in the pitch and yaw inertias are acceptable. If they are not acceptable the relative free surface option should be used.

2.7. **Fluid Superelement Model**

Stiffness and mass matrices are formed for the fluid superelement using the fluid inertance matrix, the area matrix, and the gravity stiffness matrix. The matrices include DOF for structure wetted surface grids and normal displacement DOF at the free surface grids (if any). In addition, the multipoint constraint equation that defines the incompressibility relationship must be applied at the appropriate step in the analysis (more on this later).

If the fluid has a free surface, the normal displacements of the surface can be replaced by generalized coordinates using the Craig-Bampton modal synthesis method [1]. Slosh modes are calculated with the structural wetted surface DOF restrained. There are two significant advantages to using slosh modes (generalized coordinates) to replace the free surface normal displacements. First, the modal frequencies, mode shapes, and modal effective masses are explicitly calculated and provide important information to check the properties and validity of the fluid model. Second, only the generalized coordinates of õsignificantö slosh modes need to be retained. A slosh mode is considered to be õsignificantö if it will interact with the structure and/or be excited by the forcing functions. Typically, a significant slosh mode will have large modal effective mass defined as:

$$MEM = MER^2 \tag{35}$$

where

$$MER = \phi^T M \Phi \tag{36}$$

In most cases, only the lower frequency lateral slosh modes will have large effective mass. If the fluid geometry is axisymmetric, the lateral slosh modes will occur in pairs. For an axisymmetric fluid, the first two pairs of lateral slosh modes with large effective mass are typically retained

along with the first axial slosh mode[4], and all other slosh modes are eliminated. This results in a substantial reduction of the hydroelastic model size and prevents unneeded system modes.

If the fluid has a free surface, the MPC set for incompressibility is applied during the Craig-Bampton superelement run. The dependent degree of freedom in the MPC set must be one of the free surface normal displacements. This will cause the maximum number of slosh modes (before eliminating unimportant modes) to be one less than the number of free surface normal degrees of freedom.

If the fluid does not have a free surface (fluid completely enclosed by wetted structure), the MPC set cannot be applied to the fluid model during the Craig-Bampton run. This is because there are no interior hydroelastic DOF that can be made dependent. For an enclosed fluid model, the MPC set must be applied during the processing of the downstream superelement. In this run, one of the structural DOF must be eliminated (made dependent) by the MPC relationship. Note that the DOF to be eliminated is arbitrary and may be any DOF on the surface with a nonzero area matrix coefficient.

The HYDRO procedure adds the fluid mass, stiffness and incompressibility constraints to the superelement model, but otherwise does not modify the standard superelement reduction process in NASTRAN. As discussed in Section 2.6, the fixed implementation of the free surface does not capture all the fluid mass during the reduction from the F-set to the A-set (elimination of free surface DOF). The user should therefore always check the mass properties written by WEIGHTCHECK to ensure that the error in the A-set values is acceptable. If it is not, the relative option should be used instead.

The final result of the hydroelastic finite element model for all cases other than the "fast" option is a set of data blocks that define the fluid model as an NASTRAN superelement. The data blocks created include mass and stiffness matrices and geometry information. Pressure in the fluid is not directly available but could be recovered using the transformation matrices developed to reduce the fluid model. In the case of the "fast" option, the output is a .op2 file with two matrices that can be used to construct the fluid mass. These are input into the structural model using a special-purpose DMAP alter provided with HYDRO.

The superelement representation of the fluid can either be a standard bulk data superelement (defined by SESET cards), DMIG matrices, or any external superelement representation.

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[4] The 1st axial slosh mode is the first mode that does not come in a pair. It does not have any significant axial effective mass. The axial slosh modes can interact with axial õbulgeö hydroelastic modes.

2.8. **Coupling the Fluid and Structural Models**

The fluid hydroelastic model is coupled to the structural model using standard superelement methods. NASTRAN automatically fetches the appropriate matrices from the hydroelastic model and adds them to corresponding terms in the structural model. If the fluid model does not have a free surface, the MPC set which imposes incompressibility must be included. If the fluid model has a free surface, insignificant slosh modes can be eliminated by SPC requests.

If the fluid model has a relative free surface, the pitch and yaw rotational DOF on the õrelativeö grid must be coupled to some structural DOF. Note that HYDRO adds this grid to the coupled solution run (*_cpl.dat), but it is up to the user to couple the grid to the rest of the model. Ideally the grid is coupled to a location of the model that defines the thrust vector, though the results should be acceptable when this is attached to any other location on the model.

The specifics of the coupling will depend on which superelement option was chosen. The DMIG option does not use superelements, but requires that the matrices be identified on M2GG and K2GG cards in Case Control. The external superelement[5] definitions require SEBULK and SECONCT cards in the main bulk data sections along with the EXTBULK cards written to the .pch file when generating the external superelement. In all cases a _CPL input deck is provided as a template for coupling the fluid superelement to the rest of the structure.

2.9. **Recovering Fluid Pressures**

If the user requests fluid pressure recovery these grids are added as interior to the fluid superelement, and MPC equations are written so that acceleration output for DOF 1 on these grids is the corresponding pressure. Pressures, therefore are recovered by requesting acceleration output for the pressure recovery grids.

2.10. **Fast Solution Method**

The standard HYDRO methods developed in the previous sections have worked very well for a number of different launch vehicle loads models with relatively coarse FEM meshes. However, for very fine meshes used in stress models, both the computation of the fluid mass matrix and the calculation of the coupled fluid/structure modes can become too computationally expensive. In order to address this concern, a "fast" option for HYDRO was developed, which avoids both the assembly of the mass matrix and the modal solution with the fully coupled mass matrix. It does this by first solving for the structural modes without any fluid and then using these modes as a set of basis vectors to reduce the fluid mass matrix to modal coordinates. The equations are then

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[5] The external superelements are supported in MSC Nastran starting with V2004, and NX Nastran starting with NXN 6.

coupled in the modal coordinates and a second eigenvalue solution is executed to calculate the final coupled modes. This is similar to the VMOPT,2 solution using MFLUID.

The õfastö option has a number of limitations. In its current implementation, it can only be used with a õno-sloshö free surface model (no slosh modes), it cannot be used to recover internal pressures, and it is an approximate method where the accuracy of the approximation is a function of the number of structural modes used in the reduction. However, runs that would take many days to complete or would not be feasible at all can be executed in minutes using this method, and if used with a sufficient number of structural modes it can be very accurate.

Starting with the coupled equations (25) and using the õdryö modes without the fluid mass terms as basis vectors results in the following reduced stiffness and mass matrices:

$$[\Phi_s]^T[K_{gg}^s][\Phi_s]=[\hat{K}_s] \, , \, [\Phi_s]^T[M_{gg}^s][\Phi_s]=[\ddot{M}_s] \tag{37}$$

The fluid mass matrix in modal coordinates can then be written as:

$$[\ddot{M}_f]=([\Phi_s]^T[A_{gl}])[K_{ll}^f]^{-1}([A_{gl}]^T[\Phi_s]) \tag{38}$$

Note that the number of columns in $([A_{gl}]^T[\Phi_s])$ is equal to the number of õdryö modes, which is *much* less than the number of columns in the fluid mass matrix. The mass matrix is only created in modal coordinates, and never in physical coordinates. The coupled modes are calculated in modal coordinates as follows:

$$([\ddot{K}_s]-\omega^2([\ddot{M}_s]+[\ddot{M}_f])){\phi}=0 \tag{39}$$

This method is currently limited to a õno-sloshö fluid surface, and the accuracy is a function of the number of õdryö modes retained in the solution. However, it is much more efficient than the standard HYDRO methods. Because it is currently limited to a õno-sloshö fluid surface, slosh modes are not calculated using this method, and the fluid mass in the plane of the fluid surface does not include the fluid sloshing mass. This accurately represents the coupling of the fluid to the structure as long as the fluid slosh modes are at a much lower frequency than the structural modes[6].

---

[6] Fluid slosh modes with significant effective mass are typically in the range of 1 Hz, so for most practical problems they are very well separated from the structural modes. Exceptions might be very large fluid storage containers, where the structural modes are also on the order of 1 Hz. It is possible to extend the "fast" formulation to include slosh modes, and this may be implemented in a future version of HYDRO.

3.   **OPERATION PROCEDURES**

The HYDRO procedures are implemented as a series of steps shown in Figure 3-1. These steps
and all special requirements are described in the following sections.
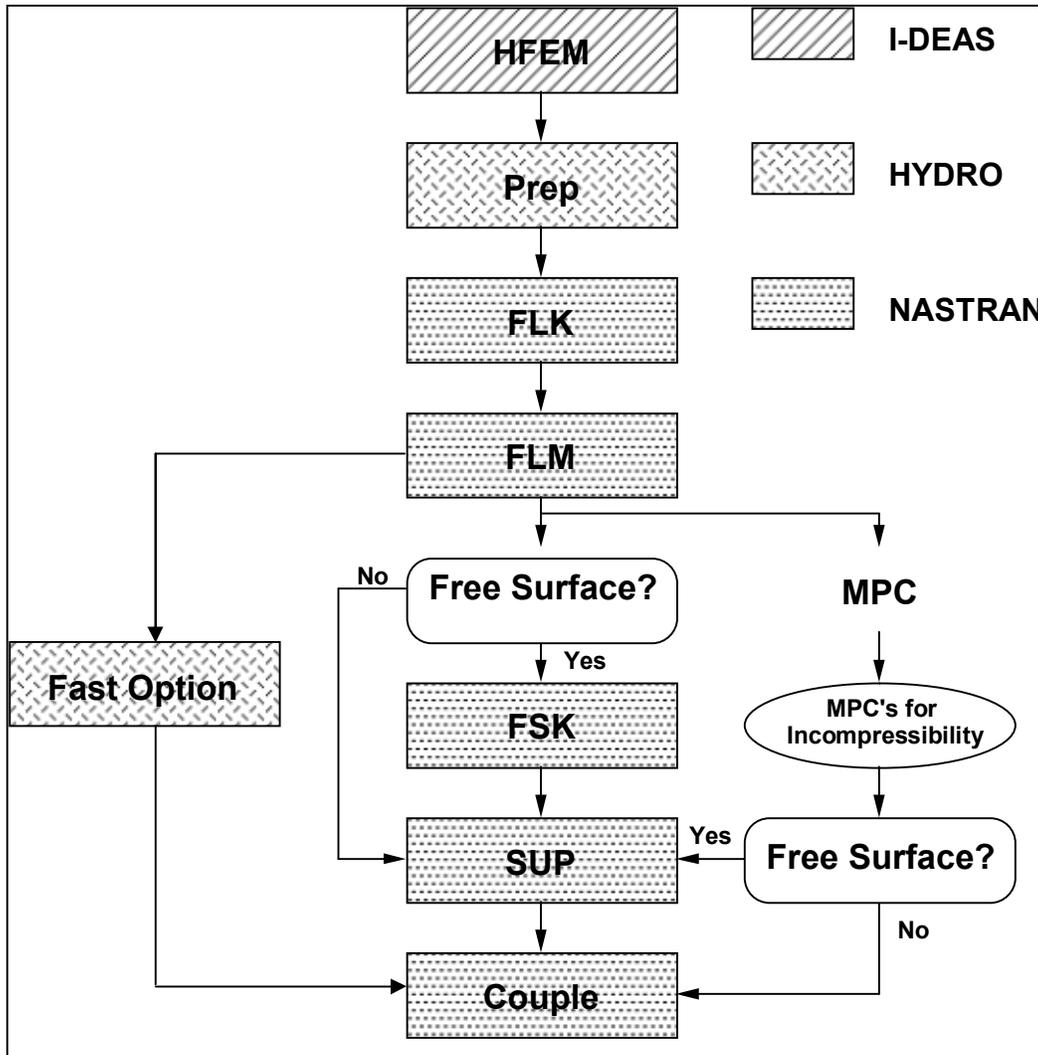
Figure 3-1. The coupled hydroelastic model is formed using NASTRAN
and a special Fortran program called HYDRO.

HYDRO reads a NASTRAN input deck, which can be created in any FEM preprocessor such as
Femap.

HYDRO offers a number of different options for representing the fluid, depending on whether it
has a free surface and how that free surface is represented. The options are:

ENCLOSED   Fluid has no free surface and is in contact with the structure over its entire
                    outer surface.

FIXED   Fluid has a free surface, which is assumed to slosh relative to an inertially fixed gravity vector. Note that this can sometimes lead to errors in the pitch and yaw moments of inertia, resulting in an error in the fluid rigid body CG location.

RELATIVE   Fluid has a free surface, which is assumed to slosh relative to a grid that moves with the structure. The relative option will result in the correct pitch and yaw moments of inertia and CG.

NO_SLOSH_STD   Fluid has a free surface, but slosh modes are not required. The fluid mass model does not include the sloshing mass on the assumption that the slosh modes are at a much lower frequency than the structural modes. This option only works with the standard bulk data superelement format.

NO_SLOSH_FAST   Same as the NO_SLOSH_STD option, except that the fluid mass matrix is never assembled in physical coordinates. Instead, the decomposed fluid inertance and area matrices are output to couple the fluid into the structural model using modal coordinates. This is an approximate approach that is many orders of magnitude faster than the standard HYDRO approaches. This method doesn't generate a superelement representation of the fluid.

The operation of HYDRO varies somewhat depending on the fluid representation chosen. In addition, for all fluid options except for NO_SLOSH_FAST, HYDRO offers a number of choices for the superelement output format. These include:

Standard Bulk Data   Bulk data superelement defined by SESET and CSUPEXT cards

DMIGPCH External   External superelement with matrices written in DMIG format to the PUNCH file

DMIGOP2 External   External superelement with matrices written in DMIG format to an OUTPUT2 file

DMIGDB External   External superelement with matrices written in DMIG format to the database

MATDB External   External superelement with matrices written to the database

MATOP4 External   External superelement with matrices written to an OUTPUT4 file

DMIGPCH Only   Matrices written in DMIG format to the PUNCH file without auxiliary EXTBULK data for external superelement. This option does not require a superelement license to couple the model.

3.1.   **Develop Hydroelastic Model**

The first step is to develop the hydroelastic finite element model. The model must include the following items:

- Grids and solid elements for the fluid
- Grids and shell elements for the wetted structure
- Grids and shell elements for the free surface (if any)

The grids connected by the fluid elements, wetted structure elements, and free surface elements must be independent. This will result in coincident grids at the fluid/structure and fluid/free surface interfaces as shown in Figure 3-2. Note that at the fluid/structure/free surface õcornerö there will be three coincident grids at each location.
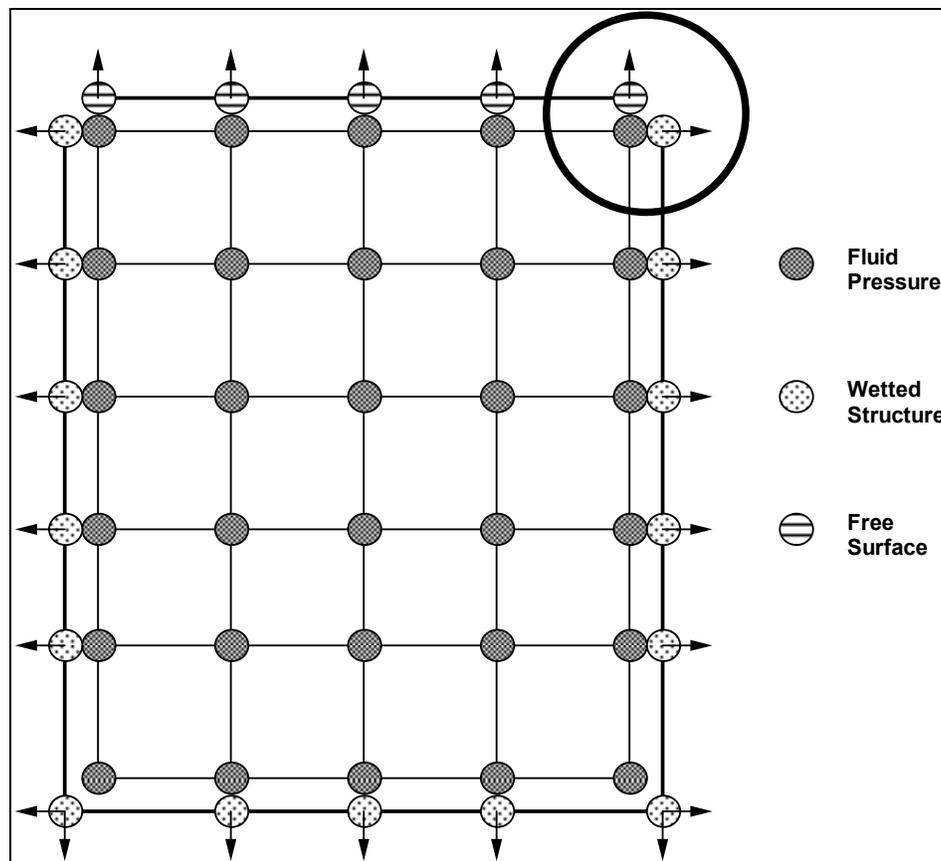
Figure 3-2. There will be three coincident grids at the intersection
of the fluid, wetted-structure and free surface.

The **grids** must defined with the following **requirements**:

- The coincident fluid/structure and fluid/free surface grids must be coincident within a tolerance defined by the user at the time of the HYDRO run. This tolerance should be smaller than the smallest element size in the model. The default is 0.01.
- The ID numbers (labels), locations, and displacement coordinate systems orientation of the wetted structure grids must be **exactly the same** as the structural model to which the hydroelastic model will be later coupled. The ID numbers for the free surface and fluid grids are arbitrary.
- The free surface, if present, must be flat and normal to the gravity vector.
- The displacement coordinate system of the free surface grids must be oriented such that the **displacement Z axis** is parallel to the gravity vector (normal to the free surface) and pointing away from the fluid (up).

The fluid, wetted structure, and free surface **elements** must be defined with the following **requirements**:

- The fluid must be modeled with linear bricks, wedges, or tetrahedrons.
- The wetted structure and free surface must be modeled with linear quadrilateral or triangular shell elements. The shell element type need not be compatible with the õcoatedö fluid element type (i.e., a quadrilateral shell can be used to couple to the triangular face of a fluid wedge or tetrahedron). However, there must be a one-to-one correspondence between grids on the outer surface for the fluid and grids on the wetted or free surface.
- All shell elements for the free surface must use the same element property ID.
- The orientation (normals) of the wetted structure and free surface shell elements must be defined to be uniformly <u>outward</u>. **Any mixing of shell element normals (some oriented inward while others oriented outward) will produce incorrect results.**
- The property ID numbers for the fluid, wetted structure, and free surface must be unique.
- The fluid model must have no unexpected free edges.
- The properties for the shell and solid elements are arbitrary. They are not used at any time in the HYDRO procedures.

A typical hydroelastic model is shown in Figure 3-3. Note that solid elements are used for the fluid, and shell elements are used for the wetted structure and free surface. In this model, the surface and fluid elements have been moved away from each other to highlight the different elements. In the actual model, these must be coincident.
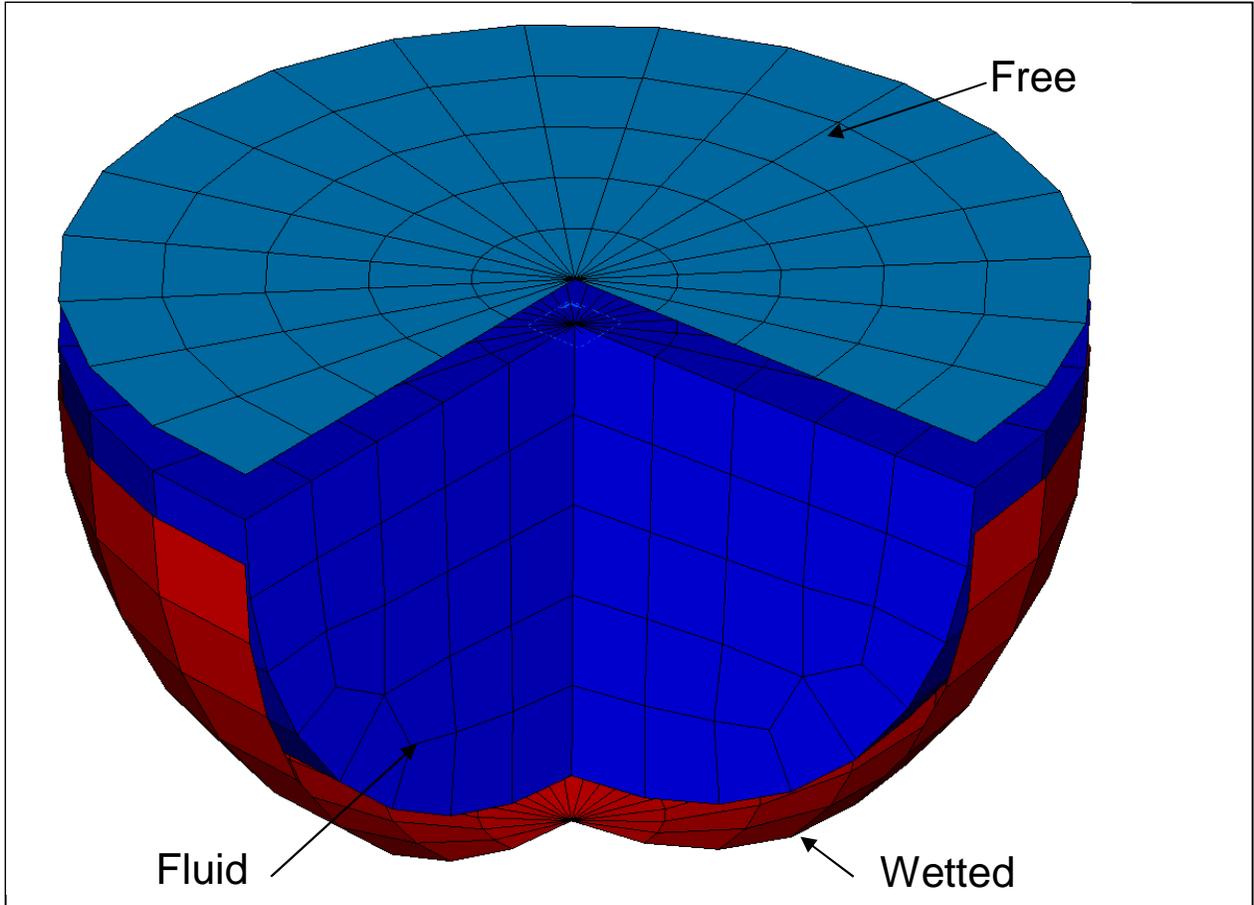
Figure 3-3. The hydroelastic finite element model will include solid elements for the fluid
and shell elements for the wetted structure and free surface (exploded view).

Several checks are highly recommended to verify the accuracy of the hydroelastic model. The
checks include:

- Fluid mass properties
- Element distortion
- Free edge checks for the fluid, wetted structure, and free surface elements
- Orientation of the shell elements for the wetted structure and free surface

These checks are described in more detail in Chapter 5.

After completing the definition and checking of the hydroelastic model, it is written as a
NASTRAN input deck (bulk data). This file is read by the HYDRO program as described in the
next section.

3.2. **HYDRO "Prep" Run**

A program called HYDRO prepares several NASTRAN input decks. The specific decks created
depend on the fluid option chosen. HYDRO is run two times for each hydroelastic model when

using the ENCLOSED, FIXED, or RELATIVE fluid options. The second run is not required for the NO_SLOSH_STD or NO_SLOSH_FAST options. The first HYDRO run reads the NASTRAN input deck with fluid, wetted surface, and free surface elements and prepares the following series of NASTRAN input decks:

- **FLK** - Generates the fluid inertance (stiffness) matrix and reduces it to the fluid boundary DOF.
- **FLM** - Generates the area matrices, transforms the fluid inertance matrix to an equivalent mass matrix, and calculates the incompressibility relationship.
- **FSK** - Generates the free surface area matrix and the gravity stiffness matrix. This run is only executed for a sloshing surface (FIXED or RELATIVE) option.
- **SUP** - Forms the Craig-Bampton hydroelastic model including slosh modes.

Each deck includes the appropriate grids and elements (fluid for the FLK run and surface for the FLM, FSK and SUP runs), along with the NASTRAN DMAP required to perform that step. The FSK and SUP runs are not generated for the NO_SLOSH_FAST option.

The second HYDRO run writes the MPC equation for incompressibility. This run is described in Section 3.6.

The HYDRO õprepö run performs the following operations:

- Identifies the fluid grids (any grid connected to a solid element).
- Identifies the fluid boundary grids (any fluid grid coincident with a grid connected to either the wetted structure or the free surface shell elements).
- Identifies the wetted structure grids (any grid coincident to a fluid boundary grid but not connected to a free surface shell).
- Identifies the free surface grids (any grids connected to the free surface shell elements).Generates the FLK input deck including grids, elements, properties, and ASET information to calculate the fluid inertance (stiffness) matrix and reduce it to the fluid boundary DOF.
- If the user requests pressure outputs, these are written to the FLK input deck as CSET cards so that the associated partition of the pressure vector can be extracted. The nodes are also written to the FLM, SUP and CPL decks to allow for recovery of pressures.
- Generates the FLM input decks including grids, elements, properties, and load information to generate the area matrices.
- For either the FIXED or RELATIVE option, generates the FSK input decks including grids, elements, properties, and load information to generate the free surface stiffness matrix.
- All options other than NO_SLOSH_FAST, generate the SUP input deck including grids and superelement data to define the fluid superelement. The superelement format is fixed at the SUP run, so different superelement output options can be run by modifying this run.

The inputs required for the HYDRO õPrepö depend on the options chosen as summarized in Table 3-1.

Table 3-1. Summary of input for the HYDRO õPrepö run.

	OPTION	ENCLOSED	FIXED	RELATIVE	NO_SLOSH_STD	NO_SLOSH_FAST
1	NASTRAN bulk file to read	required	required	required	required	required
2	free surface (y/n) ?	N	Y	Y	Y	Y
3	Surface option	N/A	fixed	relative	no_slosh_std	no_slosh_fast
4	New free surface reference grid	N/A	N/A	required	N/A	N/A
5	Existing free surface grid	N/A	N/A	required	N/A	N/A
6	free surface PID	N/A	required	required	required	required
7	coincident grid tolerance	optional	optional	optional	optional	optional
8	fluid type or density	required	required	required	required	required
9	gravity magnitude	N/A	required	required	N/A	N/A
10	fluid pressure reference grid	required	required	required	N/A	N/A
11	superelement ID	required	required	required	required	N/A
12	pressure recovery grids	optional	optional	optional	optional	N/A
13	nastran version number	required	required	required	required	required
14	nastran buffer size	optional	optional	optional	optional	optional
15	pressure model database	required	required	required	required	required
16	fluid superelement database	required	required	required	required	N/A
17	fluid stiffness input file (FLK)	required	required	required	required	required
18	fluid area matrix/mass input file (FLM)	required	required	required	required	required
19	Output2 file written by FLM run	N/A	N/A	N/A	N/A	required
20	free surface stiffness input file (FSK)	N/A	required	required	N/A	N/A
21	fluid superelement input file (SUP)	required	required	required	required	N/A
22	Template for coupled system run (CPL)	optional	optional	optional	optional	optional
23	first Q-set SPOINT	N/A	required	required	N/A	N/A
24	max frequency for modes	N/A	required	required	N/A	N/A

The inputs are defined as follows:

1. Name of NASTRAN bulk data file with fluid and surface elements (HFEM model).
2. Does the fluid have a free surface?
3. Type of free surface (FIXED, RELATIVE, NO_SLOSH_STD or NO_SLOSH_FAST).
4. SE Format. Either standard bulk data, one of the external superelement options or DMIGPCH only. Note that only the standard bulk data format is available for the

NO_SLOSH_STD free surface, and no superelement is generated for NO_SLOSH_FAST.

5. In NX Nastran 8.0 and 8.1 the External Superelement OUTPUT4 option was modified to write a sparse OP4 file. The sparse output appears to have a bug and can result in an unusable file. The workaround is to manually modify the OUTPUT4 file to an UNFORMATTED version. This is corrected in NX Nastran 8.5.

6. A number for a grid that will be added to the model for the RELATIVE surface option. The stiffness of the free surface will be relative to this grid. This grid should not exist in the HFEM.

7. Property ID of the PSHELL card defining the free surface elements.

8. Maximum distance for two grids to be coincident (default is 0.01)

9. User can either select from a menu of predefined fluid densities (in inch units) or enter a value for the fluid mass density.

10. Magnitude of gravity vector on free surface in units of length/time^2.

11. A grid number on the outer surface of the fluid elements. All pressures will be calculated relative to this grid. It is usually chosen on the free surface of the fluid, but it must be a fluid grid and not a surface grid. Only required for the ENCLOSED, FIXED, and RELATIVE options.

12. ID number of the superelement created in SUP run. Not applicable to the NO_SLOSH_FAST option.

13. One or more grid numbers on the outer surface of the fluid used for pressure recovery. The pressure recovery matrix is written from the FLM run and then processed into MPC equations during the MPC run. This allows for the pressures to be recovered as acceleration outputs from the coupled model. Pressure recovery is not available for the NO_SLOSH options.

14. Version of NASTRAN to be used (V2004, V2005, NX3, NX4, etc.). The available options are controlled by the availability of the corresponding DMAP alters in the executable directory.

15. Increased NASTRAN buffer size if required.

16. Database name for FLK, FLM and FSK runs.

17. Database name for SUP run.

18. Name of the NASTRAN input file for the FLK run.

19. Name of the NASTRAN input file for the FLM run.

20. Name of the OUTPUT2 file from the FLM run for the NO_SLOSH_FAST option. This file cannot have the same name as the _FLM run with an .op2 file type. The default is a .ou2 file type.

21. Name of the NASTRAN input file for the FSK run.

22. Name of the NASTRAN input file for the SUP run.

23. Name of the NASTRAN input template file to couple with the structure.

24. SPOINTs to create DOF for slosh modes using FIXED or RELATIVE options.

25. Number of modes to calculate using the FIXED or RELATIVE options.

The HYDRO program can be run in two modes. The default is the GUI mode, illustrated in Figure 3-4, which is executed by typing *hydro* at a Windows command line prompt, or by double-clicking on the *hydro.exe* icon. HYDRO also works in a command line mode, where the user is prompted for inputs. This mode is executed by entering *hydro –t* at a command line prompt. On the GUI, the processing option (õPrepö or õMPCö), the slosh option, and the NASTRAN version are all selected from pull-down menus. The form changes to reflect the appropriate inputs for that selection of options. Alternatively, an input file can be prepared and read using *hydro –t < file.inp*. In the command line version, the user is only prompted for those inputs that are relevant to the selected options. Both methods for running HYDRO are covered in Section 4.1.2.
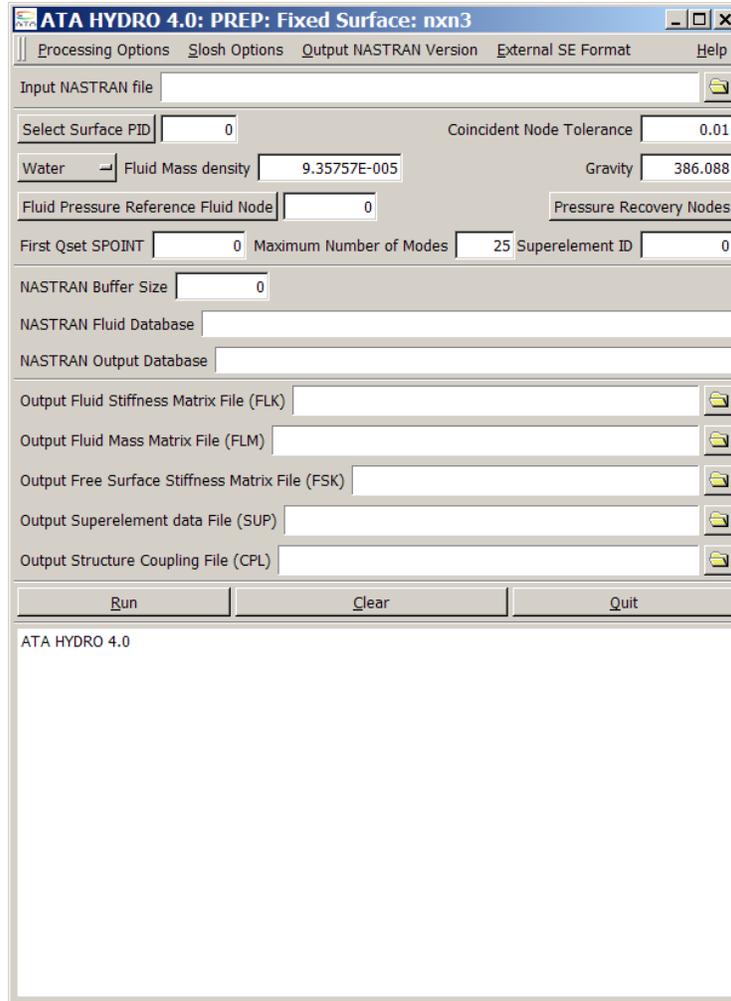
Figure 3-4. HYDRO graphical user interface.

The FLK, FLM, FSK, and SUP runs using the decks prepared by HYDRO are discussed in the following sections.

3.3.   **FLK – Generate Fluid Inertance (Stiffness) Matrix**

The FLK run generates the fluid inertance (stiffness) matrix and reduces it to the fluid boundary DOF. The run is a heat transfer analysis and uses the fluid/heat transfer analogy for the element and material properties. A special DMAP sequence performs the required operations.

ASET cards are included to identify the fluid boundary grids. For all options other than the õno-slosh,ö a SUPORT card is written to identify the fluid boundary grid that will be used as the reference point for the fluid pressure. See Section 2.3 for more information on the fluid pressure reference point.

If pressure recovery grids were selected by the user, these are identified on CSET cards in the FLK run. The CSET cards are used to partition the pressure vector output to the desired locations for later processing into MPC equations for pressure recovery.

The data for the fluid model and inertance (stiffness) matrix is stored in a database. The database dictionary is printed at the completion of the run and at a minimum should contain the PKLL datablock. For all cases other than õno-slosh,ö it should also contain the PVALR and PKLR datablocks.

3.4. **FLM – Generate Fluid Mass Matrix**

A NASTRAN run is performed to generate the area matrix and the fluid mass matrix. The run generates load vectors to form the area matrix. After completing all columns of the area matrix, the fluid inertance (stiffness) matrix generated by the FLK run is either converted to an equivalent mass matrix at the wetted structure and free surface DOF, or in the case of the NO_SLOSH_FAST option decomposed and written in OUTPUT2 format for coupling with the structure. The FLM run is performed as a restart run using the database created in the FLK run.

The Bulk Data deck includes grids and shell elements for the wetted structure. PLOAD4 cards are included to define the unit fluid pressures. The load generation capability in NASTRAN is used to convert the fluid pressures to equivalent structural forces. These terms make up the area matrix.

For all cases other than the NO_SLOSH_FAST option, the fluid inertance (stiffness) matrix is converted to an equivalent mass matrix at the wetted structure and free surface DOF, and the NASTRAN Grid Point Weight Generator output is printed[7]. The user should check this output carefully to make sure that the fluid mass is correct. For the ENCLOSED, FIXED, and RELATIVE options, the fluid mass should be the same in all three directions and should be equal to the fluid volume times its density. Any deviation from these results indicates an error in the model. For the NO_SLOSH options, the slosh modes are not calculated, but the sloshing mass is removed in the lateral direction. This means that only the mass component normal to the free surface will equal the fluid volume times its density. In the other two directions, the mass will be less. For typical models, the lateral mass components are anywhere from 10% to 80% less than the total mass.

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[7] When using the NO_SLOSH_FAST option, the mass properties are not output in NASTRAN Grid Point Weight Generator format. Instead, the mass matrix about the origin is output in MATPRN format as matrix MRIG. The (1,1), (2,2) and (3,3) elements of this matrix are then written as õmessages.ö

For all options other than NO_SLOSH_FAST, the area matrix and fluid mass matrix are stored in the database. After the final FLM run, the database dictionary is printed at the completion of the run and should contain the following additional data blocks:

AGP   Area matrix (structure g-set to pressure model)
FMOO   Fluid mass matrix ó o-set partition (FIXED/RELATIVE options only)
FMAO   Fluid mass matrix ó o-to-a coupling partition (FIXED/RELATIVE options only)
FMAA1   Fluid mass matrix ó a-set partition

For the ENCLOSED, FIXED, and RELATIVE options, the MPC coefficients are written in DMIG format to the .pch file for processing by the HYDRO õMPCö run. These are not required or output for either of the NO_SLOSH options.

If the user requested pressure output, a UTOPF matrix is also written to the .pch file with a column corresponding to each pressure output DOF. This matrix is also processed by the HYDRO õMPCö run into MPC equations that can be used to recover pressures.

When using the NO_SLOSH_FAST option, the area matrix (AGP) and the decomposed fluid inertance matrix (LDLL) are written to an OUTPUT2 file for coupling with the structure. In this case, the fluid database is not used and no superelements are created.

3.5.   **FSK – Generate Free Surface Stiffness Matrix**

The FSK run is needed only if the fluid has a free surface. The FSK run is not needed and is not generated by the HYDRO program when using the ENCLOSED option.

The FSK run is similar to the FLM run. The FSK run generates the free surface area matrix and the gravity stiffness matrix. It also generates load vectors to form the free surface area matrix. After completing all columns of the area matrix, the gravity stiffness matrix is calculated by multiplying the free surface area matrix by gravity and fluid density, as described previously in Section 2.5. The FSK run is performed as a restart run using the database accessed by the FLK and FLM runs.

The Bulk Data deck includes grids and shell elements for the free surface. PLOAD4 cards are included to define the unit fluid pressures. The load generation capability in NASTRAN is used to convert the fluid pressures to equivalent structural forces needed for the area matrices.

In the final FSK run, the free surface stiffness matrix is formed by multiplying the free surface area matrix by gravity and fluid density. No special checks are performed for the accuracy of the free surface stiffness matrix since any errors in the free surface definition would have been detected during the FLM runs.

The free surface area matrix and stiffness matrix are stored in the database. After the final FLK run, the database dictionary is printed at the completion of the run and should contain the following data blocks:

FSK1   Area matrix (free surface grids to pressure model)
FKGGDMIG   Free surface stiffness matrix (MTRXIN DMIG format)

3.6. **HYDRO "MPC" Run**

A second run of the HYDRO program is required after completing the FLM sequence of runs only when using the ENCLOSED, FIXED, or RELATIVE options[8]. The second HYDRO run reads the NASTRAN punch file (.pch) from the FLM run and writes MPC statements that define the incompressibility relationship. The following information is entered interactively for the second HYDRO run:

- HYDRO operating mode (MPC)
- Name of the final FLM .F06 file
- MPC set number
- Dependent DOF

For a fluid model with a free surface, the dependent DOF must be one of the free surface normal displacements and should be in the Z direction (normal to the surface). For a fluid model without a free surface, the dependent DOF must be a wetted structure DOF with a non-zero MPC coefficient.

If the user requested pressure outputs, the õMPCö run also processes the UTOP1 matrix in the .pch file into an MPC equation for each pressure output. The pressure outputs are labeled fluid grid numbers, with the pressures stored on DOF 1. The user should request acceleration output for that DOF to recover pressures.

3.7. **SUP – Generate Hydroelastic Model Superelement**

The SUP run combines the results from the previous runs to form the hydroelastic model superelement. The run generates the geometry data blocks required for a superelement and formats the fluid matrix into final form. For the FIXED or RELATIVE options, slosh modes are calculated and used to form the component mode generalized mass and stiffness matrices. If slosh modes are calculated, the fractional modal effective mass results are also written to the .f06 in order to facilitate the selection of important slosh modes. After completing the SUP run, the hydroelastic model is defined as either a standard NASTRAN superelement, as DMIG cards, or as an external superelement. All output options for an external superelement are supported.

---

[8] The MPC run is not required for either of the NO_SLOSH options.

These include MATDB, DMIGDB, DMIGOP2, DMIGPCH, and MATOP4. The SUP run is not executed for the NO_SLOSH_FAST option.

The data blocks to define the fluid superelement are either stored in the database or on an external file, depending on the superelement option chosen. The database dictionary is printed at the completion of the SUP run and should contain standard data blocks to define a NASTRAN superelement. If any of the external superelement options other than DMIGDB or MATDB are chosen, the matrices are written to an external file. In the case of the external superelement options, an .asm file is written by HYDRO to be included in the main bulk data section of the coupling run and a .pch file is written by the SUP run to define the PART superelement.

3.8.   <u>**Coupling of Fluid Superelement to Structural Models**</u>

For all cases other than the NO_SLOSH_FAST option, the fluid superelement is coupled to the structural model using standard methods. At this point in the HYDRO procedure, the fluid superelement is recognized as a bulk data or external NASTRAN superelement. The assembly of the fluid into the model depends on the type of superelement but does not require any special DMAP or other processing.

A template for this coupling run is provided by HYDRO. The template includes everything except for the structural model, which must be added. The form of the coupling run depends on the output format. For a standard bulk data superelement, it includes the free surface grids (if any), the CSUPEXT statements defining the exterior wetted surface grids, and the grids and SEQSET statements for the generalized coordinates of the slosh modes (if any). SPC statements can be defined to restrain (eliminate) unimportant slosh modes. If the fluid superelement is completely enclosed (no free surface), the MPC data for incompressibility must be included and processed in the downstream superelement.

For external superelements, two files need to be included for each fluid superelement. The first is the .asm file created by HYDRO. This file includes the SEBULK card required to define the external superelement format, the SECONCT card to connect it to the corresponding GRIDs in the structure, and the SPOINT cards to define the slosh modes. The second is the .pch file from the SUP run. This file includes the BEGIN SUPER card for the superelement, as well as all other required input to define the external superelement. The coupling run includes both of these, and assignments to the external superelement matrix files.

For external superelements, a DMAP alter that allows the scaling of the matrices to represent different fluid weights and steady state accelerations is also included. The concept is that a fluid superelement will be developed for a particular tank fill level in a 1G acceleration field. This

fluid model will then be scaled to match a specific fluid weight and acceleration for a particular point in the flight trajectory. The user simply enters the desired fluid mass and the acceleration (in Gs), and the DMAP alter does the scaling of the fluid matrices. The mass matrix is scaled by the ratio of desired to modeled mass, and the stiffness matrix is scaled by the product of that factor multiplied by the acceleration. This facilitates the use of a single fluid model to represent slightly different fluid weights. A different fluid model should still be used if the fill level changes significantly.

If the fluid superelement has a free surface, the model will contain a large number of slosh modes. Most of the slosh modes are not important because they have very small effective mass and will not contribute to overall responses. The critical modes to keep are the lateral slosh modes. If the fluid model is symmetric, the lateral slosh modes will occur in pairs. Typically, only the first three or four lateral slosh mode pairs are important and should be retained. If desired, the axial slosh modes can also be retained, although these modes have very low effective mass and are unlikely to contribute to axial responses. The unimportant modes are eliminated by placing the appropriate degrees of freedom of the generalized coordinates on SPC or SPC1 cards. For a Craig-Bampton model, restraining a generalized coordinate eliminates that mode but does not impose any grounding on the structure.

The coupled hydroelastic modes are calculated using a standard eigensolver (Lanczos method recommended for most problems). The mode shapes can be displayed using any NASTRAN postprocessor. If the slosh modes are important, a special õdisplayö model can be created that includes both the structural model and õdisplayö shell elements for the free surface. This allows the display of the vertical motion of the free surface as well as the motion of the structure. Note that the lateral motion of the free surface will be zero since the lateral degrees of freedom are not defined by the free surface area matrix (see Section 2.5). Therefore, some engineering judgment is required to interpret the mode shapes of the õdisplayö model including the free surface.

3.9.   **Coupling of Fluid to Structural Models Using FAST Option**

When using the NO_SLOSH_FAST option, the fluid is coupled to the structural model using a special process that requires an additional DMAP Alter. HYDRO creates a template for this run that contains everything except for the structural model. The coupled solution is based on a two-step modal approach, where the first set of modes is calculated without the fluid and then used as a basis to reduce the fluid mass matrix before calculating the second set of modes. The coupled solution run is identical to a standard modal analysis run with the following changes:

1. An INPUTT2 file assignment is required to locate the OUTPUT2 file from the FLM run. This should be assigned to UNIT 11.
2. The *hydro_couple.xxx* alter must be included immediately before the CEND card.
3. SPOINTs must be defined as DOF to store the first set of modes.
4. The SPOINT DOF must be placed in the Q-set using QSET or QSET1 cards.
5. Optionally, physical DOF can also be added to the basis vectors using BSET or BSET1 cards.
6. A PARAM,METHCMRS and a corresponding EIGRL card must be included to define the modal parameters for the first set of modes.

A typical section of the bulk data deck is listed in Figure 3-5. In this case, 250 modes are calculated in the first pass, and the six DOF on grid 31501 are added to the BSET.

```
PARAM    METHCMRS    1000
EIGRL    1000                          250
SPOINT   99000    THRU      99250
QSET1    0        99000     THRU      99250
BSET1    123456   31501
```

Figure 3-5. Bulk data added to standard modes run to perform "fast" coupled fluid solution.

The fluid mass properties and both sets of modes (without and with fluid) are written to the .f06 file. The user should check that these mass properties are correct and that the modal frequencies with the fluid are different than the modal frequencies without the fluid.

4.   **EXAMPLE PROBLEMS**

Two example problems are presented in this chapter to illustrate the HYDRO procedures. The first example problem is a hemisphere of water in the bottom of an axisymmetric thin-walled tank. This example provides a good illustration of the input and output for a typical hydroelastic model. The second example problem is more advanced and illustrates defining a õrelativeö free surface and an annular fluid volume.

4.1.   **Fluid Hemisphere and Cylindrical Tank**

The first example problem is a hemisphere of water in the bottom of an axisymmetric thin-walled tank, as shown in Figure 4-1. This model includes many important features including special definition and displacement coordinate systems. In addition, an exact solution is available for a fluid hemisphere to verify the accuracy of the solution.
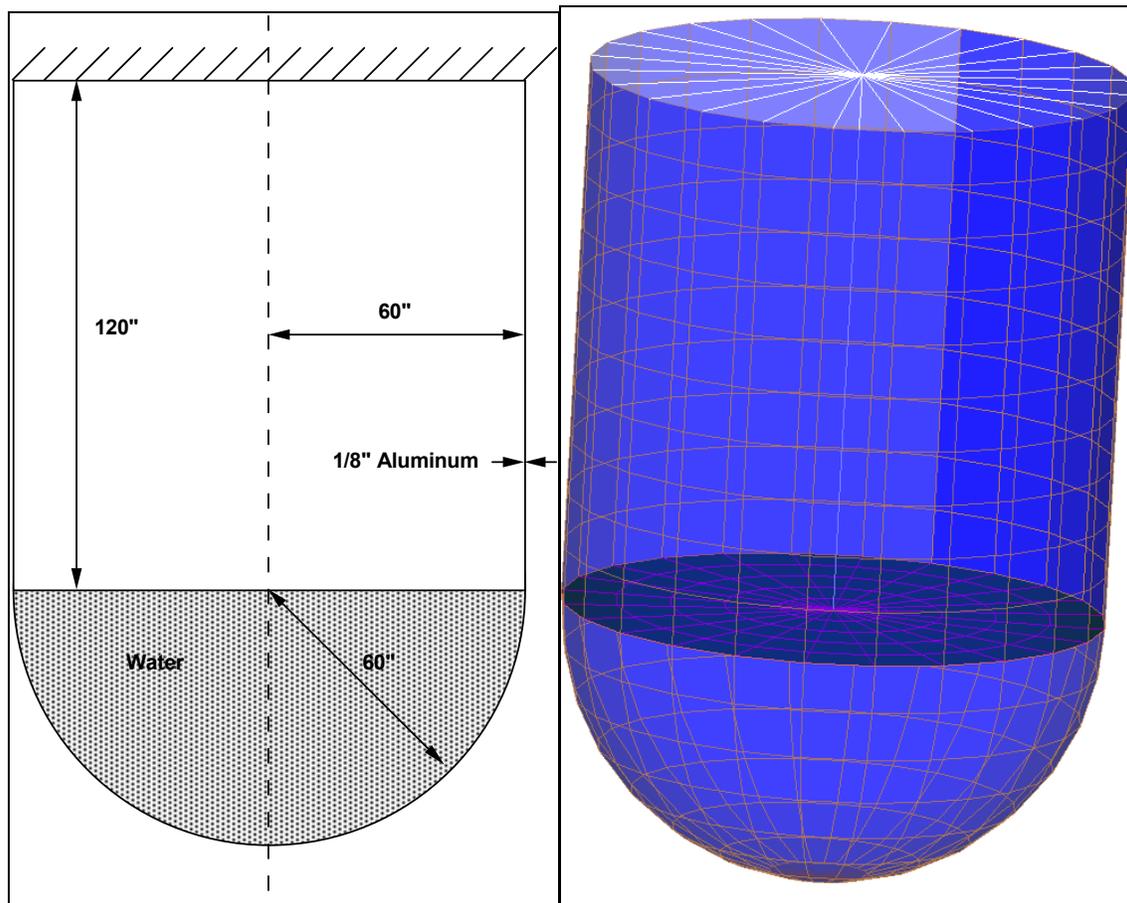
Figure 4-1. The example problem includes a hemisphere of water in a thin-walled tank.

The example problem is presented in the following steps:

- Creating the hydroelastic finite element model in I-deas
- Running the HYDRO program to develop the NASTRAN input decks
- Performing the FLK run
- Performing the FLM run
- Performing the FSK run
- Running the HYDRO program to write the MPC for incompressibility
- Performing the SUP run
- Coupling the fluid superelement to the structure

4.1.1. I-deas Hydroelastic Finite Element Model

The hydroelastic finite element model was created by revolving a cross section to create the complete model. To start the cross section mesh, a mesh area was created for the fluid illustrated in Figure 4-1. Shell elements for the fluid cross section were created using the automatic mesh generator, as shown in Figure 4-2. Grids at the fluid/wetted structure interface were copied from the fluid grids. These new wetted structure grids had the same ID numbers and displacement coordinate systems as the structural model described in Section 4.8.
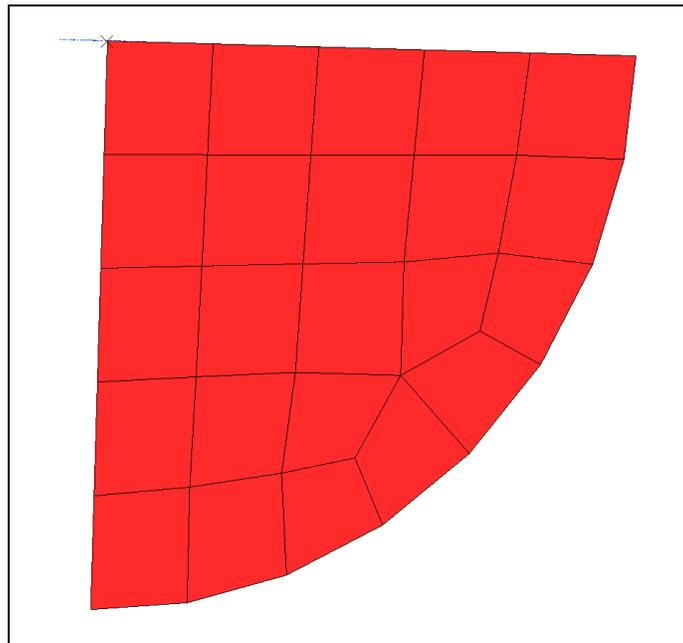
Figure 4-2. A cross section of the fluid was meshed.

The completed cross section was õrevolvedö to create the hydroelastic finite element model shown in Figure 4-3. The shell elements in the cross section generated solid brick and wedge elements for the fluid. The original cross section surface was then deleted and the outer surface was coated with both the wetted surface elements and the free surface elements. The coating was

performed in two steps so that the wetted surface elements and free surface elements would not share grids. In both cases, the master (fluid) grids were not used for the surfaces so that additional coincident grids were created.
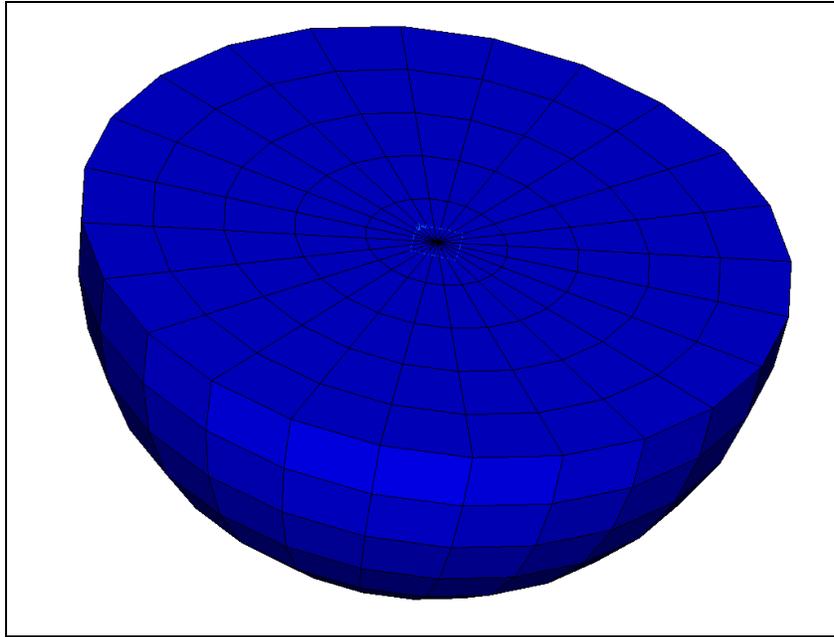
Figure 4-3. The fluid model cross section was revolved to create the hydroelastic finite element model.

The shell element orientation was checked using the element triad display to verify that all shell element normals all pointed outward. As shown in Figure 4-4, all elements were correctly oriented. Free edge checks for the wetted structure and free surface shell elements verified correct definition.
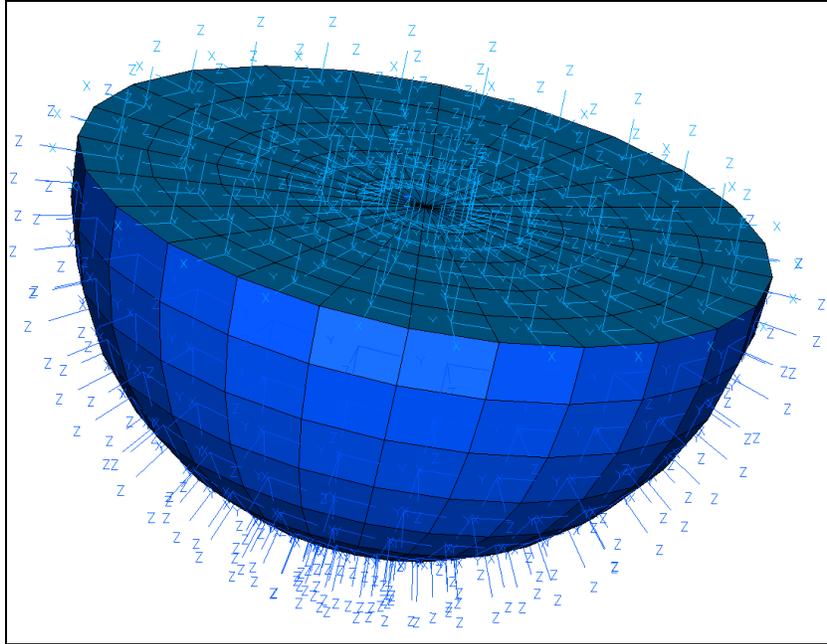
Figure 4-4. The orientation of the wetted structure and free surface shells were checked to verify that their orientation was uniformly outward.

The final hydroelastic finite element model, including the fluid elements, the wetted surface elements, and the free surface elements, was written to a NASTRAN input deck[9]. The NASTRAN input deck is read by the HYDRO program to create the NASTRAN input decks required to represent the fluid.

This model can be used for all options except for the option with no free surface (ENCLOSED). In this case, the structure must cover the top surface of the fluid so that it is fully enclosed. To do this, the structural grids around the circumference of the flat surface are merged with the wetted surface grids[10].

4.1.2. HYDRO ðPrepö Run

The HYDRO program was run to prepare the NASTRAN input decks, for all five options. The inputs depend on the option chosen, and HYDRO can be run in either command line mode or using the graphical user interface. The inputs are summarized in Table 4-1.

---

[9] This file is called hydroex.hfem and is delivered with HYDRO.
[10] This file is called enclosed.hfem and is delivered with HYDRO.

Table 4-1. Inputs to HYDRO run for hemisphere example.

	OPTION	ENCLOSED	FIXED	RELATIVE	NO_SLOSH_STD	NO_SLOSH_FAST
1	NASTRAN bulk file	enclosed.hfem	hydroex.hfem	hydroex.hfem	hydroex.hfem	hydroex.hfem
2	free surface?	N	Y	Y	Y	Y
3	Surface option	N/A	fixed	relative	no_slosh_std	no_slosh_fast
4	Free surface reference grid	N/A	N/A	40000	N/A	N/A
5	Existing free surface grid	N/A	N/A	30000	N/A	N/A
6	free surface PID	N/A	5	5	5	5
7	coincident grid tolerance	.01	.01	.01	.01	.01
8	fluid type or density	water	water	water	water	water
9	gravity magnitude	N/A	386.1	386.1	N/A	N/A
10	fluid pressure reference grid	10000	10000	10000	N/A	N/A
11	superelement ID	10	10	10	10	N/A
12	pressure recovery grids	10002, 10010	10002, 10010	10002, 10010	10002, 10010	N/A
13	nastran version number	NXN8	NXN8	NXN8	NXN8	NXN8
14	nastran buffer size	default	default	default	default	default
15	pressure model database	enclosed_P	fixed_P	relative_P	noslosh_P	fast_P
16	fluid superelement database	enclosed	fixed	relative	noslosh	N/A
17	fluid stiffness input file (FLK)	enclosed_flk.dat	fixed_flk.dat	relative_flk.dat	noslosh_flk.dat	fast_flk.dat
18	fluid mass input file (FLM)	enclosed_flm.dat	fixed_flm.dat	relative_flm.dat	noslosh_flm.dat	fast_flm.dat
19	Output2 file written by FLM run	N/A	N/A	N/A	N/A	fast_flm.ou2
20	free surface stiffness input file (FSK)	N/A	fixed_fsk.dat	relative_fsk.dat	N/A	N/A
21	superelement input file (SUP)	enclosed_sup.dat	fixed_sup.dat	relative_sup.dat	noslosh_sup.dat	N/A
22	Template for coupled system run (CPL)	enclosed_cpl.dat	fixed_cpl.dat	relative_cpl.dat	noslosh_cpl.dat	fast_cpl.dat
23	first Q-set grid	N/A	99001	99001	N/A	N/A
24	max frequency	N/A	2.5 Hz	2.5 Hz	N/A	N/A

The input decks for the command line version of HYDRO for the various options are presented in Figure 4-5 through Figure 4-9. Note that only prompts for those inputs that are relevant to the selected option are provided.

```
PREP
enclosed.hfem
N
0.01
water
10000
10
10002
10010

nxn8

enclosed_P
enclosed
enclosed_flk.dat
enclosed_flm.dat
enclosed_sup.dat
enclosed_cpl.dat
```

Figure 4-5. HYDRO input for fluid hemisphere example with ENCLOSED option.

```
PREP
hydroex.hfem
Y
NO_SLOSH_FAST
5
0.1
water
nxn8

fast_P
fast
fast_flk.dat
fast_flm.dat
fast_flm.ou2
fast_cpl.dat
```

Figure 4-6. HYDRO input for fluid hemisphere example with NO_SLOSH_FAST option.

```
PREP
hydroex.hfem
Y
FIXED
5
0.1
water
386.1
10000
10
10002
10010

nxn8

fixed_P
fixed
fixed_flk.dat
fixed_flm.dat
fixed_fsk.dat
fixed_sup.dat
fixed_cpl.dat
99001
2.5
```

Figure 4-7. HYDRO input for fluid hemisphere example with FIXED option.

```
PREP
hydroex.hfem
Y
NO_SLOSH_STD
5
0.1
water
10
10002
10010

nxn8

noslosh_P
noslosh
noslosh_flk.dat
noslosh_flm.dat
noslosh_sup.dat
noslosh_cpl.dat
```

Figure 4-8. HYDRO input for fluid hemisphere example with NO_SLOSH_STD option.

```
PREP
hydroex.hfem
Y
RELATIVE
40000
30000
5
0.1
water
386.1
10000
10
10002
10010

nxn8

relative_P
relative_
relative_flk.dat
relative_flm.dat
relative_fsk.dat
relative_sup.dat
relative_cpl.dat
99001
2.5
```

Figure 4-9. HYDRO input for fluid hemisphere example with RELATIVE option.

The GUI inputs for the various options are illustrated in Figure 4-10 through Figure 4-14.
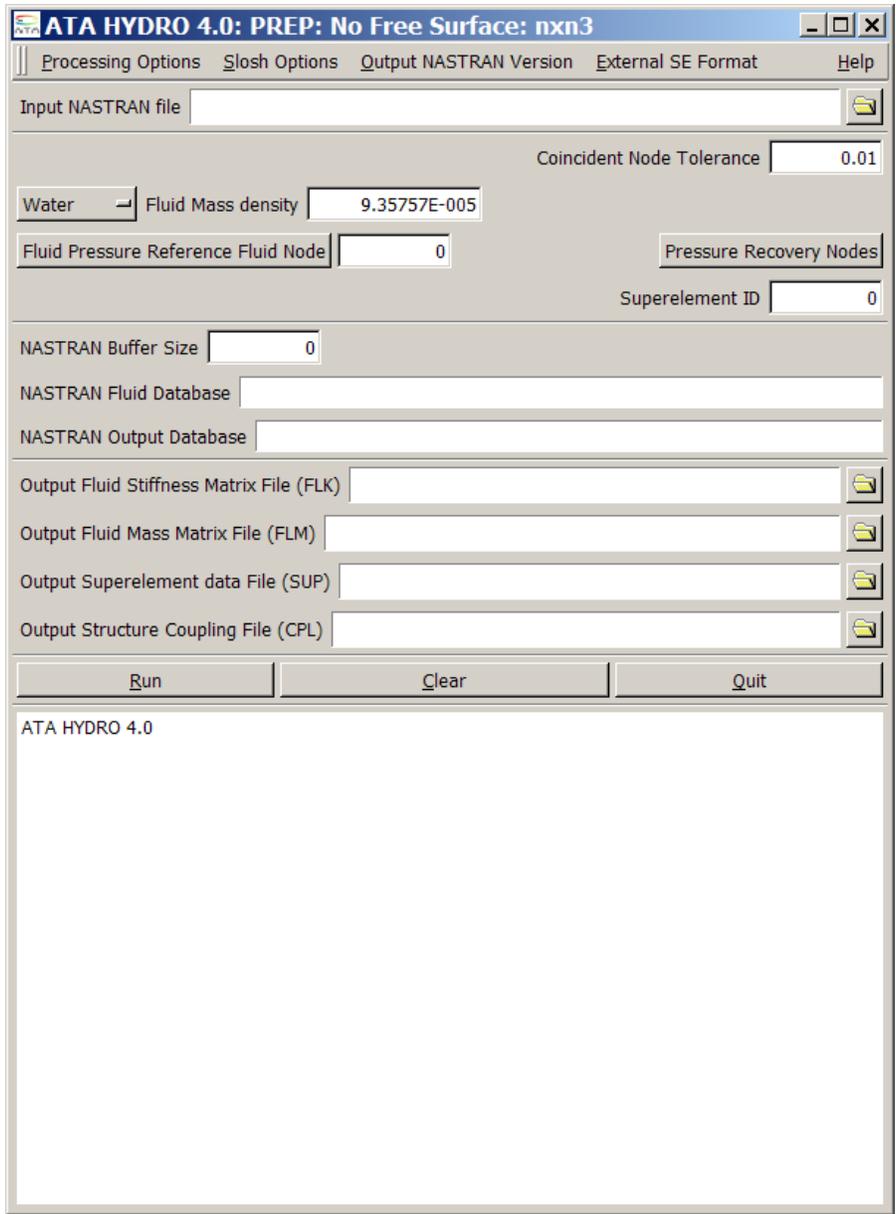
Figure 4-10. HYDRO GUI input for fluid hemisphere example with ENCLOSED option.
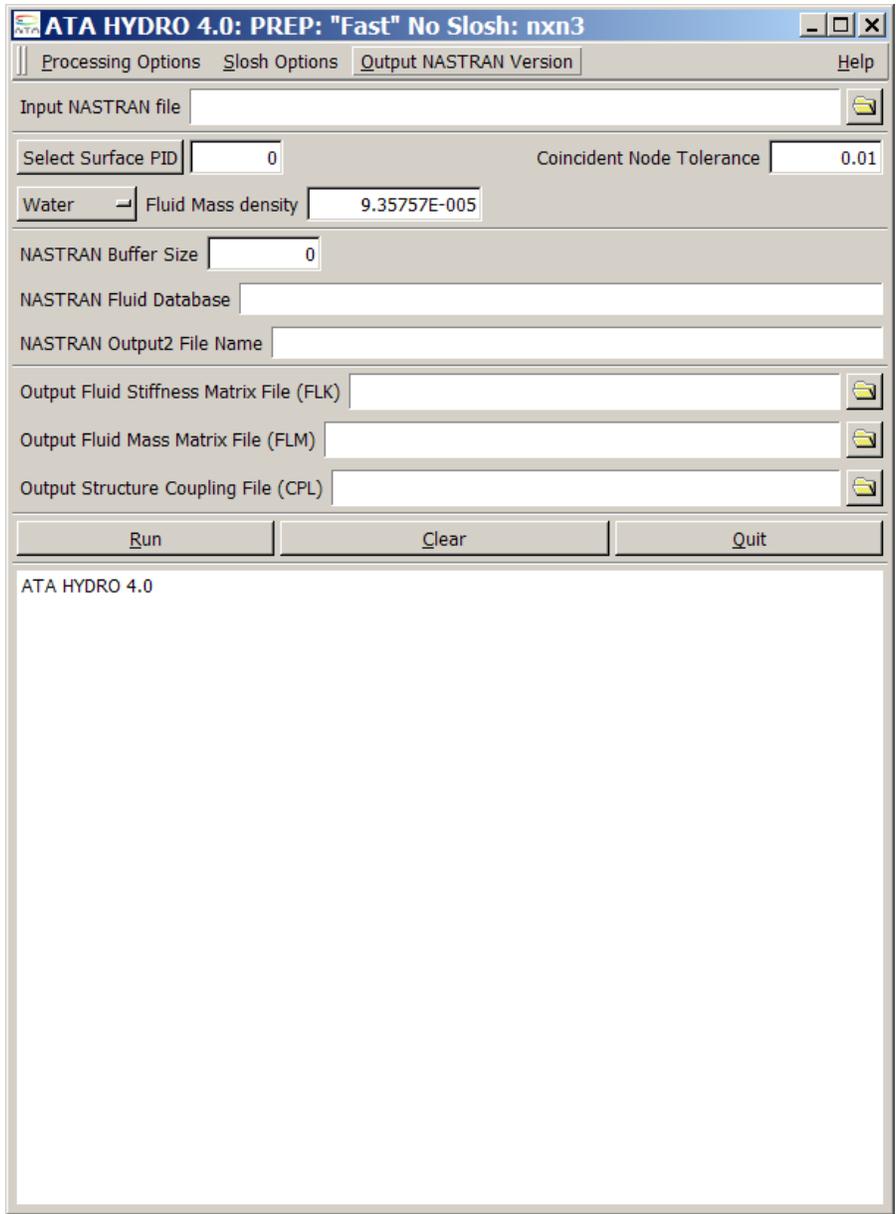
Figure 4-11. HYDRO GUI input for fluid hemisphere example with NO_SLOSH_FAST option.
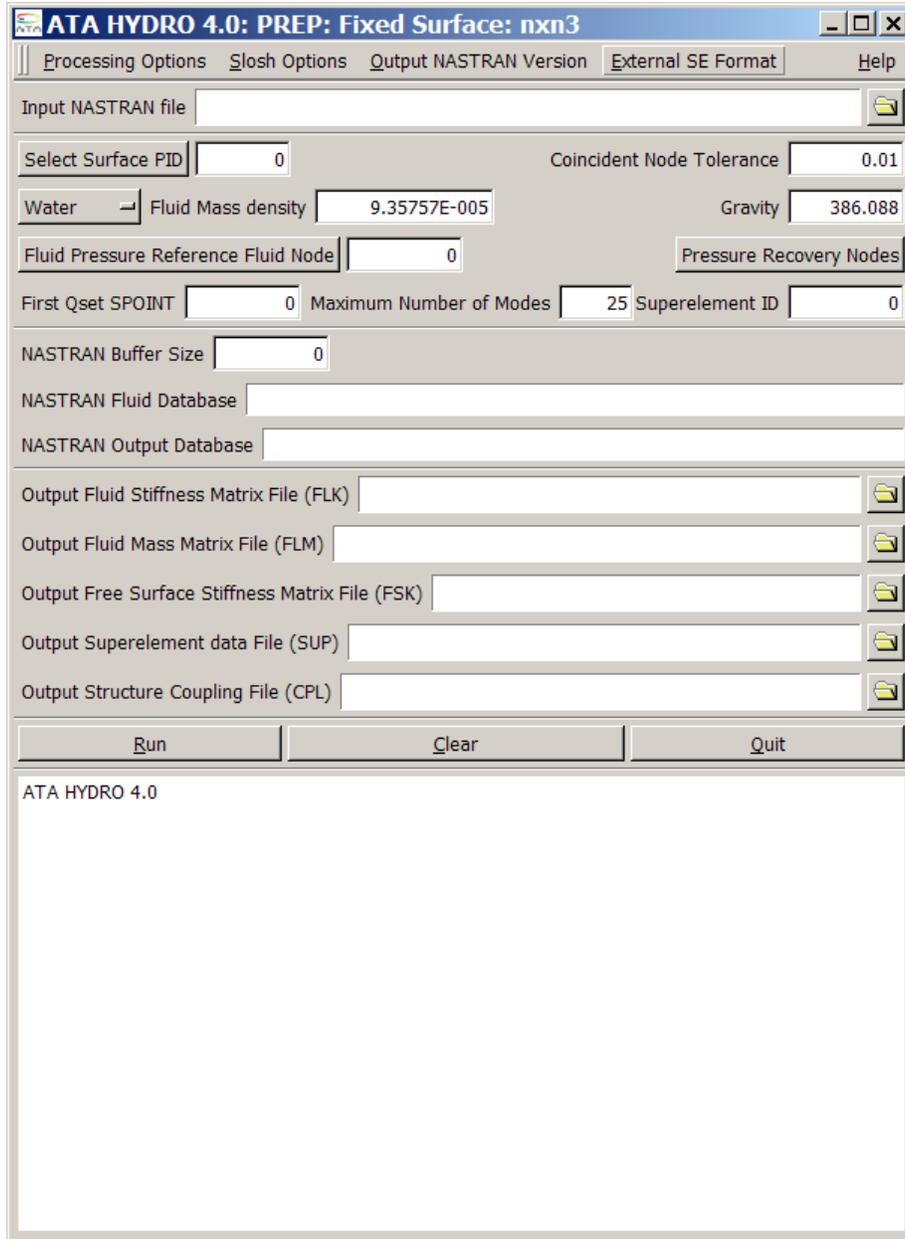
Figure 4-12. HYDRO GUI input for fluid hemisphere example with FIXED option.
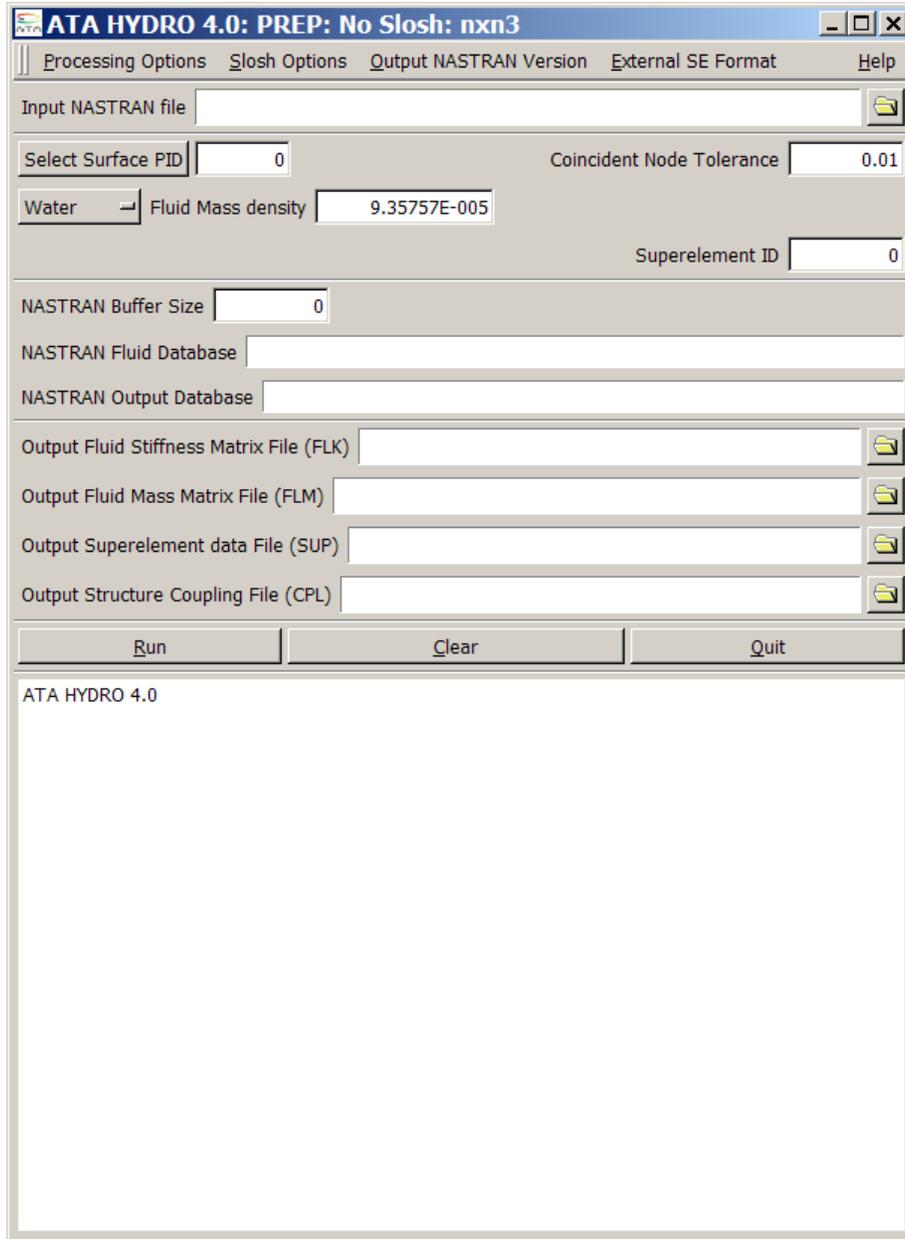
Figure 4-13. HYDRO GUI input for fluid hemisphere example with NO_SLOSH_STD option.
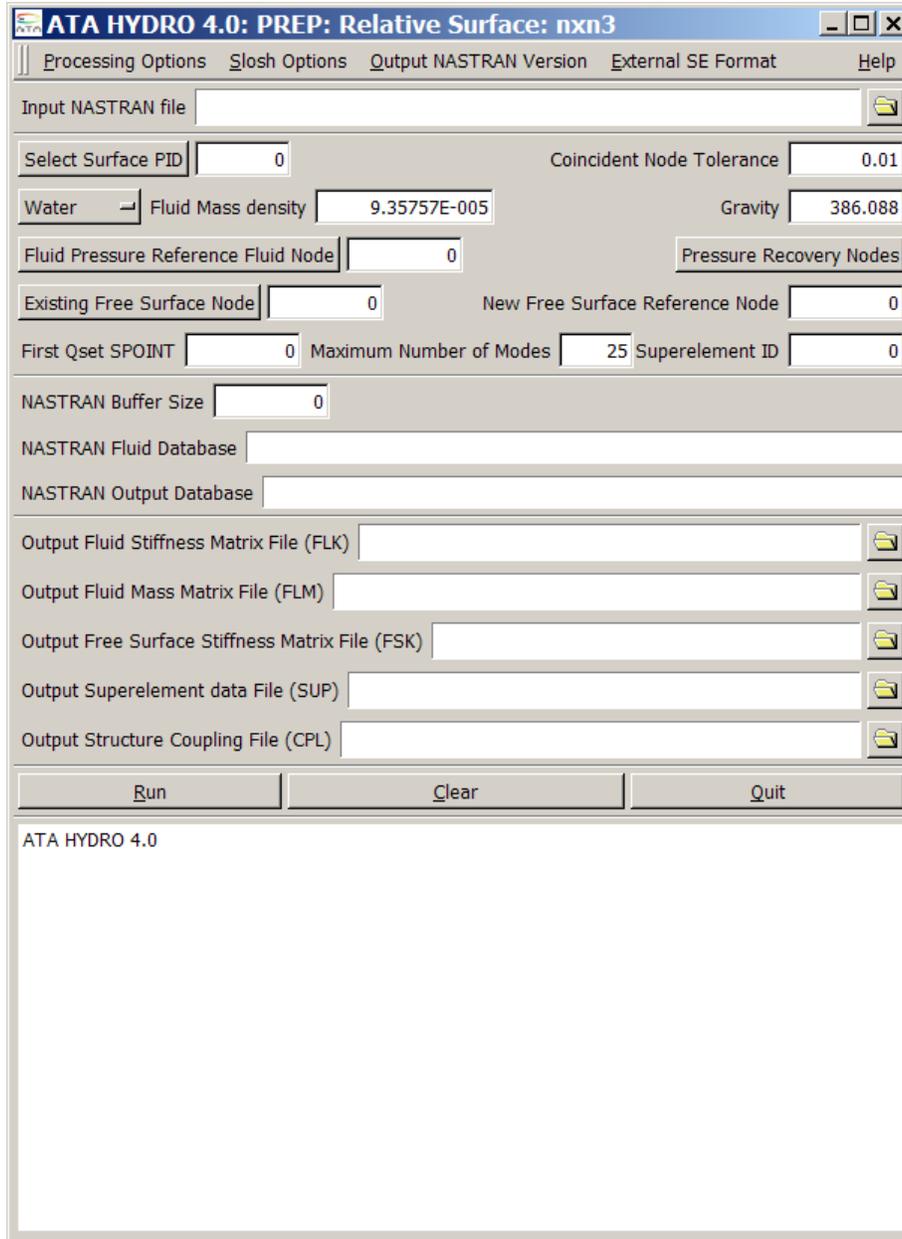
Figure 4-14. HYDRO GUI input for fluid hemisphere example with RELATIVE option.

The HYDRO run generates anywhere from three to five NASTRAN input files:

- *_FLK.DAT   - fluid stiffness matrix run (always generated)
- *_FLM.DAT   - fluid mass matrix run (always generated)
- *_FSK.DAT   - free surface stiffness matrix run (FIXED and RELATIVE options only)
- *_SUP.DAT   - fluid superelement run (all but NO_SLOSH_FAST option)
- *_CPL.DAT   - template to couple structure to fluid (always generated)

4.1.3. FLK - Fluid Stiffness (Inertance) Matrix

The FLK run generates the fluid inertance (stiffness) matrix associated with the fluid pressure model. This run does not require any editing before executing. The .f06 file should be checked for FATAL errors. For the ENCLOSED, FIXED, and RELATIVE options, the bottom part of the .f06 file will be similar to that illustrated in Figure 4-15. When using the NO_SLOSH_STD or NO_SLOSH_FAST options, the PKRL and PVALR datablocks are not created, and the output is illustrated in Figure 4-16.

```
  KEY NUMBER =    687        QUALIFIER NAME AND VALUE

                             ZNAME   =PKLL

                             ZUZR1   =              0

                             ZUZR2   =              0

                             ZUZR3   =              0


  KEY NUMBER =    688        QUALIFIER NAME AND VALUE

                             ZNAME   =PKRL

                             ZUZR1   =              0

                             ZUZR2   =              0

                             ZUZR3   =              0


  KEY NUMBER =    689        QUALIFIER NAME AND VALUE

                             ZNAME   =PVALR

                             ZUZR1   =              0

                             ZUZR2   =              0

                             ZUZR3   =              0


  KEY NUMBER =    690        QUALIFIER NAME AND VALUE

                             ZNAME   =PREC

                             ZUZR1   =              0

                             ZUZR2   =              0

                             ZUZR3   =              0



 END OF DIRECTORY PRINT
1                                        * * * END OF JOB * * *
```

Figure 4-15. NASTRAN .f06 file output for FLK run with ENCLOSED, FIXED, or RELATIVE options.

```
   KEY NUMBER =    687         QUALIFIER NAME AND VALUE
                               ZNAME   =PKLL
                               ZUZR1   =              0
                               ZUZR2   =              0
                               ZUZR3   =              0


   KEY NUMBER =    688         QUALIFIER NAME AND VALUE
                               ZNAME   =PREC
                               ZUZR1   =              0
                               ZUZR2   =              0
                               ZUZR3   =              0



 END OF DIRECTORY PRINT
1                                         * * * END OF JOB * * *
```

Figure 4-16. NASTRAN .f06 file output for FLK run with
NO_SLOSH_STD or NO_SLOSH_FAST options.

4.1.4. FLM - Fluid Mass Matrix Run

The FLM run generates the area matrix relating the boundary pressure grids to the wetted
structure and free surface grids. The area matrix is used to convert the fluid stiffness (inertance)
matrix of the pressure model to an equivalent mass matrix at the wetted structure and free surface
DOF. The FLM run also calculates the constraint equation coefficients to define a constant
volume (incompressible fluid)[11].

A critical item printed in the .f06 file of the FLM run is the Grid Point Weight Generator output
for the fluid mass matrix. The values printed for the fluid mass depend on the fluid surface
option chosen. For the ENCLOSED, FIXED, and RELATIVE options, the full fluid mass is
included[12] as illustrated in Figure 4-17. In this case the fluid mass is 41.4418 lbf-sec^2/in or
16,000 lbm, matching the value calculated based on the fluid volume multiplied by density. It
often appropriate to readjust the fluid density and rerun the FLK and FLM runs in order to
achieve the correct fluid mass.

---

[11] The MPC coefficients are not required for either the NO_SLOSH_STD or NO_SLOSH_FAST options.
[12] For these options, the mass should be the same in all three directions. However, for complex geometry a small
discrepancy in mass in the axial direction is often observed. This should be less that 1% of the total fluid mass.

```
         O U T P U T    F R O M    G R I D    P O I N T    W E I G H T    G E N E R A T O R
                              REFERENCE POINT =         0
                                           M O
 *  4.144180E+01   3.553293E-15  -3.552714E-15   1.072920E-12  -9.289819E+02   5.312211E-15 *
 *  3.553293E-15   4.144180E+01   1.551537E-14   9.289819E+02  -4.973799E-13   1.854528E-14 *
 * -3.552714E-15   1.551537E-14   4.144180E+01  -7.234720E-13  -9.031956E-12  -4.440683E-14 *
 *  1.072920E-12   9.289819E+02  -7.234720E-13   3.487495E+04  -2.671641E-12   2.585154E-13 *
 * -9.289819E+02  -4.973799E-13  -9.031956E-12  -2.671641E-12   3.487495E+04  -5.363349E-13 *
 *  5.312211E-15   1.854528E-14  -4.440683E-14   2.585154E-13  -5.363349E-13   4.370472E-15 *
                                            S
                   *  1.000000E+00   0.000000E+00   0.000000E+00 *
                   *  0.000000E+00   1.000000E+00   0.000000E+00 *
                   *  0.000000E+00   0.000000E+00   1.000000E+00 *
           DIRECTION
      MASS AXIS SYSTEM (S)      MASS              X-C.G.         Y-C.G.         Z-C.G.
              X             4.144180E+01      2.588979E-14  -1.281848E-16  -2.241654E+01
              Y             4.144180E+01      4.475017E-16  -1.200189E-14  -2.241654E+01
              Z             4.144180E+01      2.179431E-13  -1.745754E-14  -1.071547E-15
                                          I(S)
                   *  1.405039E+04   2.671641E-12   1.572056E-13 *
                   *  2.671641E-12   1.405039E+04   4.172535E-13 *
                   *  1.572056E-13   4.172535E-13   4.370472E-15 *
                                          I(Q)
                   *  1.405039E+04                               *
                   *                 1.405039E+04                *
                   *                                4.370472E-15 *
                                            Q
                   *  1.000000E+00   0.000000E+00   0.000000E+00 *
                   *  0.000000E+00   1.000000E+00   0.000000E+00 *
                   *  0.000000E+00   0.000000E+00   1.000000E+00 *
```

Figure 4-17. Grid Point Weight Generator Output for ENCLOSED, FIXED, and RELATIVE options.

The output when using the NO_SLOSH_STD format will have different mass in different directions. This is because the sloshing mass is removed from the model in the lateral directions. The mass in the direction perpendicular to the fluid surface, however, will be the full mass as illustrated in Figure 4-18. In this case the mass in the Z direction (perpendicular to the fluid surface) is 41.4418 lbf-sec^2/in as in the other cases, but the mass in the X and Y directions is 16.27371 lbf-sec^2/in. This is the total mass of the fluid minus the sloshing mass.

```
        O U T P U T    F R O M    G R I D    P O I N T    W E I G H T    G E N E R A T O R
                               REFERENCE POINT =        0
                                          M O
 *  1.627371E+01   2.460956E-15  -7.178286E-15   1.271205E-14  -4.555199E+00   3.826854E-15 *
 *  2.460956E-15   1.627371E+01   4.911870E-15   4.555199E+00   2.453593E-14   1.055308E-14 *
 * -7.178286E-15   4.911870E-15   4.144180E+01  -8.831824E-14  -8.992806E-14  -4.546347E-14 *
 *  1.271205E-14   4.555199E+00  -8.831824E-14   1.693736E+00  -4.848899E-14   3.838238E-15 *
 * -4.555199E+00   2.453593E-14  -8.992806E-14  -4.848899E-14   1.693736E+00  -4.015004E-15 *
 *  3.826854E-15   1.055308E-14  -4.546347E-14   3.838238E-15  -4.015004E-15   1.191357E-15 *
                                           S
                        *  1.000000E+00   0.000000E+00   0.000000E+00 *
                        *  0.000000E+00   1.000000E+00   0.000000E+00 *
                        *  0.000000E+00   0.000000E+00   1.000000E+00 *
              DIRECTION
        MASS AXIS SYSTEM (S)      MASS            X-C.G.         Y-C.G.          Z-C.G.
               X             1.627371E+01      7.811402E-16  -2.351555E-16  -2.799114E-01
               Y             1.627371E+01      6.484741E-16   1.507703E-15  -2.799114E-01
               Z             4.144180E+01      2.169984E-15  -2.131139E-15  -1.097044E-15
                                          I(S)
                        *  4.186840E-01   4.848899E-14  -8.843101E-16 *
                        *  4.848899E-14   4.186840E-01   2.943824E-15 *
                        * -8.843101E-16   2.943824E-15   1.191357E-15 *
                                          I(Q)
                        *  4.186840E-01                                *
                        *                 4.186840E-01                 *
                        *                                1.191357E-15 *
                                           Q
                        *  1.000000E+00   0.000000E+00   0.000000E+00 *
                        *  0.000000E+00   1.000000E+00   0.000000E+00 *
                        *  0.000000E+00   0.000000E+00   1.000000E+00 *
```

Figure 4-18. Grid Point Weight Generator output for NO_SLOSH_STD option.

When using the NO_SLOSH_FAST option, the mass properties are not output in Grid Point Weight Generator format. Instead the rigid body mass matrix and masses are printed to the .f06 file in the format illustrated in Figure 4-19. The mass in the Z direction is 41.44180 lbf-sec^2/in and the mass in the X and Y directions is 16.27371 lbf-sec^2/in as in the case of the NO_SLOSH_STD option.

```
0      MATRIX MRIG      (GINO NAME 101 ) IS A DB  PREC          6 COLUMN X           6 ROW SQUARE
MATRIX.
0COLUMN    1     ROWS      1 THRU     6     -------------------------------------------------
  ROW
     1)    1.6274D+01  1.9054D-15 -6.5954D-15  1.8350D-14 -4.5552D+00  3.2207D-15
0COLUMN    2     ROWS      1 THRU     6     -------------------------------------------------
  ROW
     1)    2.2452D-15  1.6274D+01 -1.3808D-15  4.5552D+00  1.5453D-14  7.6360D-15
0COLUMN    3     ROWS      1 THRU     6     -------------------------------------------------
  ROW
     1)   -7.4107D-15 -6.1045D-15  4.1442D+01 -3.6837D-14 -2.7311D-14 -4.5336D-14
0COLUMN    4     ROWS      1 THRU     6     -------------------------------------------------
  ROW
     1)    1.7978D-14  4.5552D+00 -3.9960D-14  1.6937D+00 -3.3057D-16  1.6208D-15
0COLUMN    5     ROWS      1 THRU     6     -------------------------------------------------
  ROW
     1)   -4.5552D+00  1.5465D-14 -2.7799D-14 -6.6277D-16  1.6937D+00 -3.8757D-16
0COLUMN    6     ROWS      1 THRU     6     -------------------------------------------------
  ROW
     1)    3.2207D-15  7.6360D-15 -4.5336D-14  1.6208D-15 -3.8757D-16  5.8951D-28
0THE NUMBER OF NON-ZERO TERMS IN THE DENSEST COLUMN =      6
0THE DENSITY OF THIS MATRIX IS 100.00 PERCENT.
 ^^^FLUID MASS IN THE BASIC X DIRECTION IS    1.627371E+01
 ^^^FLUID MASS IN THE BASIC Y DIRECTION IS    1.627371E+01
 ^^^FLUID MASS IN THE BASIC Z DIRECTION IS    4.144180E+01
```

Figure 4-19. Mass Property Output for NO_SLOSH_FAST Option.

The output of the _FLM run depends on the option chosen. For the NO_SLOSH_FAST option it is an OUTPUT2 file with the PKLL and AGL matrices for input into the coupled modes run. For the NO_SLOSH_STD and ENCLOSED options, it is a single mass matrix FMAA written to pressure database as illustrated in .

```
   KEY NUMBER =    689        QUALIFIER NAME AND VALUE
                              ZNAME    =FMAA1
                              ZUZR1    =              0
                              ZUZR2    =              0
                              ZUZR3    =              0
```

Figure 4-20. A single mass matrix is written to the database for the
NO_SLOSH_STD and ENCLOSED options.

For the FIXED and RELATIVE options, the mass matrix is written in three partitions as illustrated in Figure 4-21.

```
   KEY NUMBER =    691        QUALIFIER NAME AND VALUE
                              ZNAME    =FMOO
                              ZUZR1    =              0
                              ZUZR2    =              0
                              ZUZR3    =              0

   KEY NUMBER =    692        QUALIFIER NAME AND VALUE
                              ZNAME    =FMAO
                              ZUZR1    =              0
                              ZUZR2    =              0
                              ZUZR3    =              0

   KEY NUMBER =    693        QUALIFIER NAME AND VALUE
                              ZNAME    =FMAA1
                              ZUZR1    =              0
                              ZUZR2    =              0
                              ZUZR3    =              0

   KEY NUMBER =    694        QUALIFIER NAME AND VALUE
                              ZNAME    =UTOPG
                              ZUZR1    =              0
                              ZUZR2    =              0
                              ZUZR3    =              0
```

Figure 4-21. Three partitions of the mass matrix are written to the database
for the FIXED and RELATIVE options.

If any pressure recovery grids were requested in the FLK run, the UTOPG pressure recovery matrix is also written to the database as illustrated in Figure 4-22. The rows of this matrix are all the pressure DOF on the boundary of the fluid and the columns are the superelement DOF.

```
   KEY NUMBER =    694        QUALIFIER NAME AND VALUE
                              ZNAME    =UTOPG
                              ZUZR1    =              0
                              ZUZR2    =              0
                              ZUZR3    =              0
```

Figure 4-22. The UTOPG pressure recovery matrix is written to the database
if any pressure recovery grids were selected.

In addition the UTOP1 pressure recovery matrix is written in DMIG format to the .pch file. The columns of this matrix are the requested pressure recovery DOF and the rows are the superelement G-set DOF. The pressure is recovered as follows:

$$p = [UTOP1]^T \{\ddot{u}_G\}$$

Each column of the UTOP1 matrix is converted to an MPC equation by the õMPCö run. The dependent DOF of the MPC equation is DOF 1 on the pressure recovery grid. The pressures are recovered by requesting the acceleration of the corresponding DOF. The HYDRO MPC run converts the UTOP1 matrix to MPC equations and adds these back into the model so that the pressures can be recovered directly as grid point accelerations from any downstream simulation.

4.1.5. FSK - Free Surface Stiffness Matrix Run

For the FIXED and RELATIVE options, the FSK run is also prepared by HYDRO. The FSK run generates the area matrix relating the boundary pressure grids at the free surface to the free surface grids. The area matrix was used to generate the free surface stiffness matrix (õgravity stiffnessö) needed to calculate slosh modes.

No changes are needed to the FSK input deck written by the HYDRO program. The FSK run stores the free surface stiffness matrix (FKGG) in DMIG format into the database, as illustrated in Figure 4-23.

```
   KEY NUMBER =    696        QUALIFIER NAME AND VALUE
                              ZNAME   =FKGGDMIG
                              ZUZR1   =            0
                              ZUZR2   =            0
                              ZUZR3   =            0
```

Figure 4-23. The FSK run stores the FKGGDMIG matrix in the database.

4.1.6. HYDRO õMPCö Run

An additional run of the HYDRO program using the õMPCö option is required for the ENCLOSED, FIXED, and RELATIVE options. This takes the coefficients required to enforce incompressibility written to the .pch file from the FLM run and converts them to an MPC card.

The significant items entered into the HYDRO õMPCö run were as follows:

- õMPCö mode
- Name of the FLM .PCH file (e.g. fixed_flm.pch)
- Minimum MPC coefficient to write[13] (default is usually satisfactory)
- Dependent grid ID number = 30000 (the center grid of the free surface)

---

[13] Entering a minimum coefficient reduces the size of the MPC equation by eliminating near zero values. The default value is 1×10^{-5} times the maximum value. This is satisfactory for most problems.

- Dependent DOF = 3 (the normal displacement of free surface grid 30000)
- The name of the MPC bulk data file to be written (fixed_flm_mpc.blk)
- The superelement ID number = 10 (used for the MPC set ID number)

For the FIXED and RELATIVE options, the MPC cards for incompressibility must be included in the SUP run. For the ENCLOSED option, the MPC card is included in the structural coupling run[14].

If the user requested pressure output and the UTOP1 matrix exists in the .pch file, the õMPCö run also processes this into one MPC equation for each pressure output DOF. The pressure outputs are on DOF 1 of the pressure recovery grids.

4.1.7. SUP - Fluid Superelement Run

A SUP run is created for all options other than NO_SLOSH_FAST, though the format depends on the Superelement output option. This run takes the mass and stiffness matrices generated in the FLM and FSK runs and converts the to a NASTRAN superelement. The form of the superelement depends on the Superelement output option. If the fluid includes a sloshing free surface (FIXED or RELATIVE), the SUP run also calculates the slosh modes and associated modal effective mass. The following items are placed in the SUP input deck.

- For external superelements, an EXTSEOUT Case Control card and an associated ASSIGN card are written.
- For the FIXED and RELATIVE options, generalized coordinates are added for the slosh modes using SPOINT cards and either an SEQSET1 card, a bulk data superelement, or a QSET1 card for an external superelement.
- For a bulk data superelement, the free surface grids are identified on SESET cards and the wetted surface grids on CSUPEXT cards. For an external superelement, the wetted surface odes are identified on BSET1 cards.
- For the FIXED and RELATIVE options, an EIGR card using the Automated Householder method (AHOU) is added to calculate the first 25 slosh modes.
- The MPC equation defining the incompressibility constraint, and MPC equations defining the pressure outputs, are added using INCLUDE ─fixed_flm_mpc.blkø The user can edit this filename if necessary.

Two databases are used by the SUP run. The first database is a new database which is used to store the data blocks for the fluid superelement model. The second database is the fluid model one used by the FLK, FLM, and FSK runs. This split database technique minimizes the disk storage requirements for subsequent processing of the fluid superelement. The fluid model database used by the FLK, FLM, and FSK runs can be deleted following the SUP run.

---

[14] The incompressibility equation is not required for either of the NO_SLOSH options.

For the DMIGOP2 and MATOP4 external superelement options, the matrices are written to an external file, which is identified in an ASSIGN statement. In these cases, as well as the DMIGPCH formats, a .pch file is also written that contains the external superelement (BEGIN SUPER) definition.

The important activities performed by the SUP run for the example problem were as follows:

- The fluid mass matrix formed in the FLM run is arranged into a final form compatible with the grids in the SUP run.

- The fluid mass matrix properties are calculated and reported in the Grid Point Weight Generator output. The GPWG output from the SUP run should be **<u>identical</u>** to the output from the FLM run.

- The free surface stiffness matrix formed in the FSK run is arranged into final form compatible with the grids in the SUP run for the FIXED and RELATIVE options.

- The multipoint constraint (MPC) equation for incompressibility is imposed for the ENCLOSED, FIXED, and RELATIVE options.

- Slosh modes are calculated for the FIXED and RELATIVE options. By default, the first 25 slosh modes are calculated.

- The final stiffness and mass matrices are generated for the fluid superelement. A null KAA matrix is created to define zero static stiffness for the fluid model and to satisfy superelement requirements that a KAA matrix be present for the ENCLOSED and NO_SLOSH_STD options. The MAA matrix was created from the fluid mass matrix and static reduction. KLAA and MLAA were assembled using the slosh modes.

- If one of the external superelement options is chosen, the appropriate files are output.

- Data recovery is performed to recover the slosh mode shapes and modal effective mass is calculated. The modal effective mass results are output to the .f06 using the standard NASTRAN format.

The modal effective mass fractions for the first fifty slosh modes are illustrated in Figure 4-24. In each direction, NASTRAN lists the individual mass fraction and a cumulative sum. For this example, the first two slosh modes at 0.506 Hz have modal effective mass fractions of 57.0% in one direction and 1.3% in the other. The only other modes with greater than 1% modal effective mass are modes 10 and 11 at 0.964 Hz with modal effective mass fractions of 1.3%. The pair of modes with the third largest modal effective mass are modes 23 and 24 at 1.305 Hz, but these have less than a 1% fraction. The total modal effective mass for all of the slosh modes is 60.7%, meaning that 60.7% of the total fluid mass is involved with low frequency sloshing motion, and 39.3% is not. That implies that the lateral mass properties for the NO_SLOSH options should be

approximately 39.3% of the total fluid mass. This is $0.393*41.4418=16.2966$ lbf-sec^2/in, which is very close to the calculated value of 16.2737 lbf-sec^2/in.

For most applications, the first two pairs of slosh modes are sufficient to represent the fluid slosh (modes at 0.506 and 0.964 Hz for this example). In addition, studies have shown that the first axial mode should also be retained (0.797 Hz for this example). Slosh modes are only calculated for the FIXED and RELATIVE options.

MODAL EFFECTIVE MASS FRACTION

MODE	FREQUENCY	T1		T2		T3	
NO.		FRACTION	SUM	FRACTION	SUM	FRACTION	SUM
1	**5.062593E-01**	**1.297016E-02**	1.297016E-02	**5.704373E-01**	5.704373E-01	1.078537E-30	1.078537E-30
2	**5.062593E-01**	**5.704373E-01**	5.834074E-01	**1.297016E-02**	5.834074E-01	2.691052E-29	2.798906E-29
3	6.846851E-01	1.552514E-29	5.834074E-01	2.849645E-31	5.834074E-01	2.840684E-31	2.827313E-29
4	6.846851E-01	1.525872E-29	5.834074E-01	3.028808E-28	5.834074E-01	2.170009E-31	2.849013E-29
5	**7.974601E-01**	1.233062E-28	5.834074E-01	1.921427E-30	5.834074E-01	2.974047E-30	3.146417E-29
6	8.236362E-01	4.816121E-30	5.834074E-01	4.971105E-30	5.834074E-01	1.902101E-30	3.336628E-29
7	8.236362E-01	1.295596E-30	5.834074E-01	8.901722E-30	5.834074E-01	8.778304E-31	3.424411E-29
8	9.478566E-01	4.681830E-29	5.834074E-01	5.822181E-29	5.834074E-01	5.282532E-32	3.429693E-29
9	9.478566E-01	3.238991E-31	5.834074E-01	2.544682E-29	5.834074E-01	7.585110E-30	4.188204E-29
10	**9.636134E-01**	**1.285864E-02**	5.962660E-01	**2.656884E-03**	5.860643E-01	4.684576E-30	4.656662E-29
11	**9.636134E-01**	**2.656884E-03**	5.989230E-01	**1.285864E-02**	5.989230E-01	3.186409E-30	4.975302E-29
12	1.066545E+00	5.889817E-31	5.989230E-01	1.095011E-31	5.989230E-01	1.512929E-30	5.126596E-29
13	1.066545E+00	3.886856E-29	5.989230E-01	3.012442E-29	5.989230E-01	3.870963E-30	5.513692E-29
14	1.100664E+00	3.552001E-30	5.989230E-01	2.289398E-32	5.989230E-01	2.915512E-31	5.542847E-29
15	1.100664E+00	8.570406E-30	5.989230E-01	6.492871E-30	5.989230E-01	1.727864E-31	5.560125E-29
16	1.144128E+00	1.262682E-30	5.989230E-01	5.293579E-31	5.989230E-01	1.041758E-28	1.597771E-28
17	1.184522E+00	3.438267E-31	5.989230E-01	9.569861E-30	5.989230E-01	1.921438E-30	1.616985E-28
18	1.184522E+00	9.962396E-31	5.989230E-01	8.946802E-30	5.989230E-01	4.185433E-30	1.658840E-28
19	1.225332E+00	1.794432E-31	5.989230E-01	1.682098E-31	5.989230E-01	4.138501E-30	1.700225E-28
20	1.225332E+00	9.958014E-30	5.989230E-01	1.137127E-30	5.989230E-01	1.674197E-31	1.701899E-28
21	1.304134E+00	6.447743E-27	5.989230E-01	4.686552E-27	5.989230E-01	1.153669E-29	1.817266E-28
22	1.304134E+00	1.892847E-28	5.989230E-01	3.366656E-26	5.989230E-01	3.380244E-31	1.820646E-28
23	**1.304870E+00**	**8.825668E-04**	5.998055E-01	**3.784423E-03**	6.027074E-01	5.874356E-30	1.879389E-28
24	**1.304870E+00**	**3.784423E-03**	6.035900E-01	**8.825668E-04**	6.035900E-01	4.777724E-30	1.927167E-28
25	1.348212E+00	1.879819E-30	6.035900E-01	5.939555E-33	6.035900E-01	5.713594E-30	1.984303E-28
26	1.348212E+00	2.289398E-30	6.035900E-01	1.316847E-30	6.035900E-01	1.519128E-30	1.999494E-28
27	1.425056E+00	2.409167E-32	6.035900E-01	4.182581E-33	6.035900E-01	2.318786E-29	2.231373E-28
28	1.425056E+00	1.519143E-29	6.035900E-01	1.086413E-30	6.035900E-01	1.620910E-29	2.393464E-28
29	1.444922E+00	2.429285E-30	6.035900E-01	5.366804E-30	6.035900E-01	1.254960E-29	2.518960E-28
30	1.444922E+00	7.287729E-31	6.035900E-01	8.344713E-32	6.035900E-01	9.558692E-32	2.519915E-28
31	1.473208E+00	1.595868E-30	6.035900E-01	3.639891E-32	6.035900E-01	3.786601E-30	2.557782E-28
32	1.473208E+00	8.382120E-30	6.035900E-01	1.849642E-31	6.035900E-01	5.883709E-32	2.558370E-28
33	1.492184E+00	2.373661E-31	6.035900E-01	7.641587E-31	6.035900E-01	7.537135E-30	2.633741E-28
34	1.542882E+00	6.293576E-31	6.035900E-01	2.136295E-30	6.035900E-01	4.254760E-29	3.059217E-28
35	1.542882E+00	1.809552E-30	6.035900E-01	1.295596E-30	6.035900E-01	1.496033E-29	3.208821E-28
36	1.576986E+00	2.098652E-30	6.035900E-01	5.913165E-30	6.035900E-01	4.325261E-31	3.213146E-28
37	1.576986E+00	1.346387E-30	6.035900E-01	4.107540E-30	6.035900E-01	6.894373E-31	3.220040E-28
38	1.602213E+00	3.141583E-31	6.035900E-01	8.282556E-30	6.035900E-01	5.970304E-30	3.279743E-28
39	1.602213E+00	1.130970E-31	6.035900E-01	2.812367E-31	6.035900E-01	2.860560E-30	3.308349E-28
40	1.647240E+00	5.026533E-32	6.035900E-01	4.696237E-30	6.035900E-01	3.189457E-29	3.627295E-28
41	1.647240E+00	2.506497E-28	6.035900E-01	8.729305E-29	6.035900E-01	1.788563E-29	3.806151E-28
42	1.665575E+00	3.804302E-04	6.039703E-01	2.026315E-03	6.056163E-01	3.547705E-29	4.160921E-28
43	1.665575E+00	2.026315E-03	6.059967E-01	3.804302E-04	6.059967E-01	1.469920E-29	4.307913E-28
44	1.703785E+00	2.315209E-29	6.059967E-01	6.817096E-29	6.059967E-01	2.101764E-29	4.518090E-28
45	1.703785E+00	8.214450E-28	6.059967E-01	9.756904E-29	6.059967E-01	6.242723E-31	4.524333E-28
46	1.721696E+00	4.602516E-29	6.059967E-01	1.200892E-29	6.059967E-01	1.069064E-28	5.593396E-28
47	1.721696E+00	3.260432E-28	6.059967E-01	1.505676E-28	6.059967E-01	4.320519E-30	5.636601E-28
48	1.735862E+00	2.432842E-29	6.059967E-01	3.540136E-31	6.059967E-01	1.006866E-28	6.643467E-28
49	1.735862E+00	1.085065E-28	6.059967E-01	2.879066E-29	6.059967E-01	1.126683E-29	6.756136E-28
50	1.749068E+00	8.276119E-29	6.059967E-01	2.198469E-29	6.059967E-01	7.154508E-30	6.827681E-28

Figure 4-24. Modal Effective Mass Fractions for First 50 Modes of Hemisphere Example

To check the accuracy of the slosh modes, exact solutions [8,9] were calculated for the fundamental lateral and axial slosh modes. The results are summarized in Table 4-2.

Table 4-2. Comparison of slosh mode frequencies.

MODE DESCRIPTION	THEORY	HYDRO	ERROR
1st Lateral Slosh Mode	0.504	0.506	0.40%
1st Axial Slosh Mode	0.782	0.797	1.92%
2nd Lateral Slosh Mode	0.928	0.964	3.88%
2nd Axial Slosh Mode	1.067	1.144	7.22%
3rd Lateral Slosh Mode	1.178	1.305	10.78%

This shows excellent accuracy for the fundamental lateral slosh mode. The accuracy of the first axial and second lateral slosh modes is reasonable (less than 5% error). The accuracy of the higher modes is fair to poor. If better accuracy for the higher modes is required, a finer fluid mesh would be needed. The effect of the fluid mesh on the accuracy of the slosh modes is discussed in more detail in Section 5.1.

4.1.8.   Coupled Hydroelastic Model

HYDRO also creates a template for the structural coupling (CPL) run. The template requires some editing to add the structural model and optionally to change the parameters for the run. The data written to this deck depends on the fluid and SE options chosen and is summarized in Table 4-3 for bulk data superelements and the NO_SLOSH_FAST option and Table 4-4 for external superelement options.

Table 4-3. Data written to CPL runs for different options with standard superelements.

Data	ENCLOSED	FIXED	NO_SLOSH_STD	NO_SLOSH_FAST	RELATIVE
CSUPEXT Cards	Yes	Yes	Yes	No	Yes
hydro_cpl Alter	No	No	No	Yes	No
Free Surface GRIDs	No	Yes	No	No	Yes
Dummy interior GRID	Yes	No	Yes	No	No
SESET Cards	Yes	Yes	Yes	No	Yes
QSET Cards	No	No	No	Yes	No
SEQSET Cards	No	Yes	No	No	Yes
Pressure recovery nodes	Yes	Yes	No	No	Yes
Dummy interior PLOTEL	Yes	Yes	Yes	No	Yes
Surface Reference GRID	No	No	No	No	Yes

Table 4-4. Data written to CPL runs for different options with external superelements.

Data	DMIGPCH	DMIGOP2	DMIGDB	MATDB	MATOP4	DMIG Only
DBLOCATE	No	No	Yes	Yes	No	No
INPUTT2	No	Yes	No	No	No	No
INPUTT4	No	No	No	No	Yes	Yes
hydro_scale Alter	Yes	Yes	Yes	Yes	Yes	No
K2GG and M2GG	Yes	No	No	No	No	Yes
.asm file	Yes	Yes	Yes	Yes	Yes	No
.pch file	Yes	Yes	Yes	Yes	Yes	Yes
Pressure recovery grids	No	No	No	No	No	No
FMASS parameter	Yes	Yes	Yes	Yes	Yes	No
GRAV parameter	Yes	Yes	Yes	Yes	Yes	No

The CPL input deck template for the FIXED option with the bulk data superelement format is illustrated in Figure 4-25. The only modification required for this deck is to include the structural model of the tank. Decks for the other options with a bulk data superelement are similar.

```
ASSIGN MASTER='system.master',DELETE
ASSIGN DBALL ='system.dball',DELETE
$
ASSIGN FLUID='S:\hydroex.master'
DBLOCATE LOGI=FLUID WHERE(SEID=100 or PEID=100)
DBDIR
$
ID      HYDRO,COUPLED
SOL     103
DIAG     8 $    Print matrix trailers
$
$
CEND
TITLE    = HYDRO COUPLED SOLUTION
SUBTITLE = RELATIVE OPTION
$
ECHO = NONE $ Do not echo the bulk data deck
$
SET 1000 = 0
SEALL = 1000
DISP(PLOT) = ALL    $ Recover mode shapes
$
WEIGHTCHECK(SET=ALL) = YES
$
SUBCASE    100
 SUPER     100
 LABEL = FLUID SUPERELEMENT
 MPC       =    100 $ Incompressibility
 METHOD    =    100 $ Calculate slosh modes
 MEFFMASS(FRACSUM) = YES $ Recover effective mass
$
SUBCASE 9999
 LABEL = RESIDUAL STRUCTURE
 METHOD     = 100
 SPC        = 1
$
BEGIN BULK
$
PARAM     WTMASS 0.00259
PARAM       POST     -1
PARAM     GRDPNT      0
$
$ method for system modes
EIGRL          100          100.
$
$ placeholder for structural model bulk data
INCLUDE 'cylinder_structure.blk'
$
$ fix top of cylinder
SPC1      1         123456    241
$
$  Interior (fluid free surface) grids
$
GRID     30000       1 0.00000 0.00000 0.00000      0   12456

...
GRID     32306       1 48.0000 345.000 0.00000      1   12456
$
SESET     100   30000   30001   30003   30004   30005   30006   30101

...
SESET     100   32305   32306
$
CSUPEXT   100   20001   20002   20007   20008   20009   20010   20011
CSUPEXT   100   22310   22311   22312   22313
$ free surface reference grid
$
GRID     32307       1 0.00000 0.00000 0.00000      0
CSUPEXT   100   32307
SEUSET    100     U4   32307  123456
$
INCLUDE 'temp_flm_mpc.blk'
$
$ put pressure recovery nodes dof#1 into U1 (dependent dof on MPCs)
GRID     10002       1 0.00000 0.00000-60.0000      0
SESET     100   10002
GRID     12313       1 10.9178 345.000-58.9983      1
SESET     100   12313
$
$  Superelement QSET dof for component (slosh) modes
$
SPOINT  100001   THRU  100025
SEQSET1    100      0 100001   THRU  100025
$
$ placeholder for SPCs to remove all but first 2 slosh modes (for example)
SPC1       1      0 100003   THRU  100025
$
$
ENDDATA
```

Figure 4-25. Coupled fluid-structure template for the hemisphere example.

The hemisphere model was coupled to the tank illustrated in Figure 4-1, and modes were calculated using the different options. The structural frequencies for the various options with the tank fixed at the top are summarized Table 4-5. The frequencies with an enclosed fluid are quite different because the fluid surface is covered with a thin plate. The fixed and relative results are identical because the structure is fixed to ground along with the relative reference grid. The NO_SLOSH_STD and NO_SLOSH_FAST options do not include the slosh modes but do a good job of approximating the effect of the fluid on the structural modes. The first few lateral frequencies are within ~2%. There is an 8% frequency error in the first axial mode using the "fast" option, presumably due to the fact that there are very few axial modes of the õdryö tank used to reduce the fluid mass matrix.

Table 4-5. Comparison of structural frequencies for different fluid options.

Description	ENCLOSED	FIXED	RELATIVE	NOSLOSH_STD	Error	NOSLOSH_FAST	Error
1st Lateral	21.970	23.380	23.380	23.524	1%	23.680	1%
2nd Lateral	21.970	23.380	23.380	23.524	1%	23.680	1%
3rd Lateral	22.289	33.826	33.826	34.286	1%	34.287	1%
4th Lateral	22.289	33.826	33.826	34.286	1%	34.287	1%
5th Lateral	26.504	35.019	35.019	35.323	1%	35.323	1%
6th Lateral	26.504	35.019	35.019	35.323	1%	35.323	1%
1st Axial	33.140	35.161	35.161	35.196	0%	37.964	8%
7th Lateral	27.561	35.659	35.659	36.490	2%	36.491	2%
8th Lateral	27.561	35.659	35.659	36.490	2%	36.491	2%
9th Lateral	28.829	38.204	38.204	38.440	1%	38.440	1%
10th Lateral	28.829	38.204	38.204	38.440	1%	38.440	1%
11th Lateral	30.401	40.721	40.721	41.892	3%	41.893	3%
12th Lateral	30.401	40.721	40.721	41.892	3%	41.893	3%
13th Lateral	37.010	41.682	41.682	42.492	2%	42.496	2%
14th Lateral	37.010	41.682	41.682	42.492	2%	42.496	2%
2nd Axial	35.383	43.294	43.294	43.499	0%	43.499	0%
15th Lateral	39.585	44.179	44.179	52.257	18%	52.258	18%
16th Lateral	39.585	44.179	44.179	52.257	18%	52.280	18%

The input deck template for the DMIGOP2 external superelement output option is listed in Figure 4-26. Templates for other external superelement options are similar. To include multiple fluid superelements, multiple INPUTT2 files will need to be assigned and the UNIT numbers on the SEBULK card in the *.asm files will need to be updated to correspond to the correct values.

```
ASSIGN MASTER='S:\system.master',DELETE
ASSIGN DBALL ='S:\system.dball',DELETE
$
ASSIGN INPUTT2='text.op2', UNIT=11
DBDIR
$
ID      HYDRO,COUPLED
SOL     103
DIAG     8 $    Print matrix trailers
$
$INCLUDE 'hydro_scale.nxn8'
…
ENDALTER $
$
$
CEND
TITLE = HYDRO COUPLED SOLUTION
SUBTITLE = RELATIVE OPTION
$
ECHO = NONE $ Do not echo the bulk data deck
$
DISP = ALL    $ Recover mode shapes
$
METHOD     = 100
SPC        = 1
$
BEGIN BULK
$
$  PARAMETERS
$
$PARAM     DBDICT       2
$PARAM     USETPRT       0
PARAM     WTMASS 0.00259
PARAM       POST     -1
PARAM     GRDPNT       0
$
$ method for system modes
EIGRL        100          100.
$
$ placeholder for structural model bulk data
INCLUDE 'cylinder_structure.blk'
$
$ ASM file written by HYDRO
INCLUDE 'hydroex.asm'
SPOINT   100001   THRU  100025
$
$ placeholder for SPCs to remove all but first 2 slosh modes (for example)
SPC1         1       0 100003    THRU  100025
$
$ Connect relative DOF into top of tank
$
RBE3   99999           32307  123456 1.0     123      20001   20101
       20201   20301   20401   20501   20601   20701   20801   20901
       21001   21101   21201   21301   21401   21501   21601   21701
       21801   21901   22001   22101   22201   22301
$
$ PCH file written by hydroex_sup run
INCLUDE 'text_sup.pch'
$
$ Fluid mass and steady state acceleration
PARAM   GRAV    1.0
PARAM   FMASS   0.0
$
ENDDATA
```

Figure 4-26. External DMIGOP2 SE coupled fluid-structure template.

The template for the DMIG Only output option is listed in Figure 4-27. In this case, the DMIG matrices representing the fluid are referenced directly on K2GG and M2GG cards in case control, and there are no superelement cards.

```
$
ASSIGN MASTER='system.master',DELETE
ASSIGN DBALL ='system.dball',DELETE
$
ID      HYDRO,COUPLED
SOL     103
DIAG     8 $    Print matrix trailers
$
$
CEND
TITLE = HYDRO COUPLED SOLUTION
SUBTITLE = FIXED OPTION
$
ECHO = NONE $ Do not echo the bulk data deck
$
DISP(PLOT) = ALL    $ Recover mode shapes
$
WEIGHTCHECK(SET=G) = YES
MEFFMASS(FRACSUM) = YES $ Recover effective mass
$
METHOD      = 100
SPC         = 1
$
K2GG = KAAX
M2GG = MAAX
$
BEGIN BULK
$
$  PARAMETERS
$
PARAM       POST      -1
PARAM    GRDPNT       0
$
$ method for system modes
EIGRL        100            100.
$
$ placeholder for structural model bulk data
INCLUDE 'structure.blk'
$
$ DMIG cards for fluid
%
SPOINT   100001   THRU  10002
INCLUDE 'hydroex_sup.pch'
$
ENDDATA
```

Figure 4-27. DMIG Only coupled fluid-structure template

The NO_SLOSH_FAST option does not use a superelement to represent the fluid. In this case, the deck is different, and this is covered in greater detail in Section 4.2.5.

4.1.9. Recovering Pressures

HYDRO recovers pressures by placing the pressure recovery grids inside the fluid superelement and writing MPC equations to return the pressures as DOF 1 accelerations on those grids. For Pogo analysis, the modal pressures can be recovered as the mode shape coefficients on those

DOF. The pressures can also be recovered directly from a dynamic analysis. An example of a frequency response calculation including pressure recovery is illustrated in Figure 4-28.

```
ASSIGN MASTER='S:\system.master',DELETE
ASSIGN DBALL ='S:\system.dball',DELETE
$
ASSIGN FLUID='S:\hydroex.master'
DBLOCATE LOGI=FLUID WHERE(SEID=100 or PEID=100)
DBDIR
$
ID      HYDRO,COUPLED
SOL     111
DIAG    8 $    Print matrix trailers
$
CEND
TITLE   = HYDRO COUPLED FRF SOLUTION
SUBTITLE = RELATIVE OPTION
$
ECHO = NONE $ Do not echo the bulk data deck
$
SET 1000 = 0
SEALL = 1000
$
SET 100     = 999999,10002,12313
ACCE(PUNCH,PHASE,SORT2) = 100    $ Recover mode shapes
$
SUBCASE    100
 SUPER     100
 LABEL = FLUID SUPERELEMENT
 MPC       =    100 $ Incompressibility
 METHOD    =    100 $ Calculate slosh modes
 MEFFMASS(FRACSUM) = YES $ Recover effective mass
$
SUBCASE 9999
 LABEL = RESIDUAL STRUCTURE
 METHOD    = 100
 SPC       = 1
 DLOAD     = 101
 FREQ      = 100
 SDAMP     = 1
$
BEGIN BULK
$
FREQ1  100    0.1     0.1     999
TABDMP1 1      CRIT
       0.0    0.01    100.0   0.01    ENDT
RLOAD1 101     1                      1
TABLED1 1
       0.0    1.0     100.0   1.0     ENDT
FORCE    1    999999 0       1.0     0.0     0.0     1.0
$
…
$
ENDDATA
```

Figure 4-28. Input file for frequency response solution

In this example a unit force is being applied to the node at the top at the top of the tank and both the acceleration of that node and corresponding pressures at two locations on the tank are being recovered. The total mass of structure and fluid is 42.1 lbf-sec^2/in, so the steady state acceleration for a 1 lb force is 0.024 in/sec^2. The frequency response function for the acceleration of GRID 999999 for an input force at the same location is illustrated in Figure 4-29.
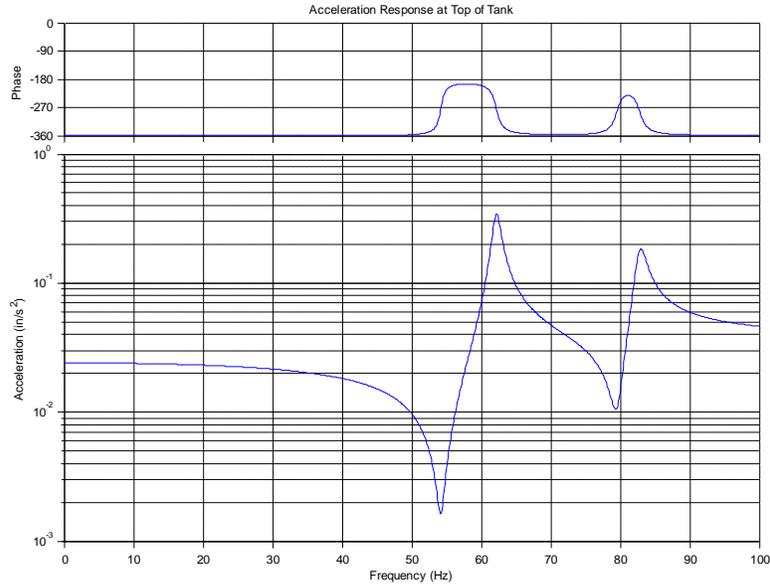
Figure 4-29. Acceleration frequency response at top of tank (0.024 in/sec^2 steady state)

The primary tank axial modes at 62.1 Hz and 82.8 Hz are clearly evident in the response.

The corresponding pressure frequency responses at the two pressure recovery GRIDS are illustrated in Figure 4-30. In this case the positive Z direction is up, so a positive Z force should result in positive pressures. The steady state pressure is ρah, where ρ=9.36E-5 lb-sec^2/in4, a=0.024 in/sec^2 and h=60 in for Grid 10002 and 59 in for Grid 12313. This should correspond to 1.355E-4 and 1.332E-4 PSI respectively, which matches the results very closely.
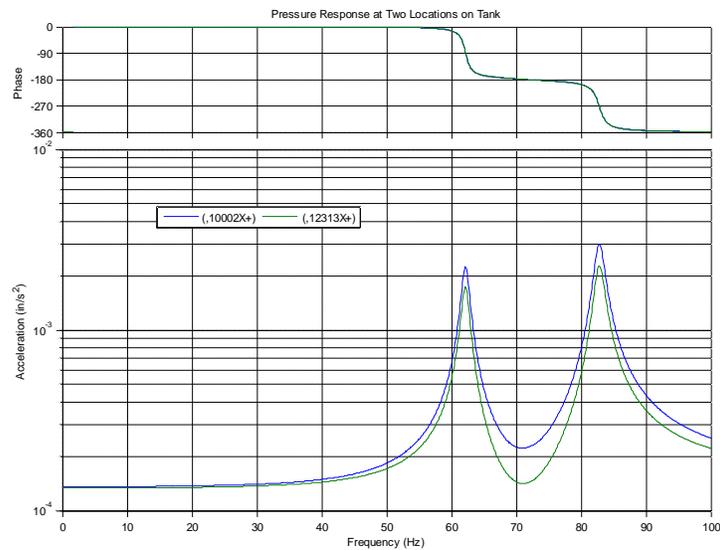
Figure 4-30. Pressure frequency response at tank recovery points (1.355E-4 and 1.332E-4 PSI steady state)

4.2.   **Motorcycle Tank Stress Model**

The second example problem is the motorcycle tank illustrated in Figure 4-31, used for dynamic stress and fatigue analysis. The mesh of the tank was partitioned at the fluid surface but otherwise was developed for the purpose of stress analysis, with very small elements in regions of high stress. The structural model had a total of 10,844 grids and 11,197 elements.
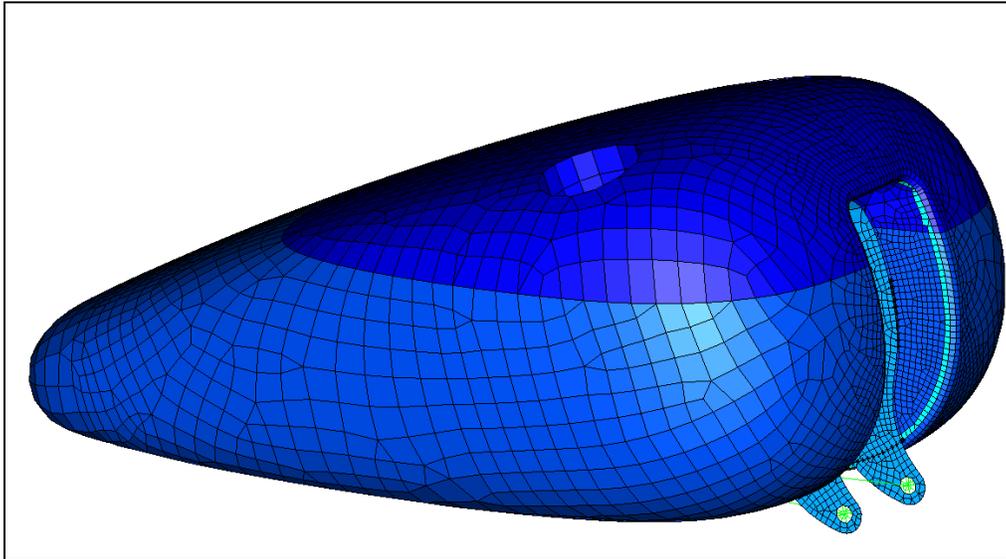
Figure 4-31. Outer shell of motorcycle tank example.

4.2.1.   I-deas Hydroelastic Finite Element Model

To develop the fluid model, the wetted surface of the tank was extracted along with the meshed free surface, as illustrated in Figure 4-32. This consists of 8,911 grids and 8,980 elements.
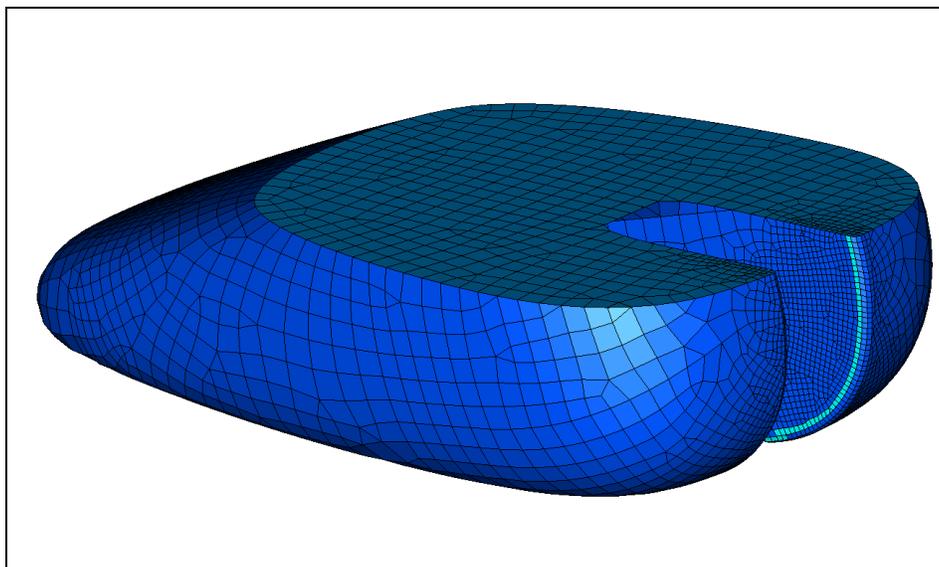
Figure 4-32. Fluid surface elements (wetted tank and free surface).

The fluid mesh was created using a free (tetrahedral) mesh on the wetted and free surface geometry. Since the surfaces were already meshed, the fluid mesh shared the same grid locations[15], as illustrated in Figure 4-33. Note that while the surface and fluid volume models must have compatible meshes in the sense that the grid locations on the surface are coincident, the elements need not be compatible. In this case, the surface is meshed largely with quadrilateral elements for accurate stress recovery, while the fluid volume is entirely meshed with tetrahedral elements. The total volume of the fluid solid elements is 1,032 in^3.
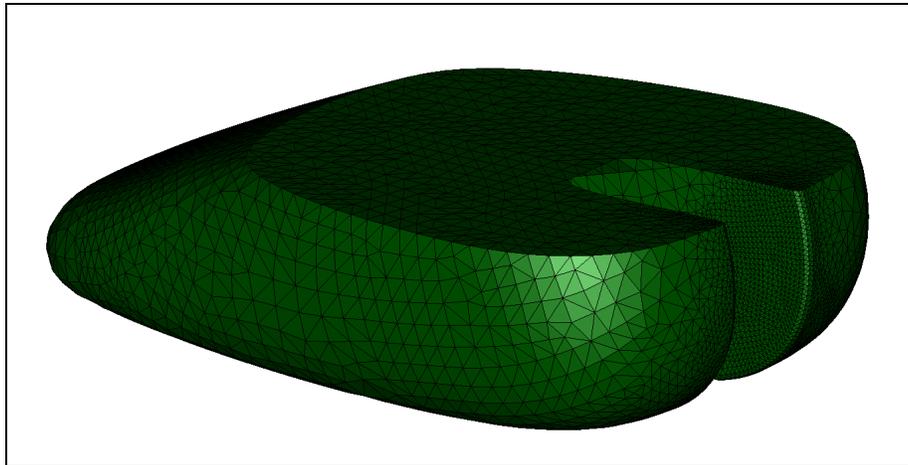
Figure 4-33. Fluid surface elements (wetted tank and free surface).

The hydroelastic model is exported in NASTRAN format for input into the HYDRO program. It consists of the wetted surface of the tank, the free surface of the fluid, and the volume elements representing the fluid. The model has the following characteristics:

1. The three parts of the model (wetted surface, free surface, and fluid) do not share any grids.
2. All the grids on the surface of the fluid are coincident with grids on either the wetted or free surface within a user-defined tolerance (0.01ö in this case). This tolerance must be smaller than the smallest element size in the model.
3. The wetted and free surface elements must have consistent element normals (pointing out in this case).
4. The free surface elements use a unique PID (three in this case).
5. The grids on the free surface have a displacement coordinate system with the Z axis oriented out of the free surface.

---

[15] While the fluid surface and fluid volume grids must be coincident on the surface, they are not the same grids. The fluid volume does not share any grids with the wetted structure or free surface. In this case, this required making a copy of the fluid and deleting the original version which did share grids on the surface.

4.2.2. HYDRO õPrepö Run

In this case, only the NO_SLOSH_FAST option is feasible, so only this option is presented. The inputs are summarized in Table 4-6.

Table 4-6. Inputs to HYDRO run for motorcycle tank example.

1	NASTRAN bulk file	hydroex.hfem
2	free surface?	Y
3	surface option	no_slosh_fast
6	free surface PID	5
7	coincident grid tolerance	.01
8	fluid type or density	water
13	NASTRAN version number	V2001
14	NASTRAN buffer size	default
15	pressure model database	fast_P
17	fluid stiffness input file (FLK)	fast_flk.dat
18	fluid mass input file (FLM)	fast_flm.dat
19	Output2 file written by FLM run	fast_flm.ou2
22	template for coupled system run (CPL)	fast_cpl.dat

The input decks for the command line version of HYDRO are presented in Figure 4-34, and the GUI inputs are illustrated in Figure 4-35.

```
PREP
tank.hfem
Y
NO_SLOSH_FAST
3
0.01
gasoline
v2001

S:\tank_P
S:\tank
fast_flk.dat
fast_flm.dat
fast_flm.ou2
fast_cplnew.dat
```

Figure 4-34. HYDRO input for motorcycle tank example.
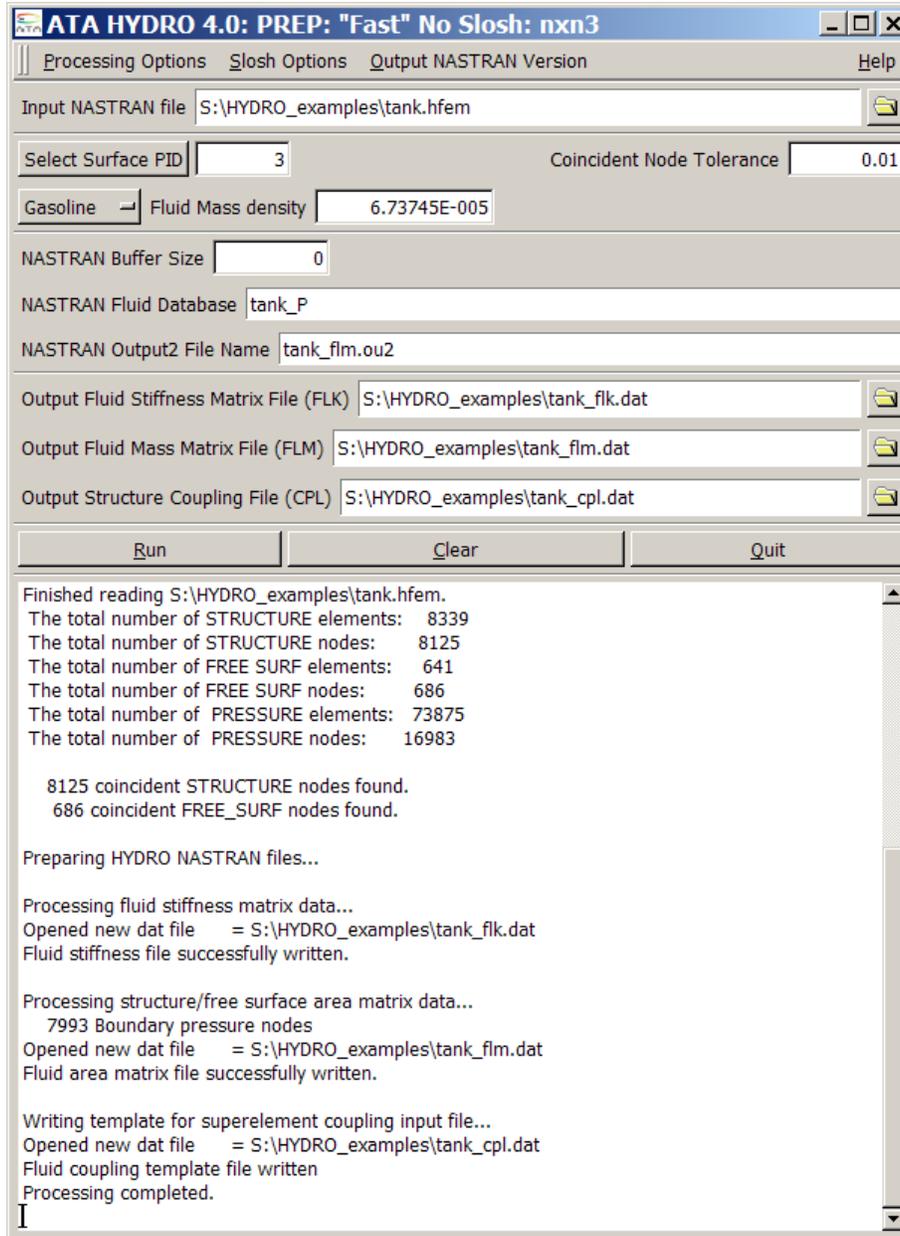
Figure 4-35. HYDRO GUI input for fluid hemisphere example with ENCLOSED option.

The HYDRO runs creates the tank_flk, tank_flm, and tank_cpl.dat NASTRAN input files.

4.2.3. FLK - Fluid Stiffness (Inertance) Matrix

The FLK run generates the fluid inertance (stiffness) matrix associated with the fluid pressure model. This run does not require any editing before executing. The .f06 file should be checked for FATAL errors. For the NO_SLOSH_FAST option, the only data stored in the database is the PKLL matrix as illustrated in Figure 4-36.

```
   KEY NUMBER =    687         QUALIFIER NAME AND VALUE
                               ZNAME   =PKLL
                               ZUZR1   =              0
                               ZUZR2   =              0
                               ZUZR3   =              0



 END OF DIRECTORY PRINT
1                                        * * * END OF JOB * * *
```

Figure 4-36. NASTRAN .f06 file output for motorcycle tank FLK run.

4.2.4. FLM - Fluid Mass Matrix Run

The rigid body mass matrix and masses for the motorcycle example are illustrated in Figure
4-37. In this case, the Y axis is perpendicular to the fluid free surface. The mass in the Y
direction is .06956879 lbf-sec^2/in. This is very close to the volume times the density
1032*6.73726E-5= 0.06953 lbf-sec^2/in. The masses in the X (.03342353 lbf-sec^2/in) and Z
directions (.04606164 lbf-sec^2/in) is somewhat less since this does not include the sloshing mass.

```
0      MATRIX MRIG     (GINO NAME 101 ) IS A DB  PREC         6 COLUMN X            6 ROW SQUARE
MATRIX.
0COLUMN     1     ROWS     1 THRU     6    ------------------------------------------------
  ROW
    1)    3.3424D-02 -4.5074D-06  1.7114D-04  2.3157D-03 -7.1927D-03 -6.7209D-01
0COLUMN     2     ROWS     1 THRU     6    ------------------------------------------------
  ROW
    1)   -4.5074D-06  6.9569D-02  9.2443D-07  7.3474D-03 -3.3366D-05  1.4620D+00
0COLUMN     3     ROWS     1 THRU     6    ------------------------------------------------
  ROW
    1)    1.7114D-04  9.2443D-07  4.6062D-02  8.4210D-01 -1.0003D+00 -8.1262D-04
0COLUMN     4     ROWS     1 THRU     6    ------------------------------------------------
  ROW
    1)    2.3157D-03  7.3474D-03  8.4210D-01  1.6472D+01 -1.8166D+01  1.3261D-01
0COLUMN     5     ROWS     1 THRU     6    ------------------------------------------------
  ROW
    1)   -7.1927D-03 -3.3366D-05 -1.0003D+00 -1.8166D+01  2.2804D+01  1.1003D-01
0COLUMN     6     ROWS     1 THRU     6    ------------------------------------------------
  ROW
    1)   -6.7209D-01  1.4620D+00 -8.1262D-04  1.3261D-01  1.1003D-01  4.5759D+01
0THE NUMBER OF NON-ZERO TERMS IN THE DENSEST COLUMN =        6
0THE DENSITY OF THIS MATRIX IS 100.00 PERCENT.
 ^^^FLUID MASS IN THE BASIC X DIRECTION IS    3.342353E-02
 ^^^FLUID MASS IN THE BASIC Y DIRECTION IS    6.956879E-02
 ^^^FLUID MASS IN THE BASIC Z DIRECTION IS    4.606164E-02
 ^^^WRITING FLUID MASS COMPONENTS TO OP2 FILE   FOR FAST HYDRO METHOD
```

Figure 4-37. Mass property output for motorcycle tank example.

The output of the _FLM run is an OUTPUT2 file (fast_flm.ou2) with the PKLL and AGL
matrices for input into the coupled modes run.

4.2.5. Coupled Hydroelastic Model

HYDRO also creates a template for the structural coupling (CPL) run. The template as output by
HYDRO is illustrated in Figure 4-38.

```
$
ASSIGN MASTER='system.master',DELETE
ASSIGN DBALL ='system.dball',DELETE
$
$ output2 file from FLM job with method=no_slosh_fast
ASSIGN INPUTT2='fast_flm.ou2' UNIT=11
$
ID      HYDRO,COUPLED
SOL     103
DIAG     8 $    Print matrix trailers
$
```

HYDRO writes the hydro_cpl.v2001 DMAP alter here

```
$
CEND
TITLE = HYDRO COUPLED SOLUTION
SUBTITLE = NO_SLOSH_FAST OPTION
$
ECHO = NONE $ Do not echo the bulk data deck
$
DISP(PLOT)  = ALL    $ Recover mode shapes
$
SPC        = 1
METHOD     = 100
WEIGHTCHECK = YES
$
BEGIN BULK
$
$  PARAMETERS
$
PARAM      WTMASS 0.00259
PARAM       POST      -2
PARAM      GRDPNT      0
$
$ method for system modes
EIGRL       100            100.
$
$ placeholder for structural model bulk data
INCLUDE 'structure.blk'
$
$ Bulk data for CMS
$
PARAM   METHCMRS    250
$           sid      f1      f2      nd
EIGRL       250                     250
SPOINT   99001   THRU   99250
QSET1       0   99001    THRU   99250
$
ENDDATA
```

Figure 4-38. Structure coupling run written by HYDRO.

For this example, the structural model is saved in a NASTRAN bulk data file called
structure.blk, so there is no need to edit this field. The structural model includes all grids and
elements of the structure, of which a subset are the grids wetted by the fluid. In this case, the
structure model also included a õlarge mass,ö since this was used to excite the model with an
input acceleration. The fluid is connected to the correct DOF on the structure because the area
matrix (AGP) is stored in DMIG format. In this case, the following changes were made to the
deck:

1. The system mode database is placed on a local (S:) drive.
2. All six DOF on seismic mass grid (31501) are placed in the BSET.
3. The SPC=1 card is removed from Case Control because it isnøt used.

4. PARAM,WTMASS was removed because this model is in mass units.
5. The frequency range for the EIGRL,100 card is increased to 250 Hz.

The edited deck is illustrated in Figure 4-39.

```
$
ASSIGN MASTER='S:\system.master',DELETE
ASSIGN DBALL ='S:\system.dball',DELETE
$
$ output2 file from FLM job with method=no_slosh_fast
ASSIGN INPUTT2='fast_flm.ou2' UNIT=11
$
ID       HYDRO,COUPLED
SOL      103
DIAG     8 $    Print matrix trailers
$
```
HYDRO writes the hydro_cpl.v2001 DMAP alter here
```
$
CEND
TITLE = HYDRO COUPLED SOLUTION
SUBTITLE = NO_SLOSH_FAST OPTION
$
ECHO = NONE $ Do not echo the bulk data deck
$
DISP(PLOT)  = ALL    $ Recover mode shapes
$
METHOD      = 100
WEIGHTCHECK = YES
$
BEGIN BULK
$
$   PARAMETERS
$
PARAM     WTMASS 0.00259
PARAM        POST      -2
PARAM      GRDPNT       0
$
$ method for system modes
EIGRL        100            250.
$
$ placeholder for structural model bulk data
INCLUDE 'structure.blk'
$
$ Bulk data for CMS
$
PARAM   METHCMRS     250
$           sid      f1      f2      nd
EIGRL        250                    250
SPOINT   99001   THRU   99250
QSET1        0   99001   THRU   99250
BSET1   123456   31501
$
ENDDATA
```

Figure 4-39. Structure coupling run after editing.

NASTRAN calculates two sets of modes. The first set is the first 250 modes without fluid mass. These frequencies are presented in Table 4-7. The first mode is at 78 Hz, followed by one at 300 Hz. The 250th mode is over 3,000 Hz, well above the frequency range of interest. However, the calculation of 250 modes without fluid mass is very fast and increases the accuracy of the final solution.

Table 4-7. Frequencies of 250 tank modes without fluid.

# 1-25	# 26-50	# 51-75	# 76-100	# 101-125	# 126-150	# 151-175	# 176-200	# 201-225	# 226-250
78.04	833.50	1192.64	1470.57	1761.83	2028.70	2264.23	2478.25	2716.12	2935.84
299.64	844.58	1196.51	1482.01	1767.79	2038.64	2275.24	2491.20	2729.74	2941.11
332.00	861.42	1212.77	1496.44	1780.31	2050.78	2288.16	2509.72	2732.84	2951.03
387.08	889.05	1230.52	1513.32	1791.59	2055.03	2300.11	2527.33	2742.65	2961.24
391.06	906.38	1236.80	1522.75	1831.88	2079.45	2303.76	2531.38	2744.90	2974.07
405.26	917.53	1241.19	1540.32	1833.84	2084.60	2317.63	2540.45	2764.42	2976.75
414.75	923.46	1252.00	1546.09	1835.68	2097.58	2336.31	2543.70	2774.20	2981.21
440.95	929.61	1267.31	1560.38	1845.91	2099.47	2346.91	2558.18	2781.94	2988.35
490.74	941.85	1279.81	1576.97	1859.10	2107.34	2354.52	2572.56	2786.82	2993.12
523.43	979.29	1304.07	1605.10	1870.26	2118.37	2357.71	2579.88	2795.60	2994.23
567.59	984.33	1310.52	1613.42	1887.90	2129.44	2368.24	2594.74	2801.04	3005.59
584.42	993.56	1328.91	1623.30	1892.60	2136.03	2382.82	2606.50	2805.44	3009.49
618.39	1000.61	1337.87	1634.70	1899.02	2159.31	2388.09	2623.27	2820.79	3014.59
624.11	1016.73	1358.07	1640.14	1911.41	2170.01	2400.42	2628.44	2835.54	3017.11
629.83	1030.15	1362.52	1653.32	1917.54	2174.22	2405.23	2632.72	2844.00	3026.31
636.14	1043.07	1371.18	1660.65	1923.50	2182.45	2411.00	2652.50	2848.81	3032.18
649.81	1065.43	1382.70	1671.90	1933.95	2200.20	2416.12	2656.72	2856.90	3034.40
661.64	1081.68	1394.71	1685.44	1958.10	2205.40	2426.55	2664.97	2863.47	3045.30
670.82	1097.36	1398.73	1695.77	1962.53	2209.74	2434.96	2670.56	2868.10	3053.48
695.01	1116.22	1415.94	1708.73	1970.50	2225.11	2439.07	2676.52	2887.28	3055.69
751.96	1117.90	1422.64	1714.59	1977.23	2234.75	2441.66	2686.37	2897.82	3066.26
771.90	1133.46	1438.76	1722.61	1991.38	2236.14	2454.15	2694.95	2903.12	3071.72
787.16	1140.20	1446.18	1733.22	2002.32	2242.78	2461.61	2702.94	2915.65	3087.19
808.98	1155.85	1448.10	1745.12	2015.39	2249.33	2464.79	2710.45	2922.88	3094.26
823.44	1166.56	1464.44	1750.22	2024.16	2262.88	2470.82	2712.59	2925.72	3107.31

After calculating modes without the fluid, the code imports the fluid matrices from the previous HYDRO runs and calculates the fluid mass. The output is listed in Figure 4-40[16]. The mass matrix is identical to that listed in the FLM run, though NASTRAN reverses the X and Y masses when listing the mass. This is because it is transforming the system to õprincipal massö directions. The actual directions of the mass properties can be seen by examining the first three diagonal elements of the mass matrix.

---

[16] The fluid properties are only written in Grid Point Weight Generator format if a BSET is included in the run. If not, they are written in matrix format as in Figure 4-19.

```
      O U T P U T   F R O M   G R I D   P O I N T   W E I G H T   G E N E R A T O R
                              REFERENCE POINT =        0
                                          M O
*  3.342353E-02 -4.507408E-06  1.711373E-04  2.315744E-03 -7.192718E-03 -6.720948E-01 *
* -4.507408E-06  6.956879E-02  9.244342E-07  7.347360E-03 -3.339222E-05  1.462014E+00 *
*  1.711373E-04  9.244342E-07  4.606164E-02  8.420973E-01 -1.000327E+00 -8.126191E-04 *
*  2.315744E-03  7.347360E-03  8.420973E-01  1.647192E+01 -1.816632E+01  1.326114E-01 *
* -7.192718E-03 -3.339222E-05 -1.000327E+00 -1.816632E+01  2.280418E+01  1.100272E-01 *
* -6.720948E-01  1.462014E+00 -8.126191E-04  1.326114E-01  1.100272E-01  4.575937E+01 *
                                          S
                       *  1.250179E-04  9.999083E-01  1.353765E-02 *
                       * -1.000000E+00  1.250294E-04  0.000000E+00 *
                       * -1.692604E-06 -1.353764E-02  9.999084E-01 *
             DIRECTION
    MASS AXIS SYSTEM (S)      MASS            X-C.G.          Y-C.G.          Z-C.G.
           X             6.956879E-02     -4.690336E-04  2.101609E+01  1.788956E-01
           Y             3.342121E-02     -2.010402E+01  3.944988E-04  1.899992E-01
           Z             4.606396E-02     -1.827857E+01  2.171845E+01  3.232848E-02
                                         I(S)
                       *  1.079558E+00  1.212184E-01 -8.218560E-03 *
                       *  1.212184E-01  1.076675E+00  2.344169E-03 *
                       * -8.218560E-03  2.344169E-03  1.522825E+00 *
                                         I(Q)
                       *  1.199170E+00                           *
                       *                 9.568596E-01            *
                       *                                1.523028E+00 *
                                          Q
                       *  7.108311E-01  7.030321E-01  2.156421E-02 *
                       * -7.029818E-01  7.111211E-01 -1.110768E-02 *
                       * -2.314381E-02 -7.263563E-03  9.997057E-01 *
```

Figure 4-40. Fluid mass properties from structure coupling run.

The frequencies of the coupled modes of vibration below 250 Hz are listed in Table 4-8. The first six modes are rigid body modes because the tank is attached to a õlarge massö in order to enforce acceleration inputs. The first flexible mode, illustrated in Figure 4-41, is a lateral bending mode of the tank on its brackets. This mode has shifted from 78.0 Hz without fuel to 55.6 Hz with fuel. The second flexible mode, illustrated in Figure 4-42, is a local mode of the top rear surface of the tank. This has shifted from 299.6 Hz without fuel to 149.4 Hz with fuel.

Table 4-8. Frequencies of tank modes below 250 Hz with fluid mass.

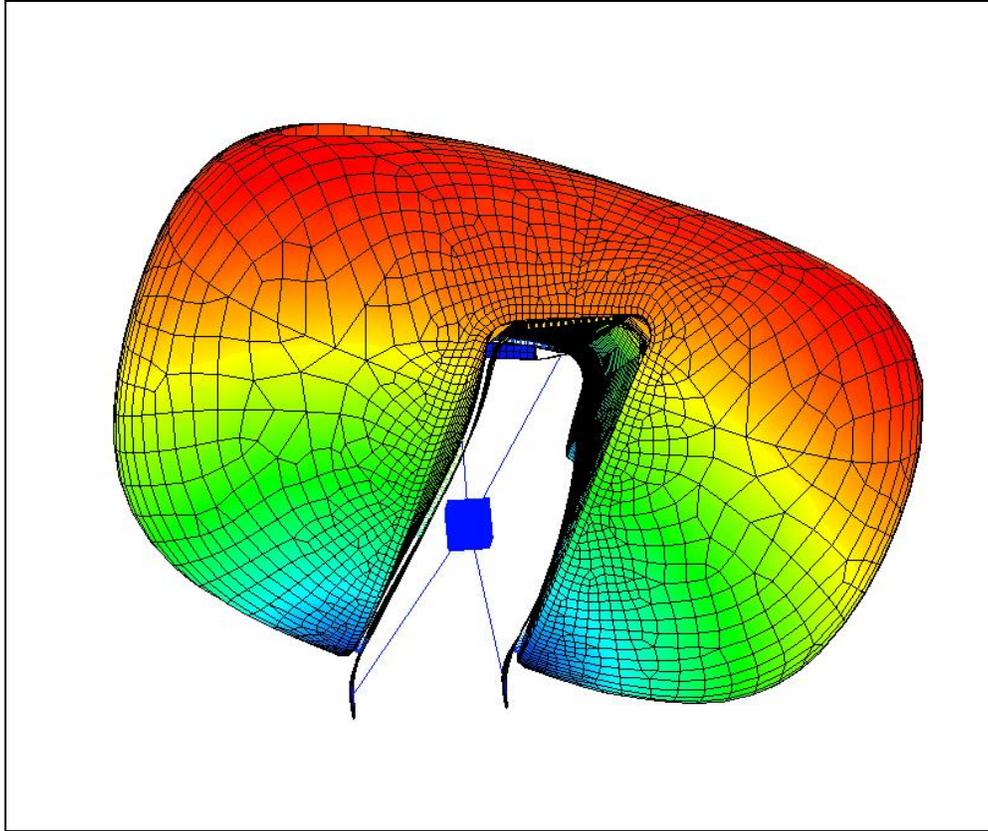| Mode	Freq (Hz)
1	0.000
2	0.000
3	0.000
4	0.000
5	0.000
6	0.000
7	55.625
8	149.388
9	190.082
10	207.222
11	218.837

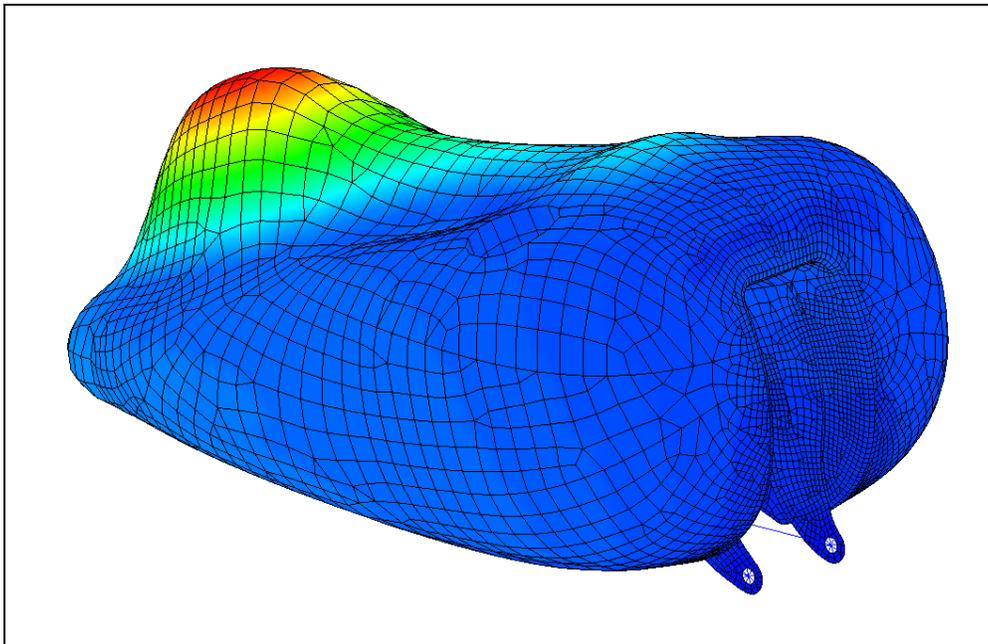Figure 4-41. First flexible coupled mode for motorcycle tank.

Figure 4-42. First flexible coupled mode for motorcycle tank.

5.   **ACCURACY CHECKS**

This chapter discusses several accuracy checks which should be performed to verify that the fluid model has been accurately defined. Accuracy checks include the following important areas:

- Fluid mesh considerations for accurate fluid properties
- Coordinate systems
- Coincident grid check
- Element quality check
- Mass property check
- Proper execution of the NASTRAN runs to create the fluid superelement
- Correct coupling of the fluid superelement and structural model
- Correct pressure recovery is requested

5.1. **Fluid Mesh Refinement**

The mesh refinement for the fluid model depends on the number of accurate slosh modes required. For many applications, most of the lateral effective mass is in the first lateral slosh mode pair. However, situations requiring high accuracy will probably require additional slosh modes.

A study was performed using the Titan IV/Centaur modal survey test configuration shown in Figure 5-1. For the modal survey test, the liquid oxygen tank was mostly filled with water. Analytic studies were performed to determine the mesh refinement needed to accurately obtain various lateral and axial slosh modes. Four meshes were analyzed in NASTRAN. The number of elements across the free surface was varied from a coarse value of eight elements to a fine value of twenty elements. The results are plotted in Figure 5-2 as frequency ratios relative to the results of the twenty-element mesh. The modal frequencies and errors relative to the solution with twenty-element mesh are listed in Table 5-1.
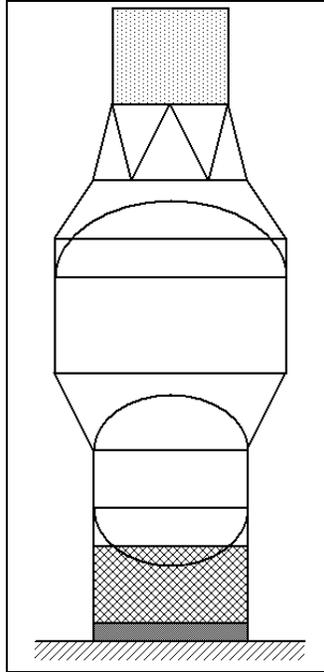
Figure 5-1. Titan/Centaur modal survey configuration.
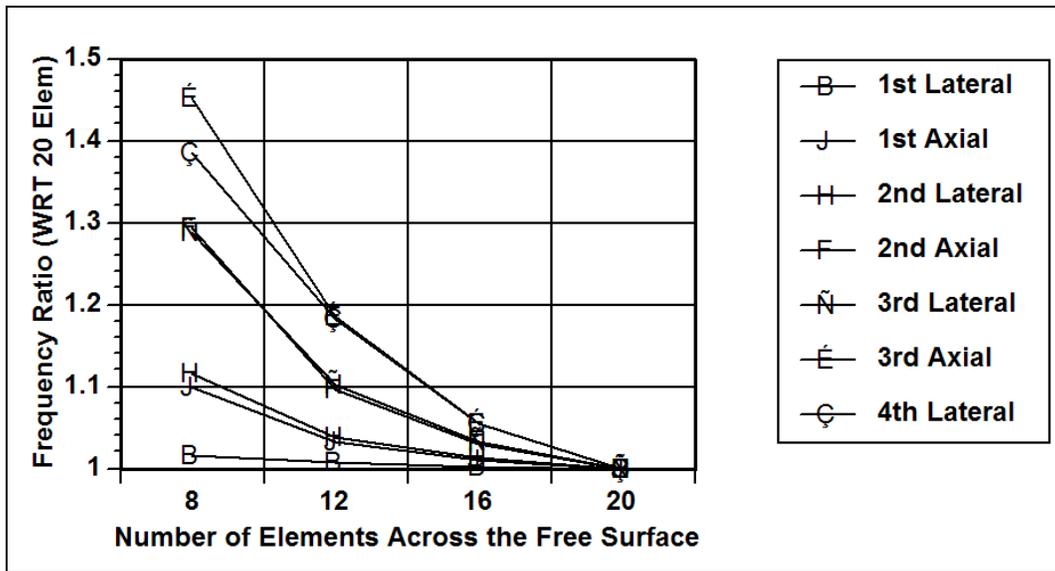

Figure 5-2. At least sixteen elements across the free surface were required to obtain 5% accuracy
on the third lateral slosh mode for the Titan IV Centaur modal survey test configuration.

Table 5-1. Slosh mode frequencies for the Titan IV Centaur modal
survey test configuration for several fluid mesh refinements.

	8		12		16		20
Mode	Freq (Hz)	Error	Freq (Hz)	Error	Freq (Hz)	Error	Freq (Hz)
1st Lateral	0.676	1.5%	0.670	0.6%	0.667	0.2%	0.666
1st Axial	1.011	9.9%	0.949	3.2%	0.928	0.9%	0.920
2nd Lateral	1.224	11.6%	1.139	3.8%	1.111	1.3%	1.097
2nd Axial	1.674	29.4%	1.420	9.7%	1.331	2.9%	1.294
3rd Lateral	1.864	28.9%	1.593	10.2%	1.491	3.1%	1.446
3rd Axial	2.411	45.2%	1.970	18.6%	1.752	5.5%	1.661
4th Lateral	2.497	38.4%	2.131	18.1%	1.901	5.4%	1.804
4th Axial			2.624	27.3%	2.231	8.2%	2.061
5th Lateral			2.747	24.9%	2.370	7.8%	2.199
5th Axial			3.128	24.6%	2.775	10.6%	2.510
6th Lateral			3.160	19.7%	2.894	9.6%	2.641

A second study was performed using the example problem described in Chapter 4. Using the
same geometry, a second hydroelastic finite element model was developed which had a finer
fluid mesh, as shown in Figure 5-3. The fine mesh model was analyzed using the HYDRO
procedures in NASTRAN. Results are compared with theoretical results obtained from [7] in
Table 5-2. As expected, the fine model had much better agreement with theory than did the
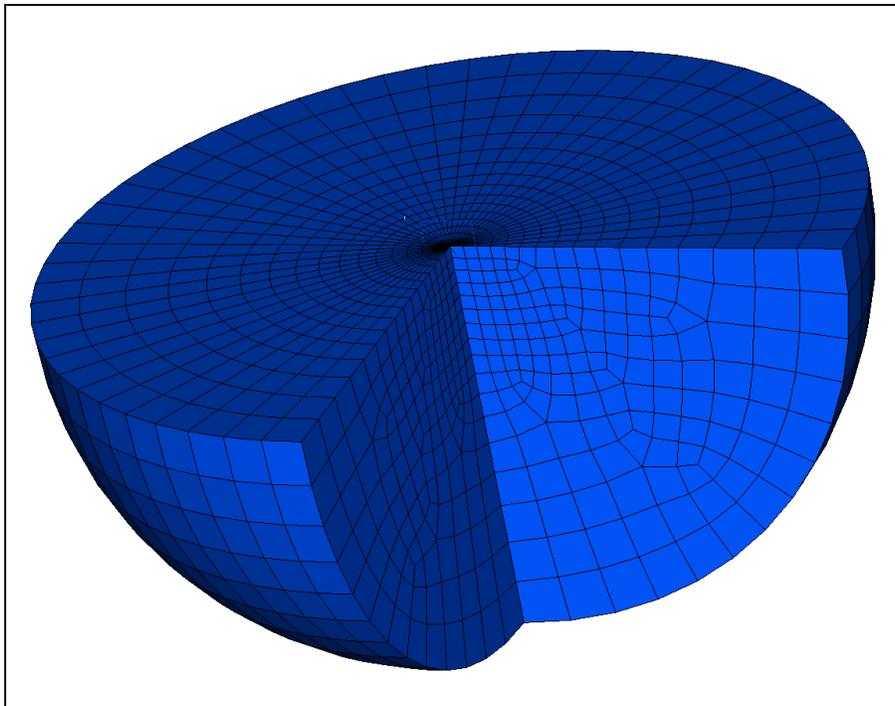coarse model.

Figure 5-3. Fine mesh representation of hemisphere example problem.

Table 5-2. Slosh mode frequencies for the hemisphere with coarse and fine meshes.

Description	Theory	Coarse		Fine	
		HYDRO	Error	HYDRO	Error
1st Lateral	0.504	0.506	0.4%	0.504	0.1%
1st Axial	0.782	0.797	2.0%	0.785	0.4%
2nd Lateral	0.928	0.964	3.8%	0.934	0.7%
2nd Axial	1.067	1.144	7.2%	1.079	1.2%
3rd Lateral	1.178	1.304	10.7%	1.199	1.8%
3rd Axial	1.287	1.492	15.9%	1.342	4.2%
4th Lateral	1.381	1.602	16.0%	1.428	3.4%

The results of the two studies show that the frequency of the first lateral slosh mode can be accurately obtained with a coarse mesh. However, if the higher slosh modes are important, additional elements are needed to obtain accurate results. For the Centaur example, sixteen elements across the free surface diameter were needed to calculate the frequency of the third slosh mode to 5% accuracy (relative to a twenty-element solution). For the hemisphere problem, 24 elements across the free surface provided accuracy within 8% for the third lateral slosh mode.

A general rule is to use eight elements across the free surface per slosh mode desired. This will provide good accuracy but may require a very fine mesh if higher slosh modes are necessary. Less refined models may provide acceptable results depending on the skill of the modeler and engineering judgment.

If possible, the fluid mesh should be more refined near the free surface and less refined at the bottom of the fluid (assuming that the fluid depth/width ratio is greater than one). For õdeepö tanks, most of the slosh behavior is near the surface, while the fluid at the bottom of the tank is nearly stationary. Appropriate gradients of the mesh refinement will result in accurate slosh modes without an excessively fine fluid model.

5.2.   **Coordinate Systems**

The special requirements for coordinate systems are reviewed below:

- The definition coordinate system for the fluid, wetted structure, and free surface grids must be the same.
- The displacement coordinate systems for the coincident fluid, wetted structure, and free surface grids must be the same at each location but may vary throughout the model. For example, the grids on the axis of a cylindrical system should use the basic displacement system, while other grids could use a cylindrical displacement coordinate system.

- The coincident fluid/structure and fluid/free surface grids must be exactly coincident as expressed in the definition coordinate system. The coincidence check performed by the HYDRO program uses the local coordinates as defined in Iódeas (no transformation performed to a global or basic system).

Grids which are on the centerline Z axis of a cylindrical coordinate system should **not** use that cylindrical coordinate system as the gridsødisplacement coordinate system. The radial and tangential directions are not defined for a grid located on the axis of a cylindrical coordinate system. Grids which are on the centerline Z axis of a cylindrical coordinate system should use a rectangular coordinate system as the gridsødisplacement coordinate system.

5.3. **Coincident Grid Check**

A coincident grid check can be performed in Iódeas, FEMAP or any other pre-processor for the HFEM. The check should properly list the coincident pressure/wetted structure and pressure/free surface grids. The coincident grids must **not** be merged.

5.4. **Element Quality Checks**

A variety of element quality checks can be performed, including:

É   Free edge
É   Coincident elements
É   Warping
É   Interior angle
É   Distortion

The free edge check is especially useful for checking the HFEM. This check should be performed on the fluid, wetted structure, and free surface elements as individual groups. The free edge check should present correct results, as shown in Figure 5-4. The free edge check in FEMAP is performed by choosing a "Free Edge" model style on the View Select form.
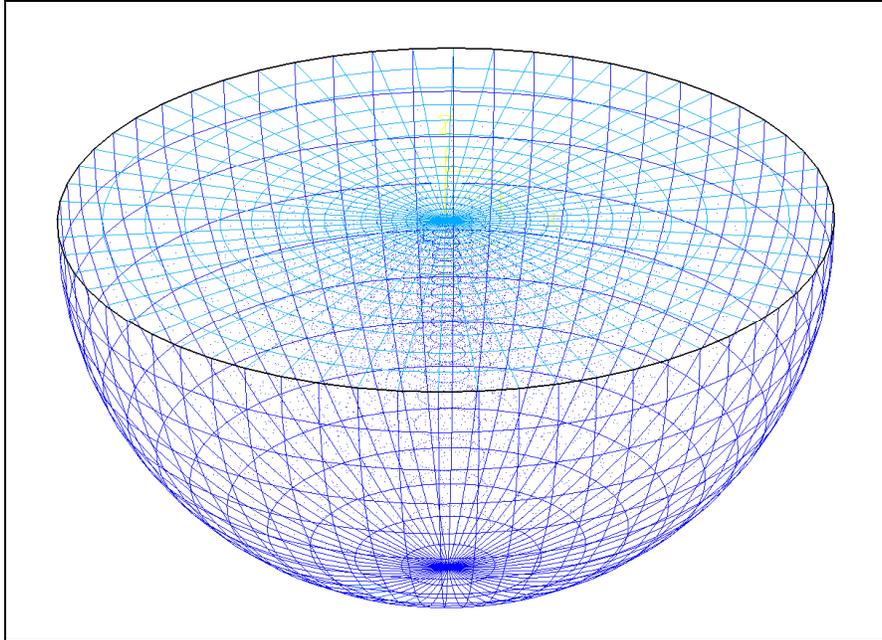
Figure 5-4. Free edge check can identify errors in the HYDRO FEM.

The element warping and distortion checks should indicate no improperly formed elements. A coincident element check should indicate no coincident elements.

5.5.   <u>**Shell Element Normals**</u>

The normal direction of the shell elements for the wetted structure and free surface must all point **<u>outward</u>**. If there is any inconsistency in the shell element orientation (some of the shells point inward while other point outward), the fluid mass matrix will be incorrect along one or more of the basic coordinate system axes as reported by the NASTRAN Grid Point Weight Generator. If the shell element normals point uniformly inward, the fluid mass properties will be correct, but the sign of the fluid stiffness matrix will be incorrect (negative terms on the diagonal of the gravity stiffness matrix).

The orientation of the shell element normals can be easily checked in Iódeas by defining a unit pressure load on the wetted structure and free surface shell elements. The model graphic display, such as that shown previously in Figure 4-4, should be checked carefully to verify that all pressure vectors point outward. In FEMAP, the shell element normal display is activated by turning on Normal Vectors for Element-Directions on the View Options form as illustrated in Figure 5-5.
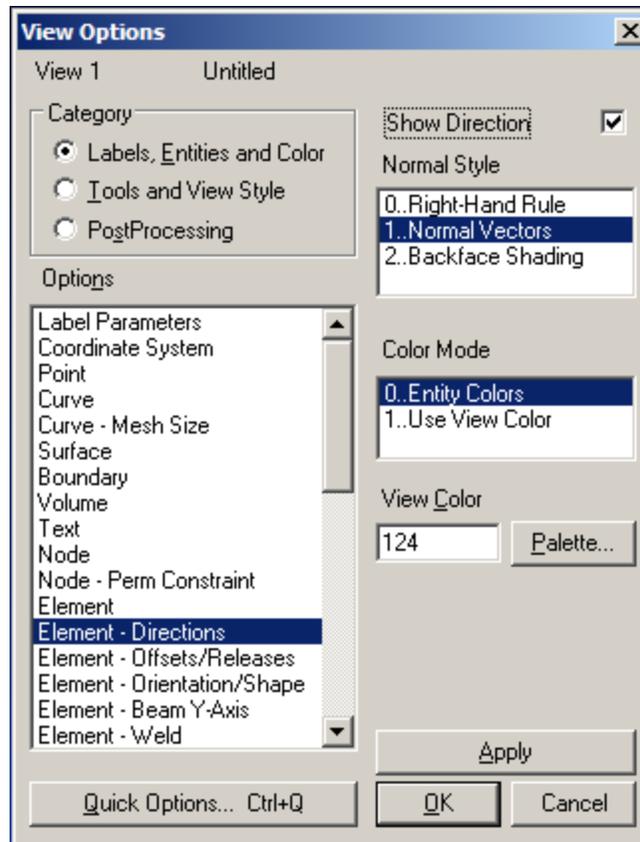
Figure 5-5. Element normal vector display is selected on the View Options form in FEMAP.

5.6. **Fluid Mass Check**

The mass of the fluid elements should be checked in the pre-processor. The material table must be modified to have the correct mass density.

The mass calculated by NASTRAN in the FLM and SUP runs should agree very closely with the pre-processor value (within 1%). In addition, the NASTRAN mass calculation should be checked to make sure that the mass values in the X, Y, and Z axes are essentially identical (within 1%)[17]. There may be a slight difference between the mass values along each axis because of the accuracy of the area matrices generated by quadrilateral and triangular shell elements. However, if there is significant variation in the mass values, this indicates errors in the wetted structure and/or free surface shell elements. The most likely error is inconsistent shell element normals (some pointed inward while others pointed outward). Another possibility is improper definition of the free surface (improper free edges or all free surface elements not using the same property ID).

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[17] For the NO_SLOSH options, only the mass properties normal to the free surface will be equal to the total fluid mass. The mass properties in the plane of the fluid surface will be less.

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Appendix A

New Features and Enhancements in HYDRO Version 2

ATA HYDRO Version 2 has the following new features and enhancements:

- Hydroelastic models can be processed using MSC.NASTRAN Versions 66A and 67 as well as Version 65.

- For MSC/NASTRAN Versions 66A and 67, the user enters the database names for the pressure model and the superelement model. The file management section (FMS) commands are written by HYDRO to the NASTRAN decks.

- Multiple finite element models may be in the SDRC I-deas universal file. The user is prompted to select the finite element model which is the hydroelastic finite element model (HFEM).

- SDRC I-deas default coordinate systems 1 (cylindrical) and 2 (spherical) are automatically written to the MSC/NASTRAN bulk data deck.

- In the HYDRO õMPCö run, the user specifies a minimum significant MPC coefficient. Degrees of freedom whose MPC coefficients are less than the user-specified value are assumed negligible and are eliminated from the MPC equation.

- In the HYDRO õMPCö run, default values are no longer available for the dependent grid and DOF. The previous default was simply the first grid and DOF printed by MSC/NASTRAN. This was not necessarily a good selection. Therefore, a default value is no longer provided by HYDRO, and the dependent grid and DOF must be entered by the user.

Appendix B

New Features and Enhancements in HYDRO Version 3

ATA HYDRO Version 3 is a complete rewrite of HYDRO. This version can be executed from the command line by typing õhydro ótö or through a GUI by typing õhydroö. In addition, the following changes have been made.

- The DMAP is no longer contained in the code but is stored in the HYDRO executable directory. This makes it much easier to generate versions of HYDRO for future versions of either MSC or NX Nastran. To add any new version of DMAP, the following five files should be added to the HYDRO executable directory:

  hydro_flk.xxx

  hydro_flm.xxx

  hydro_fsk.xxx

  hydro_sup.xxx

  hydro_cpl.xxx

  where .xxx refers to the NASTRAN version (v2006, nx5, etc.). The code will find all available versions, so no updates of the HYDRO code will be required to support future versions of NASTRAN. HYDRO version 3 is initially delivered with support for MSC Nastran V2004 and V2005 and NX Nastran NXN3 and NXN4. An "_" reflects a "." in the version, so to include NXN V6.1 the filetype for the alters should be .nxn6_1. To remove a version, remove the files from the executable directory with the extension for that version.

- All size limitations have now been removed from the code. The only limitation on the size model that can be handled is the amount of memory available.

- Any bulk format can be read (free field, narrow, wide, include files, replication cards)

- Grids no longer need to be defined in the same definition coordinate system since the code transforms these internally to the basic Cartesian system.

- Tolerance for coincident grid check can be set by user (previously 0.1) and is applied to the basic Cartesian coordinates. The default is now 0.01.

- The code is considerably faster for large models.

- GRID cards written to new input files with their original X ,Y, and Z definitions (not F8.3) to preserve all original significant digits, whether narrow field or wide field.

- MPC coefficients are read from the .pch file, rather than the .f06 file, in order to make the process more stable across multiple NASTRAN versions.

- Capability to read model data from Universal files has been eliminated. The only input format is NASTRAN.

- HYDRO now supports a "fast" option that doesnøt assemble the full fluid mass matrix. This option writes out components of the fluid mass matrix in OUTPUT2 format for

input into the structural modes run. This method allows õno-sloshö HYDRO fluid representations to be included in large stress models.

HYDRO now writes a template for the deck to couple the structural and fluid models.

Appendix C

New Features and Enhancements in HYDRO Version 4

ATA HYDRO Version 4 includes the options for external superelement processing that is available in NX NASTRAN version 6.0 and higher and MSC.NASTRAN version 2004 and higher. The external superelement option can be accessed by the GUI as shown in Figure 5-6.
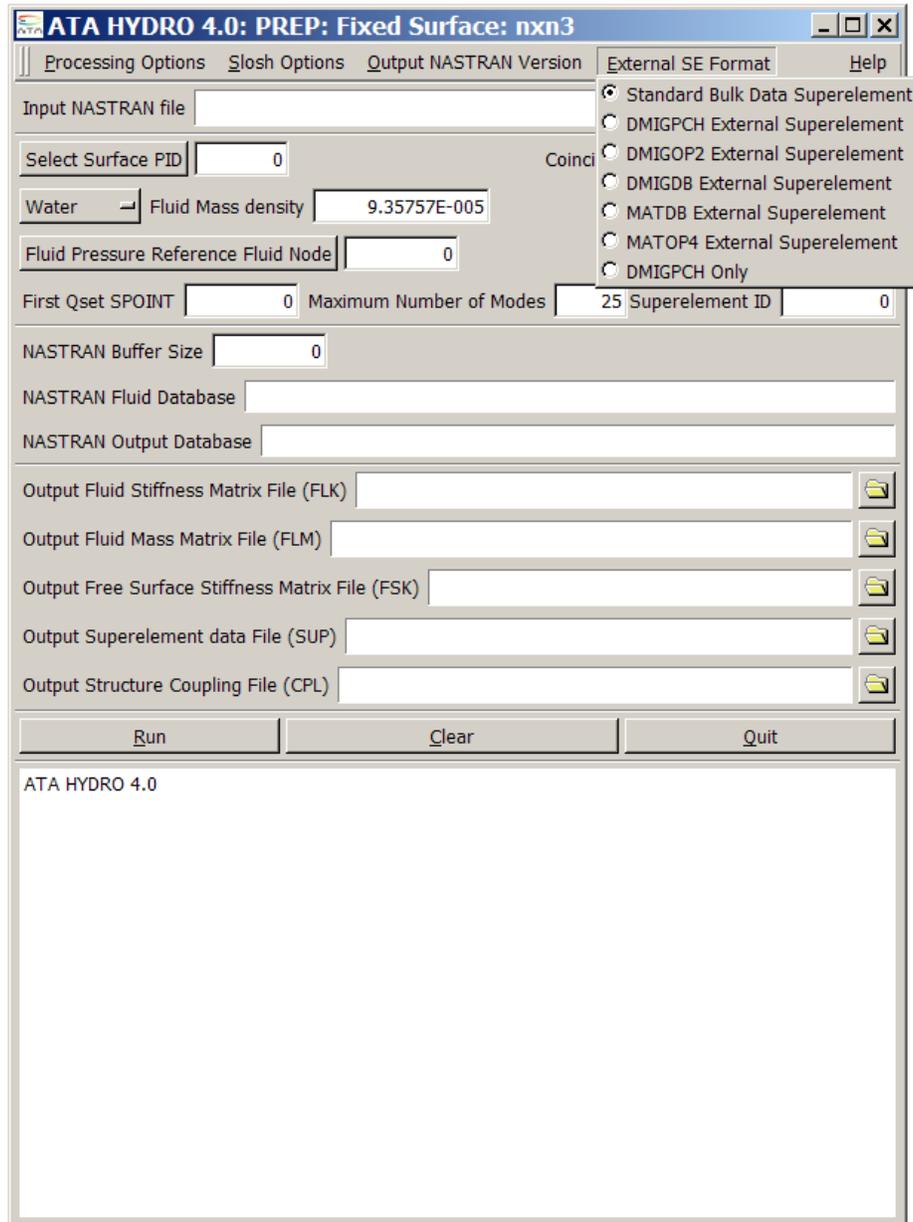

Figure 5-6. External superelement options.

The external superelement options are shown below:

      Standard Bulk Data Superelement

      DMIGPCH External Superelement

      DMIGOP2 External Superelement

    DMIGDB External Superelement

    MATDB External Superelement

    MATOP4 External Superelement

    DMIGPCH Only

Choosing any of the external superelement options will write the appropriate SUP file, the corresponding CPL file and a .asm file to include in the CPL run.

Some minor modifications to the code include:

1. SPOINTs rather than GRIDs are used to store modal DOF. This can be changed by editing the SUP and CPL files if necessary.

2. A number of slosh modes rather than a cutoff frequency is specified. The default value is 25.

Version 4.1 cleaned up the recovering of fluid pressures for POGO analysis. The pressures can now recovered directly as internal grid point accelerations in the Hydro superelement, and manual processing of the UTOP matrix is no longer required.

Version 4.1.1 contains minor cleanups.

Version 4.1.2 disables advanced superelement options when using a Nastran version that does not support this feature. A hydro_scale.xxx file is required, where .xxx is the Nastran version as described in Appendix B.

Version 4.1.3 contains a minor bugfix writing MAT4 cards.

Version 4.1.4 contains a minor bugfix for releasing licenses when running Hydro in command-line mode.

Nastran Versions currently supported:

- MSC.Nastran: 2001, 2005, 2012, and 2013

- NX Nastran: 3, 4, 5, 5.1, 6, 7, 8, 8.5, 9, and 10