Fluid added mass modeling in LS-DYNA and its application in structural vibration

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1 Introduction

Many structures, machines, or devices are operated partially in water, like surface ships, vessels, semi-submersible platforms. Some others may work completely in water, like submarines. For any of them, water has an important influence on their dynamic response. For most cases, a strong coupling between structures and surrounding water is required to get a good simulation of vibration response of structures subjected to shock or wave loadings. Unfortunately, a fully coupled simulation involving both structures and water explicitly can be expensive. Besides, with the traditional finite element method, meshing a large volume water body and defining non-reflection boundary conditions (e.g., Perfectly Matched Layer [1]) on the truncated boundary can be challenging and needs some experience.

As a general-purpose CAE software, LS-DYNA has been used in many fields including offshore industry and shipbuilding industry. Naturally, there has been a big demand for LS-DYNA to develop an effective and efficient method to model the fluid surrounding the structure and integrate this fluid effect in structural vibration analysis.

To meet the needs of these users, starting from the R15 release of LS-DYNA, a new feature of FLUIDM has been implemented. It computes the fluid added mass by using a boundary element method, without modeling the exterior fluid body explicitly. Following this implementation, an efficient wet-mode eigensolver using LOBPCG technology is developed, which computes eigenfrequencies and eigenmodes of structures fully or partially immersed in fluid. Furthermore, a series of vibration analysis can be performed based on the fluid added mass and the wet modes of the structures, to account for the influence from the surrounding fluid.

This paper aims to give a brief introduction of this new feature and provide some examples to show the capabilities and scope of the method. Some possible applications of this method are also discussed.

2 Implementation and Key steps in LS-DYNA

The approach taken here involves four key computational techniques:

- A boundary integral formulation of the incompressible, inviscid fluid behavior (BEM) to minimize model setup and meshing time.
- A block low rank representation of the boundary element matrices (BLR) to reduce the memory footprint and accelerate the computation of the fluid boundary mass.
- A novel strategy for the inclusion of the fluid added mass in the solution of the eigenvalue problem for the structure that takes advantage of the matrix-free nature of the locally optimal block preconditioned conjugate gradient (LOBPCG) eigen-solver, thereby reducing the memory requirement and computational time dramatically.
- Seamless integration with the existing LS-DYNA linear dynamics solvers.

3 Keywords

To facilitate using this new feature, a series of new keywords have been introduced to LS-DYNA (see LS-DYNA keyword manual R15)

3.1 *BOUNDARY_FLUIDM

Card 1	1	2	3	4	5	6	7	8
Variable	SSID	RHOF	IEIGEN	ICURV	BESIMF			
Type	I	F	I	I	I			
Default	none	none	0	0	0			

- Request the calculation of the external, fluid boundary mass on a structural surface in an inviscid, incompressible fluid.
- Unless accompanied by **`*BOUNDARY_FLUIDM_FREE_SURFACE`** or **`*BOUNDARY_FLUIDM_BOTTOM`**, the fluid is assumed to be infinite.
- Eigenvalue solution flag is set by IEIGEN. LS-DYNA can run in-fluid eigenvalue analysis for structures directly, using the calculated fluid added mass; or write a superelement for the fluid added mass matrix to file FLUIDM.DMIG.
- With BESIMF, one can choose boundary element solution method for external fluid mass from
  - LAPACK direct matrix solution.
  - Block low rank (BLR) direct solution without pivoting.
  - Pseudo-block GMRES iterative solution.
- The eigenvalue solution must use LOBPCG method, which is defined by EIGMTH = 102 in **`*CONTROL_IMPLICIT_EIGENVALUE`**.

3.2 *BOUNDARY_FLUIDM_BOTTOM

- Includes the effects of a flat, arbitrarily oriented bottom in the calculation of the **`*BOUNDARY_FLUIDM`** mass matrix. A finite bottom impedance may be included with a normalized, reflection coefficient. **`*BOUNDARY_FLUIDM_BOTTOM`** can be combined with **`*BOUNDARY_FLUIDM_FREE_SURFACE`** in very shallow conditions.

3.3 BOUNDARY_FLUIDM_INTERIOR

- Request calculating the added mass for an inviscid, incompressible fluid in a closed, internal volume/tank with a free surface. An input deck may contain multiple instantiations of this keyword when there are multiple separate internal volumes. It is intended for structural eigenvalue solutions and linear dynamic solutions based on modal superposition.
- Please note that the outward normal vectors for the segments in the set should be directed out of the internal fluid volume.

3.4 *BOUNDARY_FLUIDM_FREE_SURFACE

Card 1	1	2	3	4	5	6	7	8
Variable	DISTFS	CXFS	CYFS	CZFS				
Type	F	F	F	F				
Default	none	none	none	none				

- Includes the effects of a flat, arbitrarily oriented free surface in the calculation of the **`*BOUNDARY_FLUIDM`** mass matrix. Keyword **`*BOUNDARY_FLUIDM_BOTTOM`** can be combined with **`*BOUNDARY_FLUIDM_FREE_SURFACE`** in very shallow conditions.
- The reason for this keyword is because of the “proximity effect”. When nearby, a free surface will reduce the added mass experienced by a submerged structure.

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4 Examples

Several examples are included in this section, to validate this new feature, or to illustrate the possible applications of this new feature.

4.1 Fluid added mass computation.

4.1.1 Added mass for a sphere in an infinite fluid

For this example, the added mass on a sphere in an infinite fluid is computed, with different numbers of boundary elements for the modeling. The purpose of this study is to check the convergence of the results with respect to the number of elements for the mesh.

The fluid density is .96e-04 lb-sec^2/in^4 and the radius of the sphere is 10 in. In theory, the added mass Am is [2]

$$A_m = \frac{2}{3}\pi\rho R^3 \quad (1)$$

The model changes from 24 to 7,776 boundary elements.

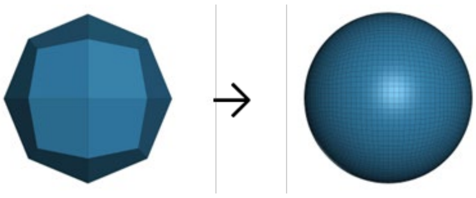

Fig.1: Sphere model with coarse and refined meshes.

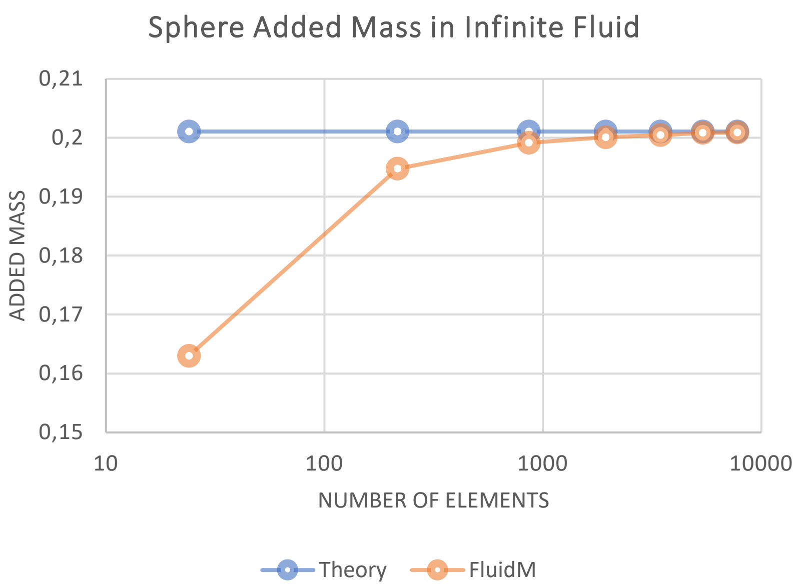

Fig.2: Sphere added mass in infinite fluid.

4.1.2 Added mass for a sphere in a fluid with free surface

For the same model described above (4.1.1), we computed the fluid added mass with a different distance between the sphere center and the free surface. As depicted in the references [2] and [3], when the depth (D) from the center of the sphere is large enough (e.g., larger than 4 in this case), the added mass is almost a constant value,

$$A_m = \frac{2}{3}\pi\rho R^3 = 0.20106 \quad (2)$$

The results given by LS-DYNA FluidM match very well with this prediction when the mesh is refined more and more.

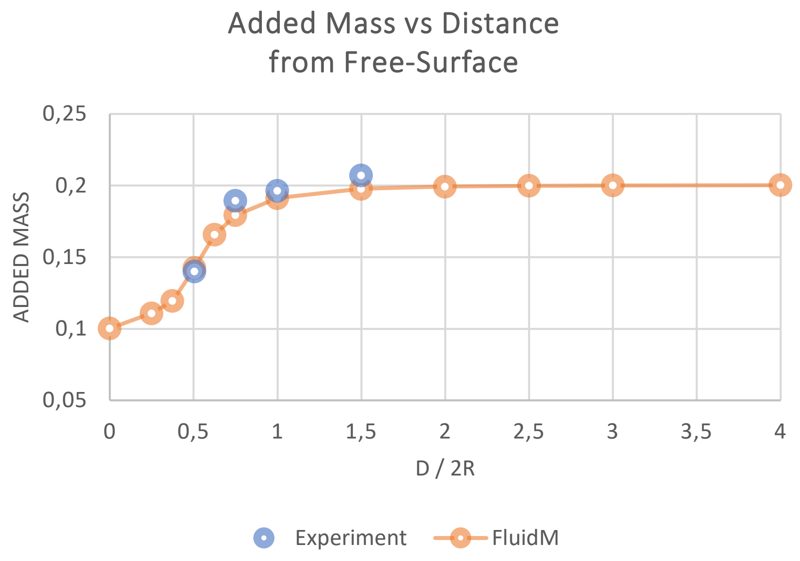

Fig.3: Sphere added mass in fluid with free surface.

4.1.3 Added mass for a sphere in a fluid with rigid bottom

Rigid bottom proximity effect on a submerged sphere in vertical motion is theoretically the opposite of the free surface effect – it increases the added mass rather than reduces it.
For the same model described above (4.1.1), we computed the fluid added mass with different distance between sphere center and a rigid bottom. When D > 4, the added mass is almost a constant value

$$A_m = \frac{2}{3}\pi\rho R^3 = 0.20106$$

The results given by LS-DYNA match very well with this prediction.

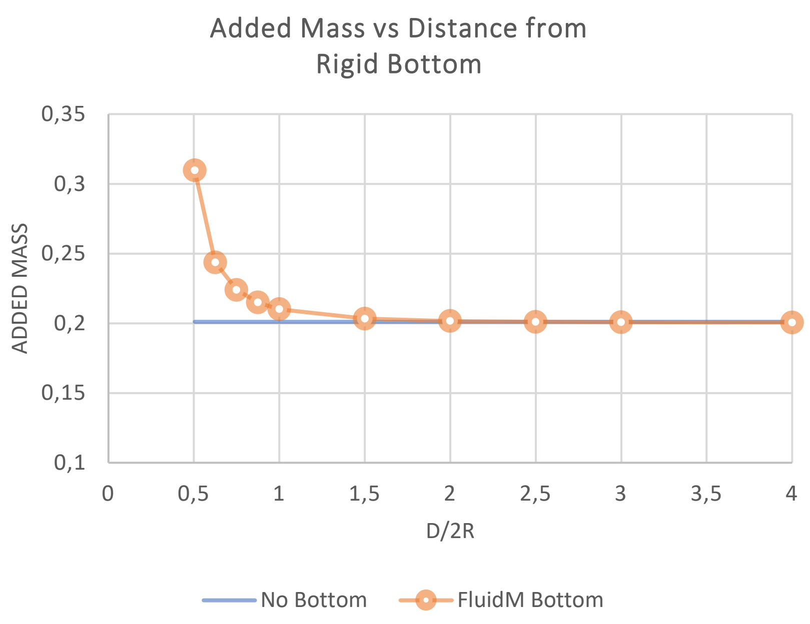

Fig.4: Sphere added mass in fluid with a rigid bottom.

4.1.4 Added mass for a sphere in a spherical cavity.

Sometimes the fluid may be inside the structure and the fluid added mass on structures can still be computed using the boundary element method.

For this example, a sphere with fluid filled inside is considered and the added mass is computed against the refined mesh. The theoretical result can be found in [2]. The fluid density is 997 kg/m3. The inner radius is 10 m and the outer radius is 15 m. The FLUIDM boundary element mesh is refined from 48 elements to 1728 elements.

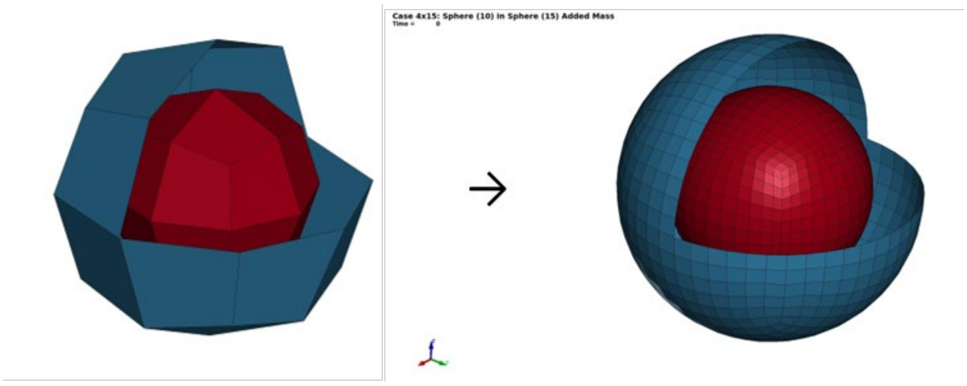

Fig.5: Refinement of the boundary element mesh (48->1728)

The added mass computed with LS-DYNA converges to the theoretical results when the FluidM mesh gets refined.

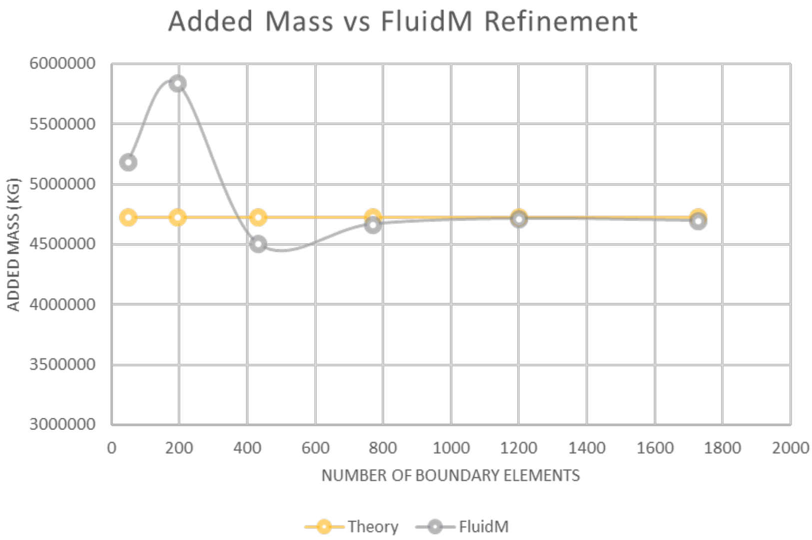

Fig.6: Added mass vs fluidM boundary element mesh.

4.2 Wet mode analysis with fluid added mass

4.2.1 Natural frequencies of a free-free plate in an infinite fluid

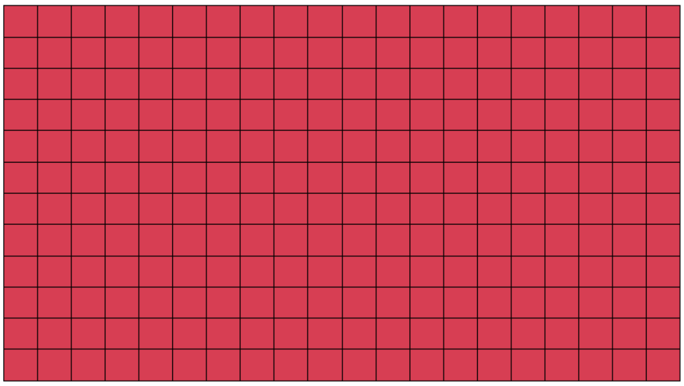

Fig.7: A free-free rectangular plate in an infinite fluid

Eigenvalue analysis is performed for a plate of 0.1495 m x 0.27 m x 0.00893 m, under both dry and wet conditions (for "wet" condition, we assume that the plate is immersed in water completely). The plate is modelled by solid elements. Since there are not any constraints, the plate has 6 rigid body modes. Starting from mode 7 (the first non-rigid body mode), LS-DYNA's eigenfrequencies have a good match with those from Analytical solution and from experiments.

Mode	Analytical	Experiment	LS-DYNA
7	645	641	650
8	716	712	721
9	1585	1577	1597
10	1766	1766	1779
11	2115	2139	2135

Table 1: Sundqvist Plate: In-Air Natural Frequencies (Hz)

Mode	Analytical	Experiment	LS-DYNA
7	489	497	505
8	561	575	582
9	1277	1293	1320
10	1411	1408	1446
11	1740	1758	1789

Table 2: Sundqvist Plate: In-Water Natural Frequencies (Hz)

One can see that the in-water natural frequencies are lower than the corresponding ones for the in-Air case. This is reasonable as with the fluid added mass, the structures become heavier.

The figures below show the modal shapes of the free-free plate in the infinite fluid.

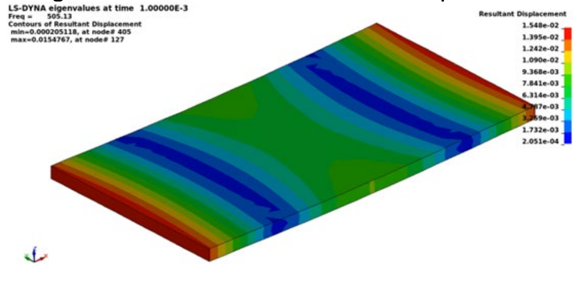

Fig.8: In-Fluid Mode 7

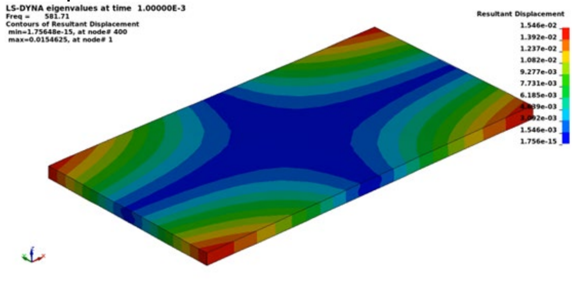

Fig.9: In-fluid mode 8

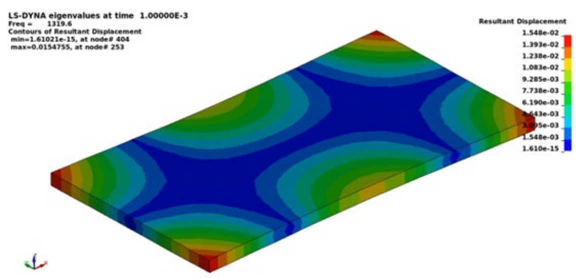

Fig.10: In-fluid mode 9

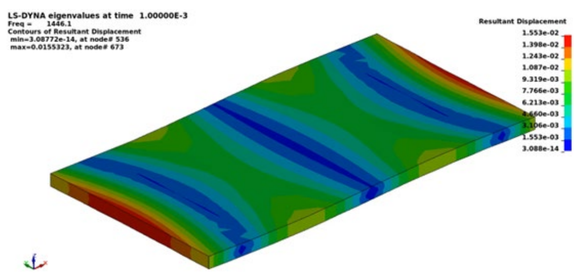

Fig.11: In-fluid mode 10

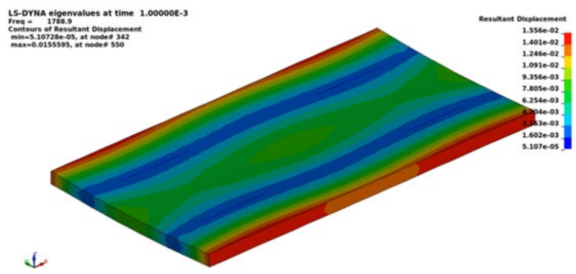

Fig.12: In-fluid mode 11

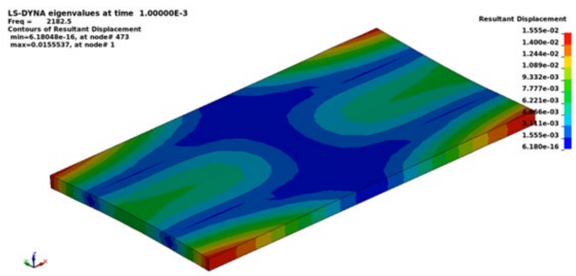

Fig.13: In-fluid mode 12

More of this example can be found in the references [4], [6] and [7].

4.2.2 Natural frequencies of a stiffened, floating box

The model studied here is a floating (or partially-submerged) box. Both in-air and in-fluid modal tests were conducted by Cambridge Acoustical Associates in 1998. The stiffened box is 32 ft long and 1.17 ft wide with a draft of 1.96 ft.

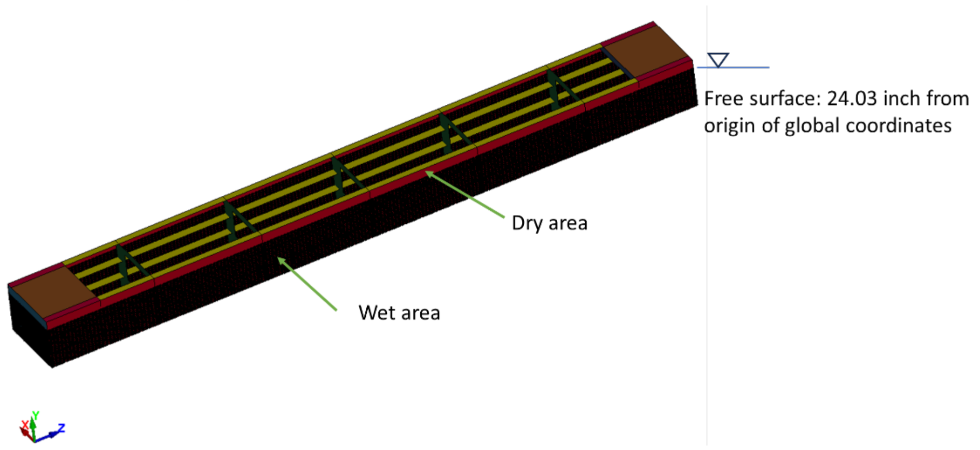

Fig.14: Illustration of wet and dry areas on the box exterior

The first 5 non-rigid body eigenmodes can be found in the table below.

Mode	Description	In-Air (Hz)		In-Fluid (Hz)	
		Experiment	LS-DYNA	Experiment	LS-DYNA
7	Torsion	16.1	15.6	14.9	14.8
8	Lateral bending	29.0	29.5	25.6	25.5
9	Vertical bending	38.3	37.1	29.5	28.5
10	Lateral bending	62.6	62.9	55.0	54.0
11	Vertical bending	94.2	91.0	68.5	65.8

Table 3: In-Air and In-Fluid natural frequencies of a stiffened, floating box

Note: modes 1-6 are rigid body modes.

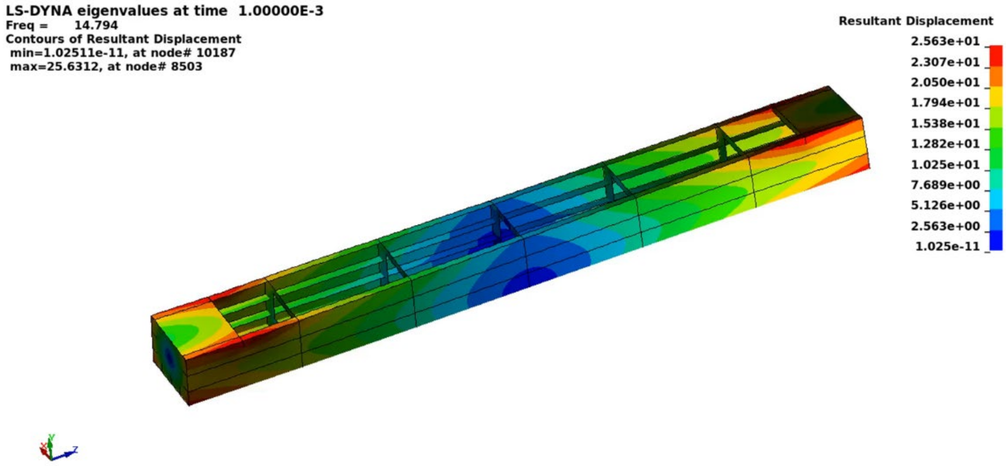

Fig.15: In-fluid mode 7 (1st torsion)

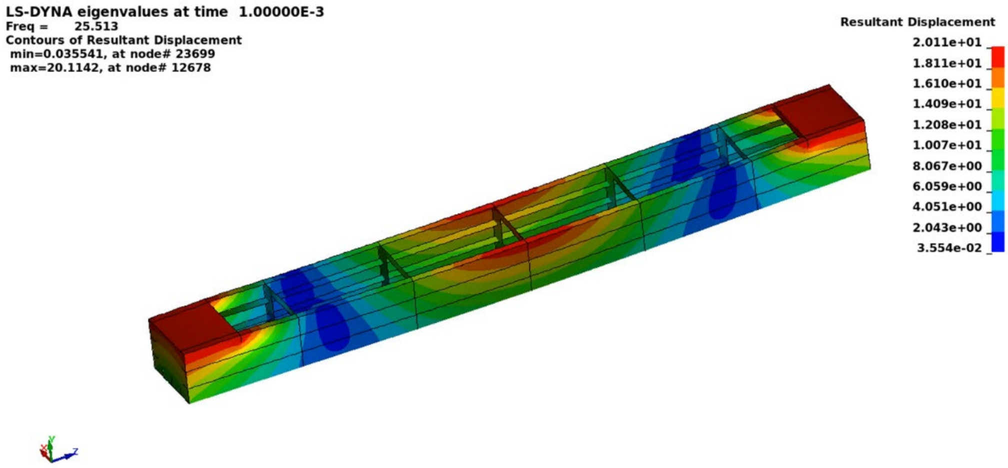

Fig.16: in-fluid mode 8 (1st lateral bending)

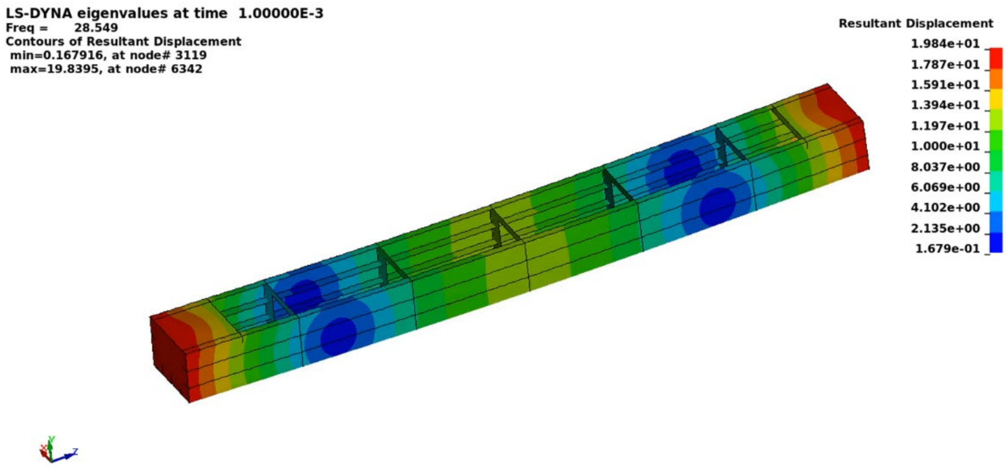

Fig.17: in-fluid mode 9 (1st vertical bending)

4.2.3 Natural frequencies of a partially filled cylindrical tank

For this example, a partially filled cylindrical tank (80%) is considered for eigenvalue analysis.The same model has been studied in [7]. The steel cylinder has radius R = 99.58 mm, thickness t = 1.16 mm, length L = 398.0 mm. The luid (water) has depth h=318.2 mm in the tank. The fluid (water) has a free surface condition (pressure =0). The model can be seen in Figure 18.

For the shaker table testing [7], there are no empty tank frequencies reported and the modes n=2,3,4 are identified (see Table 4 below).

With LS-DYNA, to compute the natural eigenfrequencies for this model, there are two methods.
- Using FLUIDM (as in other examples) and assuming that the water is incompressible;
- Using **`*CONTROL_IMPLICIT_SSD_DIRECT`** to run harmonic sweep for the coupled water-tank system to get frequencies for the peak values in the response curve. In this case, the fluid is assumed to be compressible.

Fig.18: A partilly filled cylinder

Mode	Wave (n,m)		Test (Hz)	LS-DYNA FLUIDM (Hz)	LS-DYNA SSD DIRECT (Hz)
1	3	0	190	201	192
2	2	0	203	245	226
3	4	0	296	308	303
4	5	1	-	464	471
5	1	0	-	559	488
6	4	1	-	528	525

Table 4: Natural frequencies of a partially filled cylindrical tank

4.3 Vibration analysis with fluid added mass

A series of time domain and frequency domain vibration analysis can be performed for the fully or partially submerged structures, including.
- Modal transient analysis
- Frequency Response Functions (FRF)
- Steady State Dynamics (SSD)
- Random vibration
- Response spectrum analysis
- Dynamic Design Analysis Method (DDAM)

4.3.1 SSD analysis for a floating box

With the same model in 4.2.2, harmonic nodal force excitation is applied for the frequency range of 1-200 Hz at the bottom of the floating box (node 533). The response of nodal displacement, velocity and acceleration for selected nodes can be found in database **`d3ssd`** for the whole model, or in ASCII database **`nodout_ssd`**, which is dumped to the binary scratch file binout.

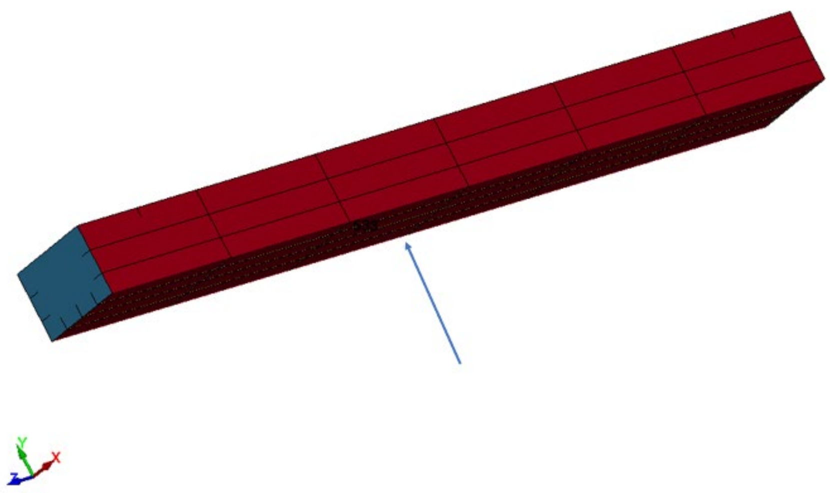
Fig.19: Harmonic Nodal force applied to the bottom of the floating box.

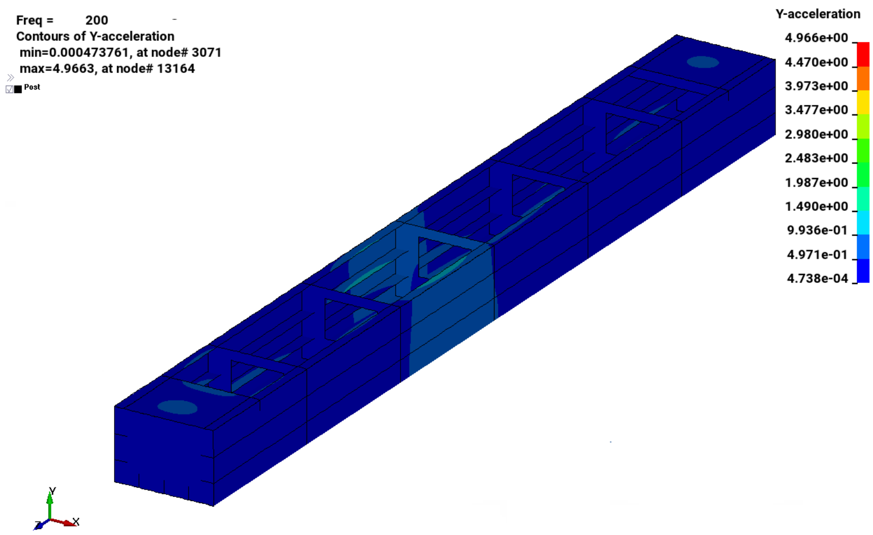

Fig.20: Amplitude of y-acceleration response at 200 Hz (Dry condition)

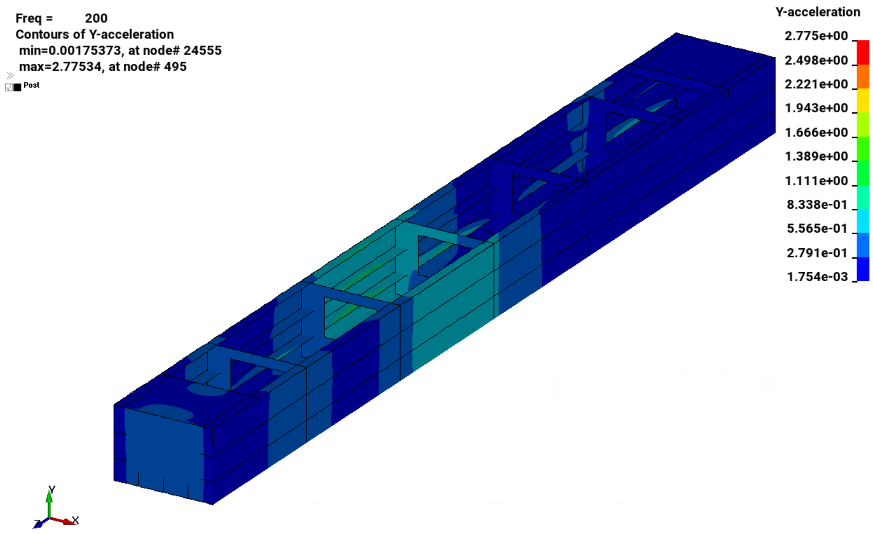

Fig.21: Amplitude of y-acceleration response at 200 Hz (Wet condition)

One can notice, that in wet conditions, the maximum value of the amplitude of the y-acceleration response is reduced from 4.966 inch/s^2 to 2.775 inch/s^2.

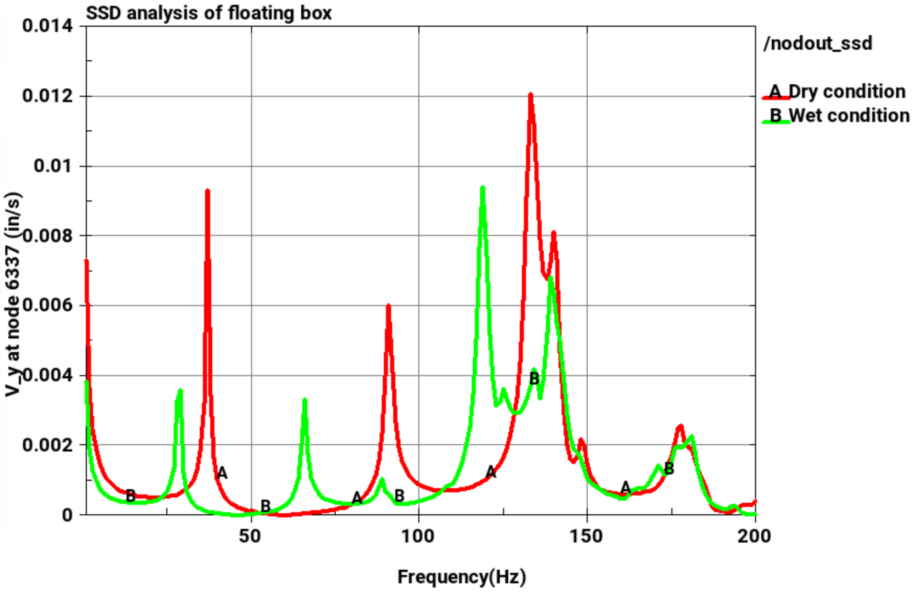

Fig.22: y-directional velocity in dry and wet condition

The y-directional nodal velocity at node 6337 is computed in dry condition and wet condition and plotted together in Figure 22. The peak value of the vibration response is reduced in wet conditions, compared to that in dry conditions. Besides, the resonance frequencies in wet conditions are lower than the corresponding ones in dry conditions. This is because, with the added mass from the surrounding fluid, the structure becomes heavier, thus its dynamic response is reduced.

5 Summary

The objective of this development effort is the implementation of a more efficient method to simulate the vibration response of structures whose response is affected by the presence of an incompressible, inviscid fluid, typically water. “Efficiency” encompasses multiple considerations; including

- Model setup and meshing time
- Memory usage and CPU time

The prediction of structural natural frequencies and mode shapes may be the analyst’s goal, or it may simply be the initial step in modal steady state and transient analyses.

This paper presents the output of this development - a new feature of fluid added mass computation in LS-DYNA. The paper also discusses its application including wet mode analysis, and structural vibration analysis. The corresponding keywords are introduced. Some examples are included to illustrate the effectiveness and accuracy of this new method, and to show its possible application.

Naturally, this fluid added mass computation feature can find many applications in the shipbuilding industry, where one always needs to consider the full interaction between the ship and the surrounding infinite water.

6 Literature

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