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

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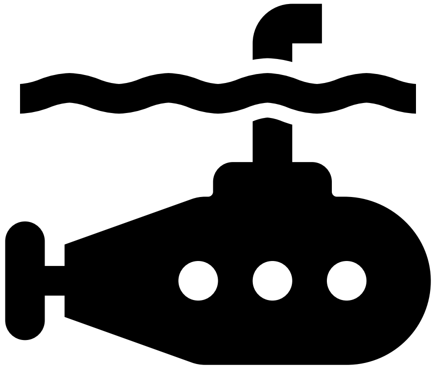
Introduction

Motivation and Objective

- For ships and submarines, surrounding water has significant effect on the dynamic response.
- The objective of this work is to implement an 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
  - 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
- The most comparable competitor’s capability being targeted is the MFLUID boundary element feature in NASTRAN



Approach and key steps

The approach involves the following key computational techniques:

1. A boundary integral formulation of the incompressible, inviscid fluid behavior (BEM) to minimize model setup and meshing time
2. A block low rank representation of the boundary element matrices to reduce the memory footprint and accelerate the computation of the fluid boundary mass
3. 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 with RCI) eigen-solver, thereby reducing the memory requirement and compute time … dramatically
4. Seamless integration with the existing LS-DYNA linear dynamics solvers

Keywords

Related Keywords and their usage

Keywords	Description
*BOUNDARY_FLUIDM	Request the calculation of the external, fluid boundary mass on a structural surface in an inviscid, incompressible fluid.
*BOUNDARY_FLUIDM_FREE_SURFACE	Includes the effects of a flat, arbitrarily oriented free surface in the calculation of the *BOUNDARY_FLUIDM mass matrix
*BOUNDARY_FLUIDM_BOTTOM	Includes the effects of a flat, arbitrarily oriented bottom in the calculation of the *BOUNDARY_FLUIDM mass matrix. Due to proximity effect, when nearby, a bottom will increase the added mass experienced by a submerged structure.
*CONTROL_IMPLICIT_EIGENVALUE	Eigmth = 102 for LOBPCG eigensolver.
*FREQUENCY_DOMAIN_	Various frequency domain vibration analysis using eigensolutions

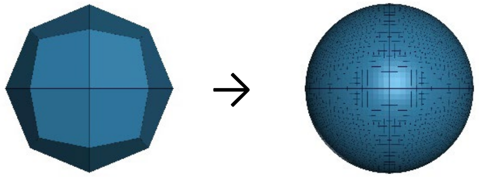
Note:
Keyword *BOUNDARY_FLUIDM_BOTTOM can be combined with *BOUNDARY_FLUIDM_FREE_SURFACE in very shallow conditions.

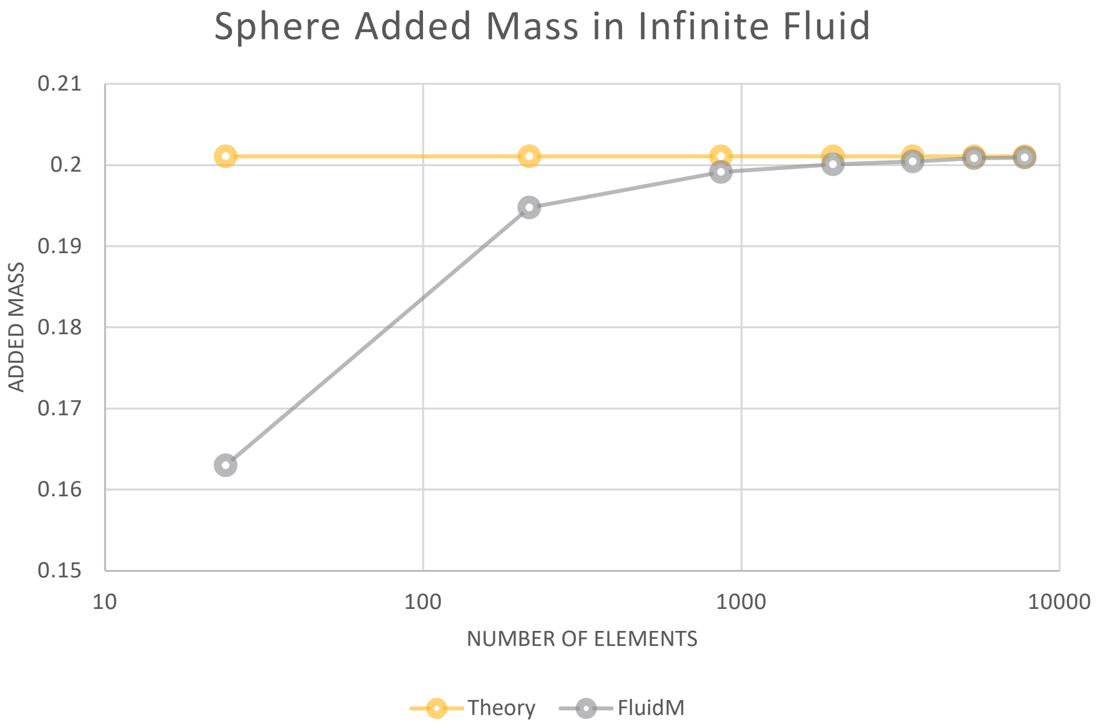
Examples

Fluid added mass computation

Example: a sphere in an infinite fluid w/ refinement

- R.D. Blevins, *Formulas for Natural Frequencies and Mode Shape*, Ch 14, Table 14-2.8, Added Masses of Bodies, Van Nostrand Reingold, 1979.
- Parameters
  - Fluid Density = .96e-04 lb-sec^2/in^4
  - Radius (R) = 10 in
  - Theory $A_m = 2/3\ \pi\rho\ R^3$
  - FLUIDM models from 24 to 7,776 boundary elements

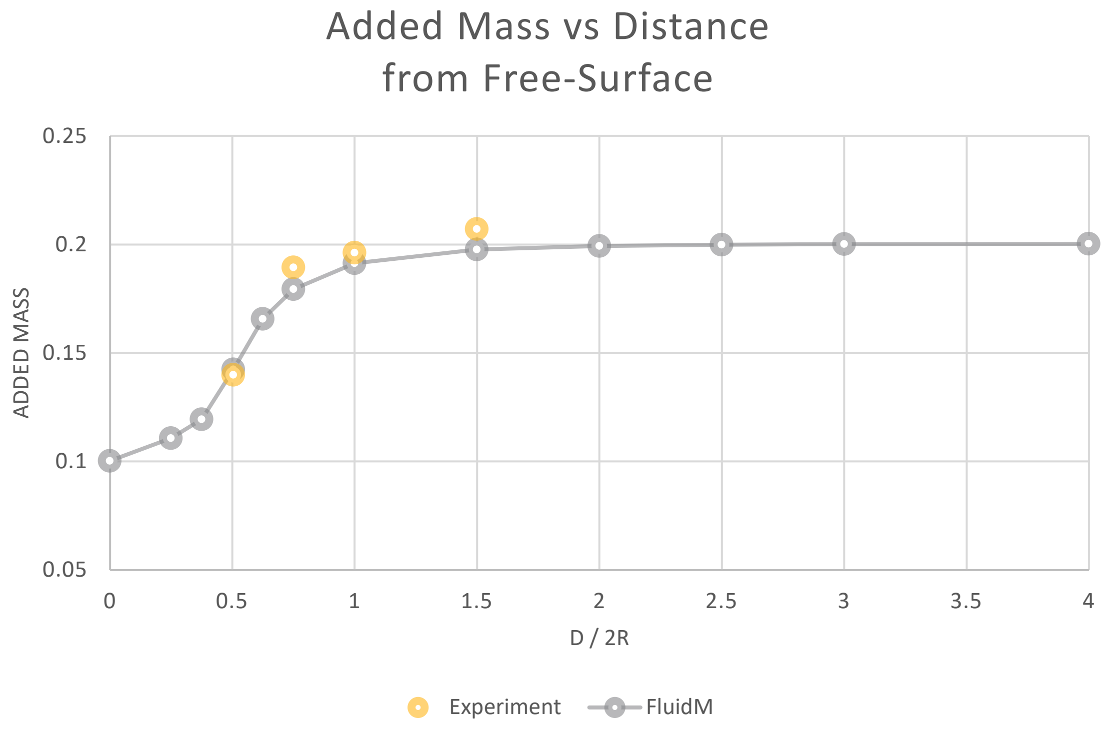




- LS-DYNA computes and prints A_m in d3hsp

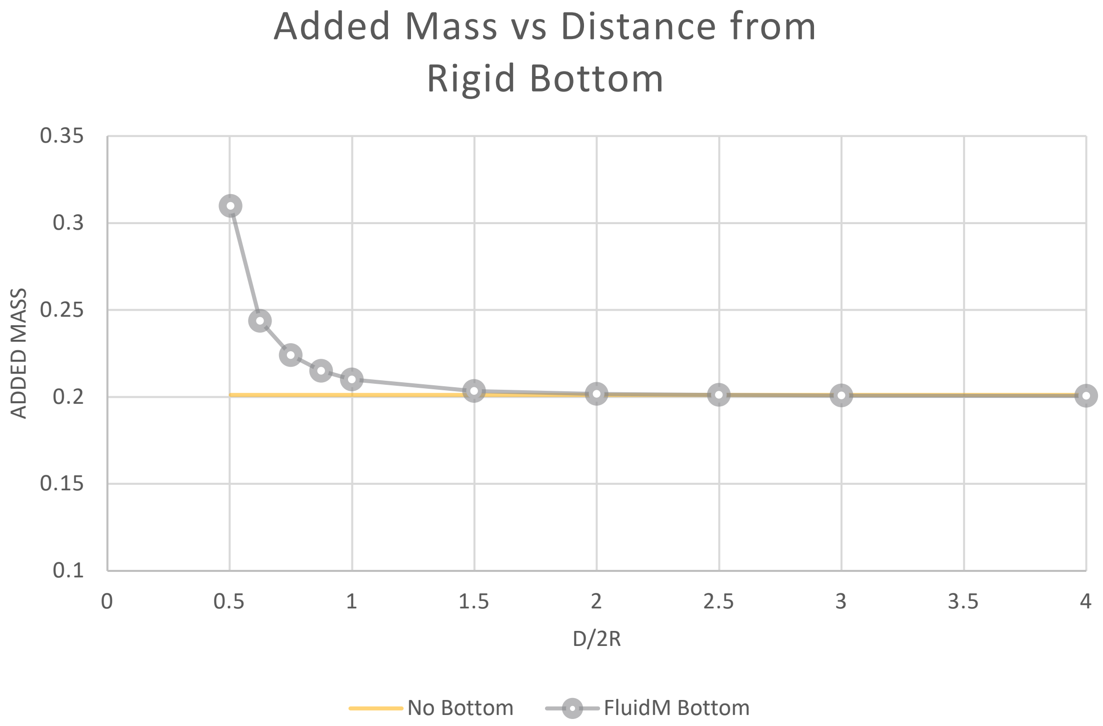
Example: a sphere vs distance from free surface

- R.D. Blevins, *Formulas for Natural Frequencies and Mode Shape*, Ch 14, Table 14-2.12, Added Masses of Bodies, Van Nostrand Reingold, 1979.
- J.G. Waugh and A.T Ellis, “Fluid free surface proximity effect on a sphere vertically from rest,” *J. Hydrodynamics*, 3, pp 175-179, 1969.
- Parameters
  - Fluid Density = .96e-04 lb-sec^2/in^4
  - Radius (R) = 10 in
  - Depth (D) from center of sphere
  - D > 4, $A_m = 2/3\ \pi\rho R^3 = 0.20106$
- LS-DYNA computes and prints A_m in d3hsp



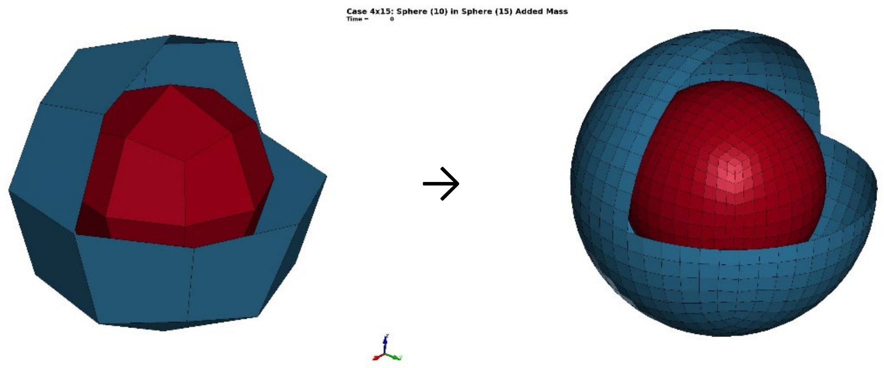
Example: a sphere vs distance from a rigid bottom

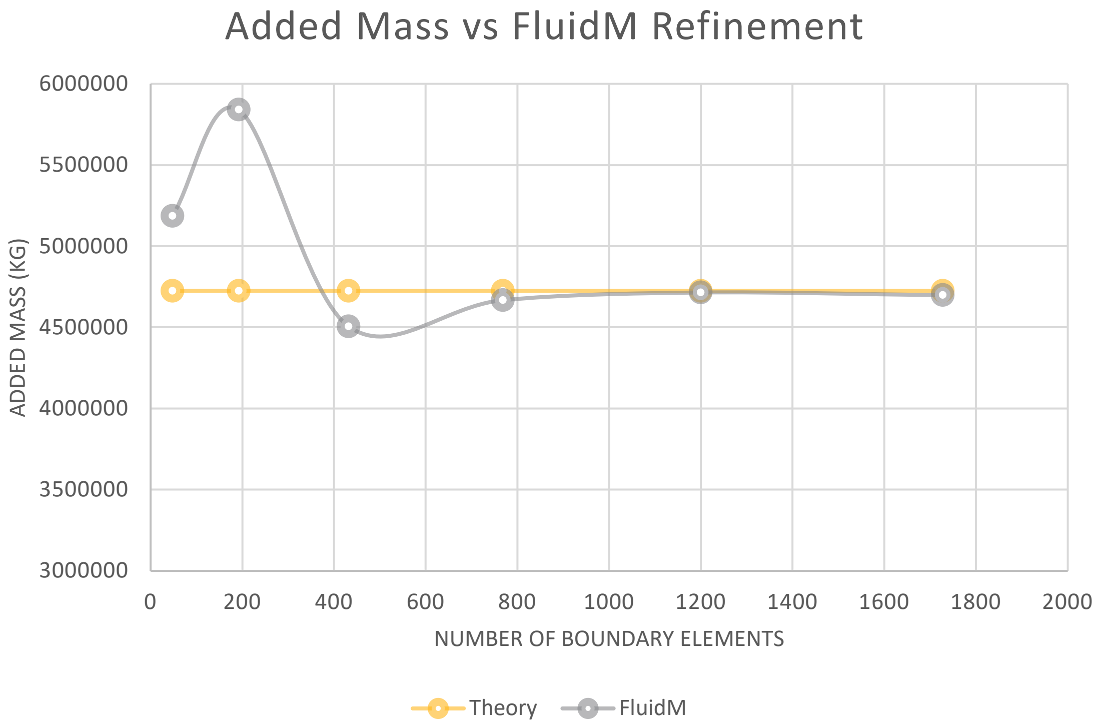
- Rigid bottom proximity effect on a submerged sphere in vertical motion is theoretically the opposite of the free surface effect – it increases the added mass rather than reduces it.
- Parameters
  - Fluid Density = .96e-04 lb-sec^2/in^4
  - Radius (R) = 10 in
  - Distance (D) from center of sphere to bottom
  - D > 4, $A_m = 2/3\ \pi\rho R^3 = 0.20106$
- LS-DYNA computes and prints A_m in d3hsp



Example: a sphere in a spherical cavity

- R.D. Blevins, *Formulas for Natural Frequencies and Mode Shape*, Ch 14, Table 14-2.15, Added Masses of Bodies, Van Nostrand Reingold, 1979.
- Parameters
  - Fluid Density = 997 kg/m^3
  - Inner Radius = 10m, Outer Radius = 15m
  - From 48 → 1728 FLUIDM boundary elements





Added mass A_m determined through Implicit Newmark solution for acceleration with a constant force on inner sphere

Examples

Wet mode computation

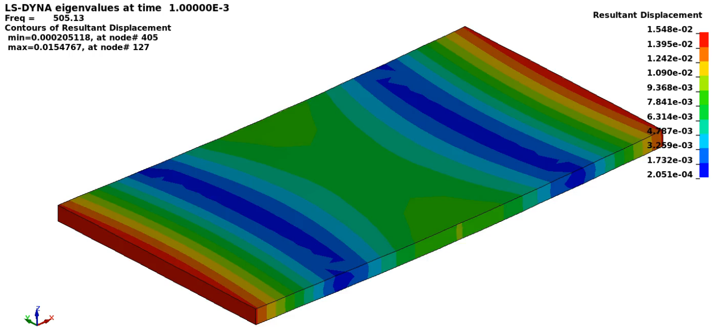
Example: a free-free plate in an infinite fluid

- J. Sundqvist, "Application of ADINA to the solution of fluid-structure interaction problems," *Computers & Structures*, 17, pp 793-807, 1983.
- D.K. Gupta, C.V. Ramakrishnan, and J.S. Rau, "Fluid-structure interaction problems in turbine blade vibration," *Advances in Fluid-Structure Interaction*, ASME, AMD-64, pp 89-96, 1984.
- L.G. Olson and K.-J. Bathe, "Analysis of fluid-structure interactions. A direct symmetric potential formulation based on the fluid velocity potential," *Computers & Structures*, 21, pp 21-35, 1985.

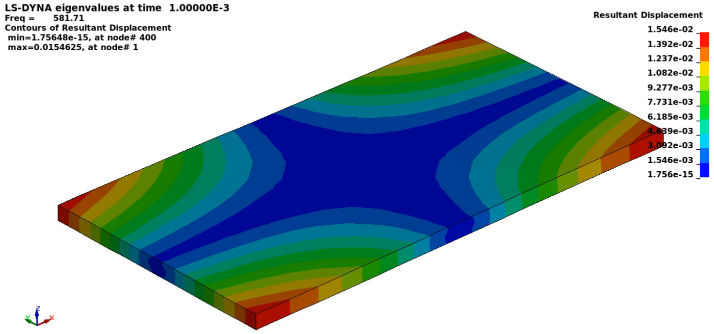
Sundqvist Plate: In-Air Natural Frequencies (Hz)			
Mode	Analytical	Experiment	LS-DYNA
7	645	641	650
8	716	712	721
9	1585	1577	1597
10	1766	1766	1779
11	2115	2139	2135

Sundqvist Plate: In-Water 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
12	2133	2133	2182

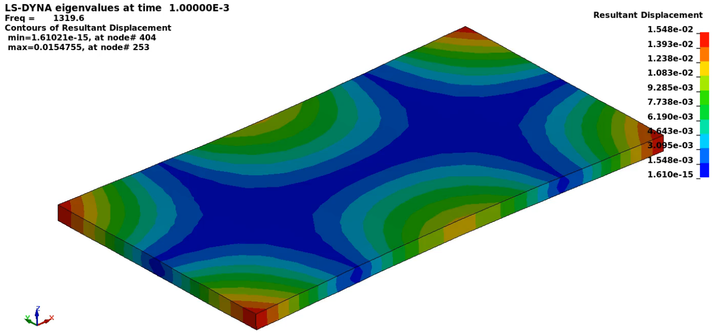
Mode shapes of the free-free plate in an infinite fluid



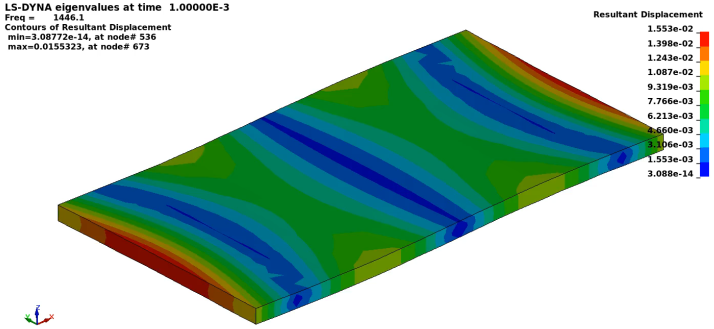
In-Fluid Mode 7



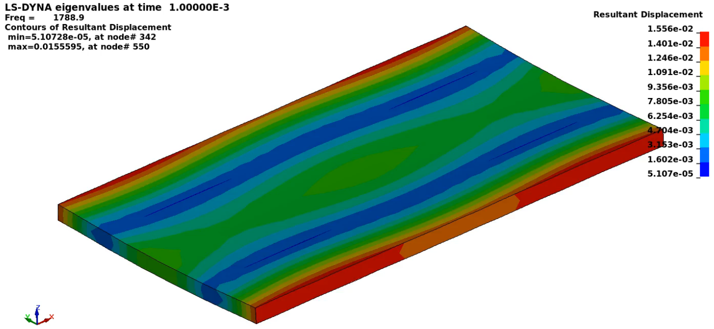
In-Fluid Mode 8



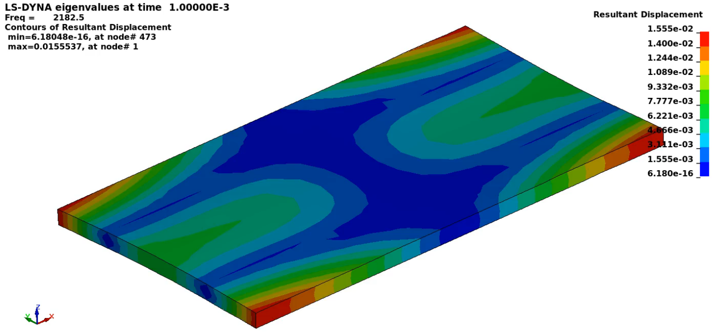
In-Fluid Mode 9



In-Fluid Mode 10



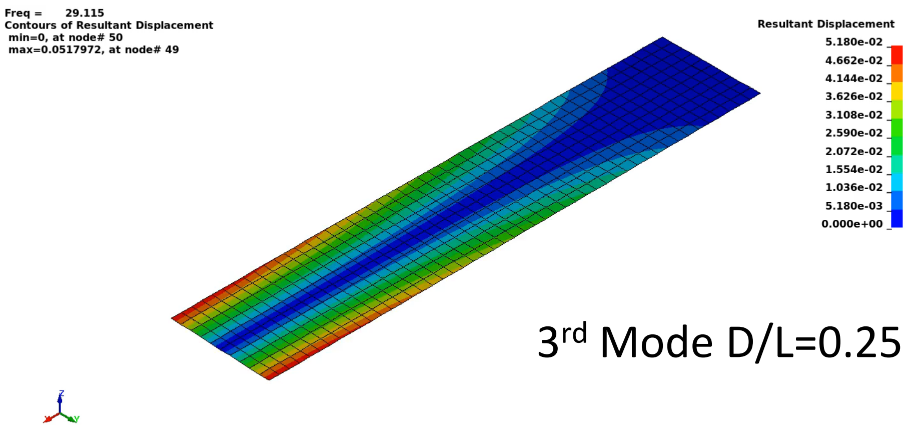
In-Fluid Mode 11



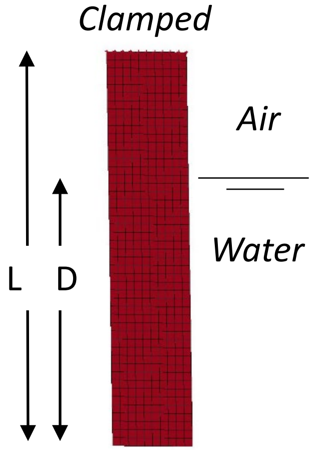
In-Fluid Mode 12

Example: a partially-submerged cantilever plate

- U.S. Lindholm, D.D Kana, W.-H. Chu, and H.N. Abramson, “Elastic vibration characteristics of cantilever plates in water,” *Journal of Ship Research*, 9, 11-22, 1965.
  - Parameters: L=1016 mm, W=203.2 mm, t=4.84 mm, steel in fresh water.



3^{rd} Mode D/L=0.25



Mode	Type	In-Air		Depth/Length=0.25		Depth/Length=0.75	
		Test (Hz)	LS-DYNA	Test (Hz)	LS-DYNA	Test (Hz)	LS-DYNA
1	S	3.84	3.94	2.17	2.24	1.79	1.81
2	S	24.20	24.67	21.01	21.38	11.99	11.99
3	A	39.10	39.07	29.75	29.12	24.20	23.89
4	S	68.10	69.25	57.36	59.03	38.27	37.88
5	A	121.00	119.46	106.35	104.80	79.00	76.32

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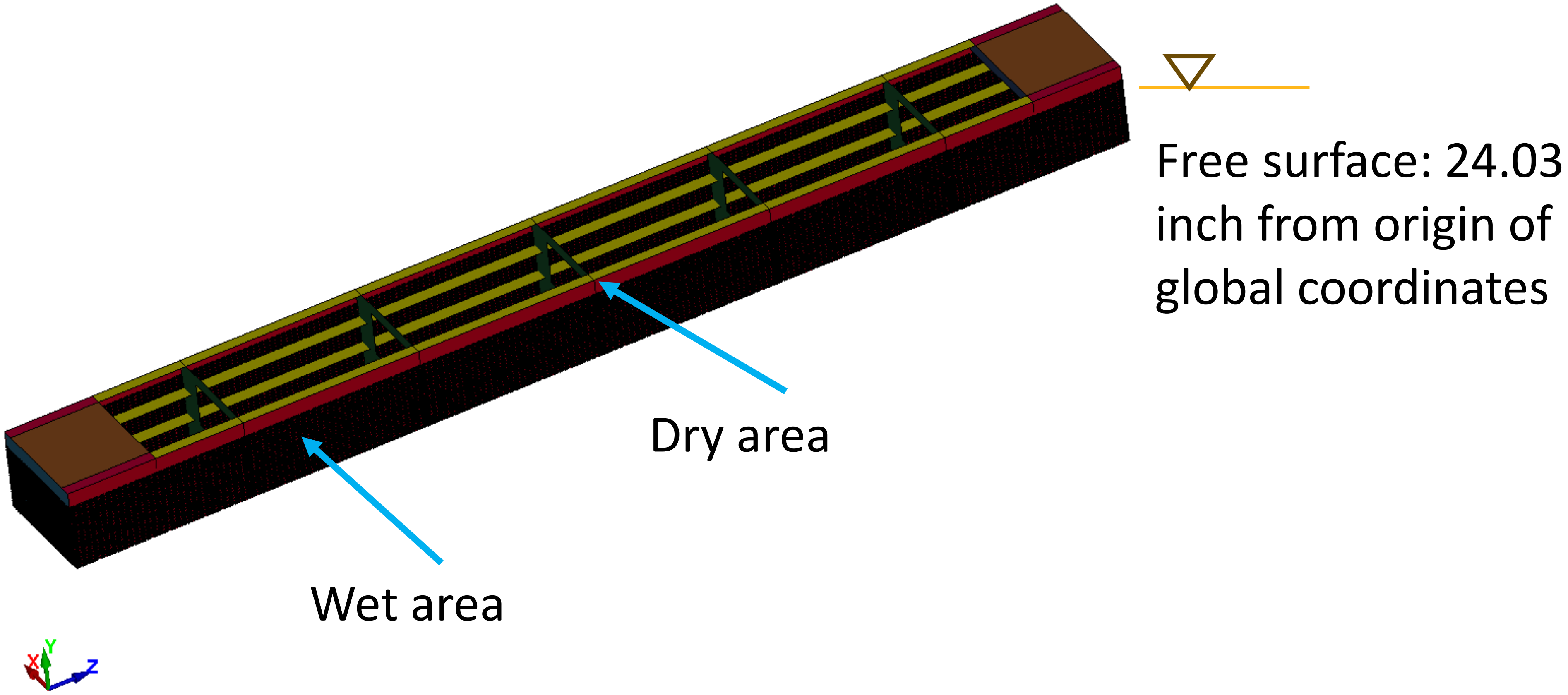
Example: a stiffened, floating box

- 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.



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Natural frequencies in-air and in-fluid

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

Note: modes 1-6 are rigid body modes

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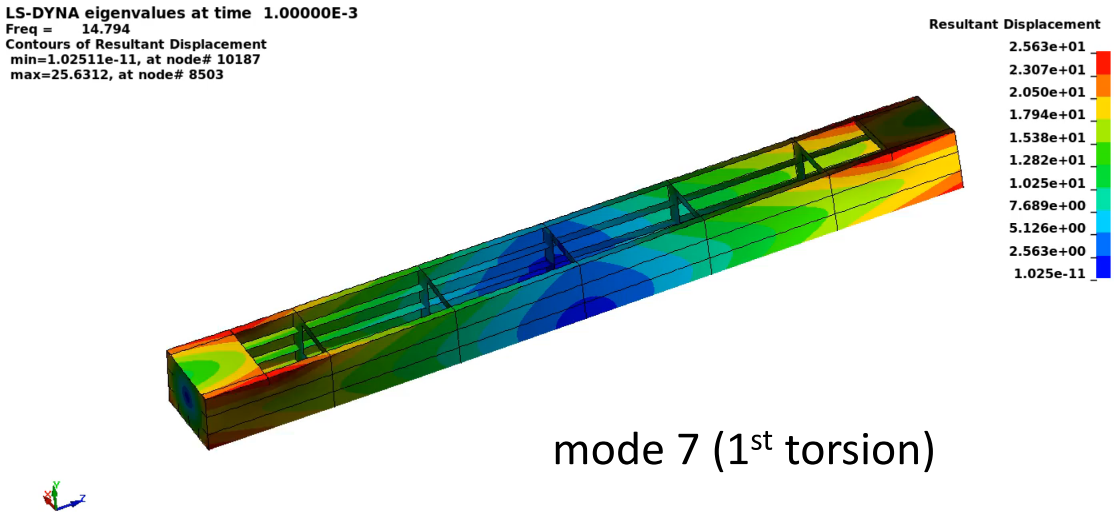
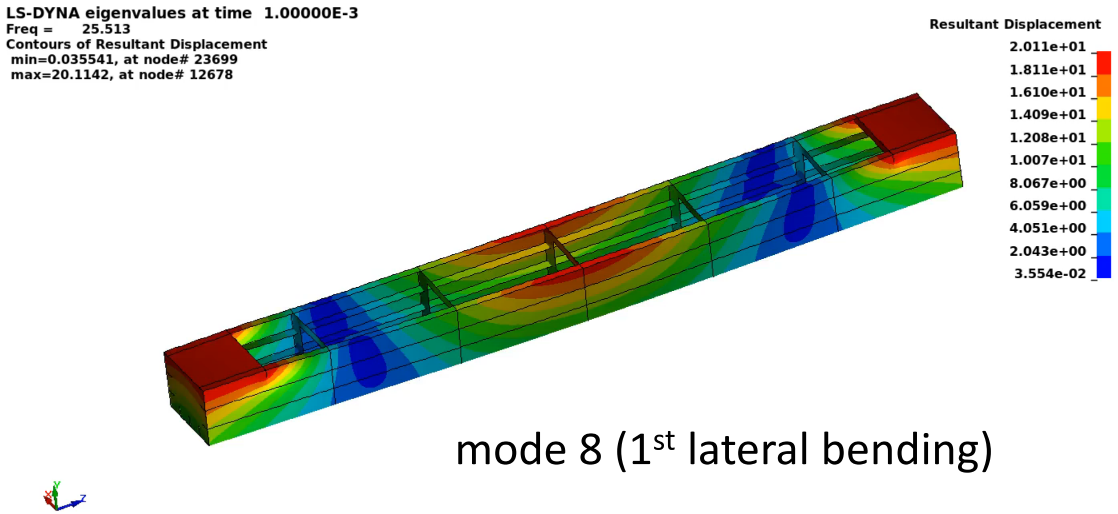
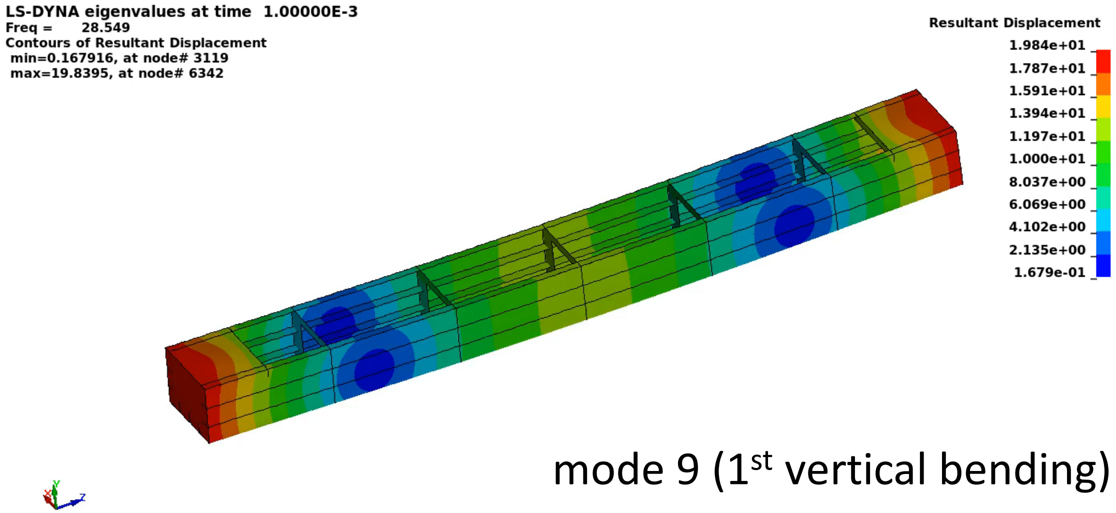
In-fluid eigenmodes for the floating box



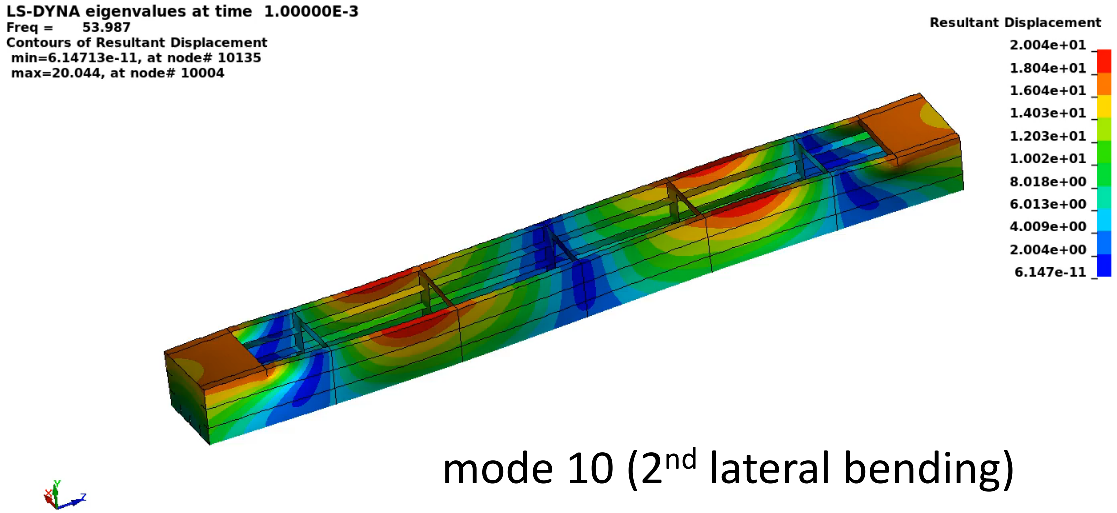
mode 7 (1^{st} torsion)



mode 8 (1^{st} lateral bending)



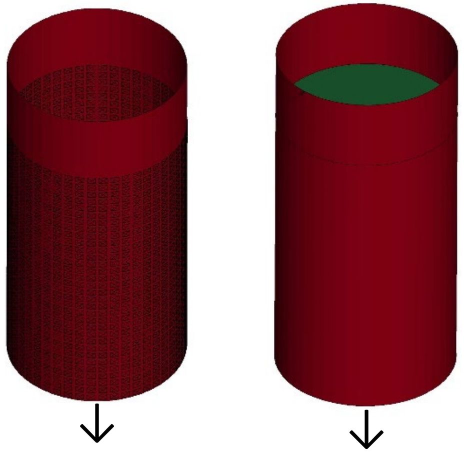
mode 9 (1^{st} vertical bending)



mode 10 (2^{nd} lateral bending)

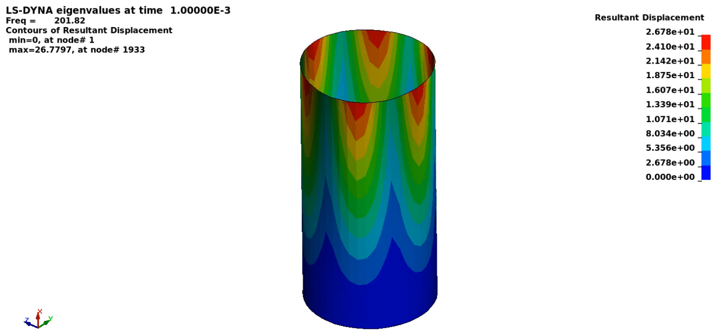
Example: a partially filled cylindrical tank

- J. Mistry and J.C. Menezes, “Vibration of cylinders partially-filled with liquids,” *Journal of Vibration and Acoustics*, ASME, 117, pp 87-93, 1995.
- Parameters
  - Steel cylinder, R=99.58 mm, t=1.16 mm, L=398.0 mm
  - Fluid (water) depth h=318.2 mm
  - Free surface condition pressure=0
- Testing by shaker table
  - No empty tank frequencies reported
  - Modes n=2,3,4 identified
- LS-DYNA analysis with FLUIDM eigen-analysis and SSD_DIRECT harmonic sweep
  - FLUIDM is incompressible fluid
  - SSD_DIRECT is compressible fluid
    - No indication of acoustic modes < 600Hz

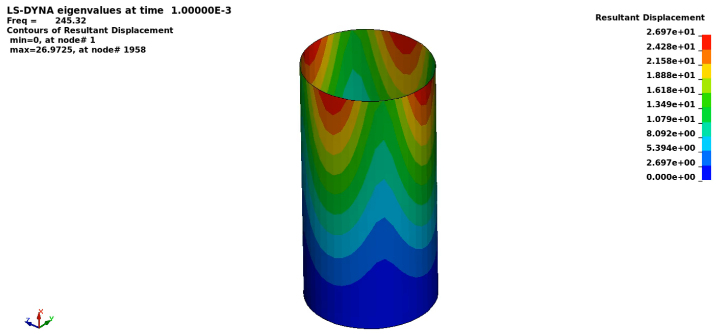


Mode	Wave (n,m)		Test (Hz)	LS-DYNA FLUIDM	LS-DYNA SSD_DIRECT
1	3	0	190	201	192
2	2	0	203	245	226
3	4	0	296	308	303
4	5	1	-	464	471
5	1	0	-	559	488
6	4	1	-	528	525

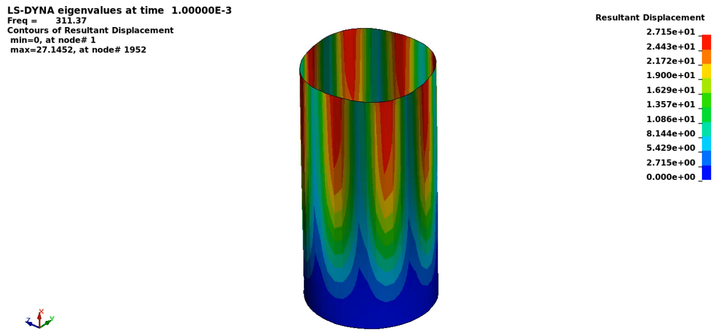
Eigenmodes of the partially filled tank



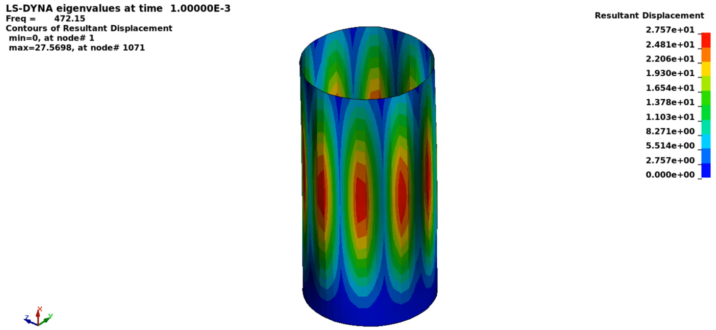
FLUIDM Mode 1 : 201 Hz



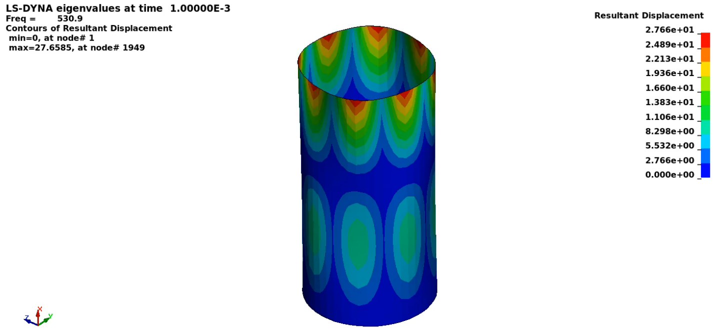
FLUIDM Mode 2 : 245 Hz



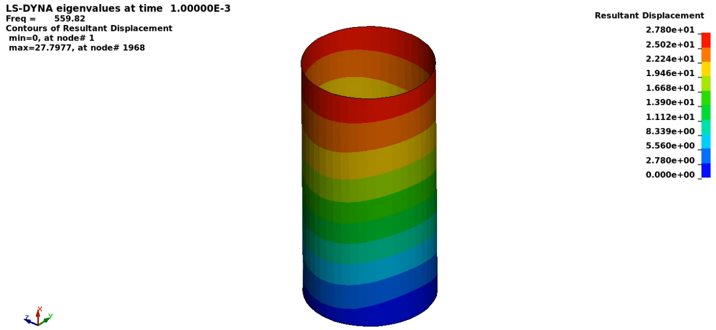
FLUIDM Mode 3 : 308 Hz



FLUIDM Mode 4 : 464 Hz



FLUIDM Mode 5 : 528 Hz



FLUIDM Mode 6 : 559 Hz

Examples

Vibration analysis with fluid added mass

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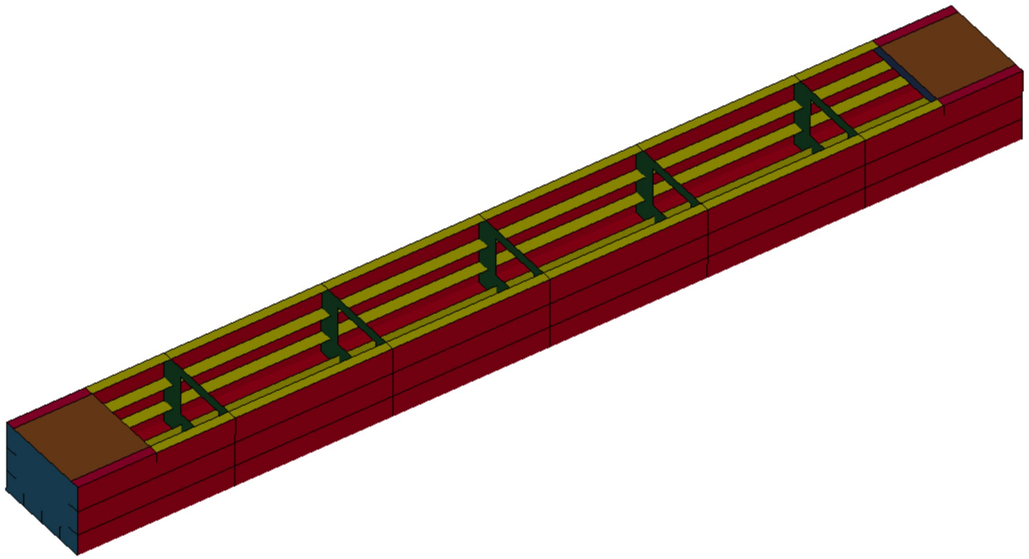
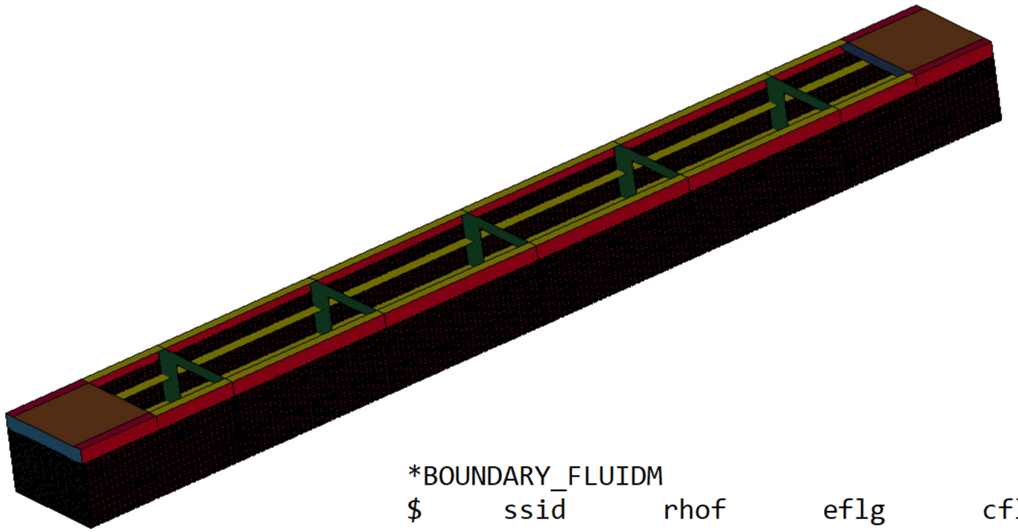
Example: SSD analysis with a floating box

Dry mode model



Wet mode model



```
*BOUNDARY_FLUIDM
$      ssid      rhof      eflg      cflg
          1  0.935e-4         0         1
*BOUNDARY_FLUIDM_FREE_SURFACE
$      dist      cxfs      cyfz      czfs
      24.03       0.0       1.0       0.0
```

Modal analysis

Dry modes

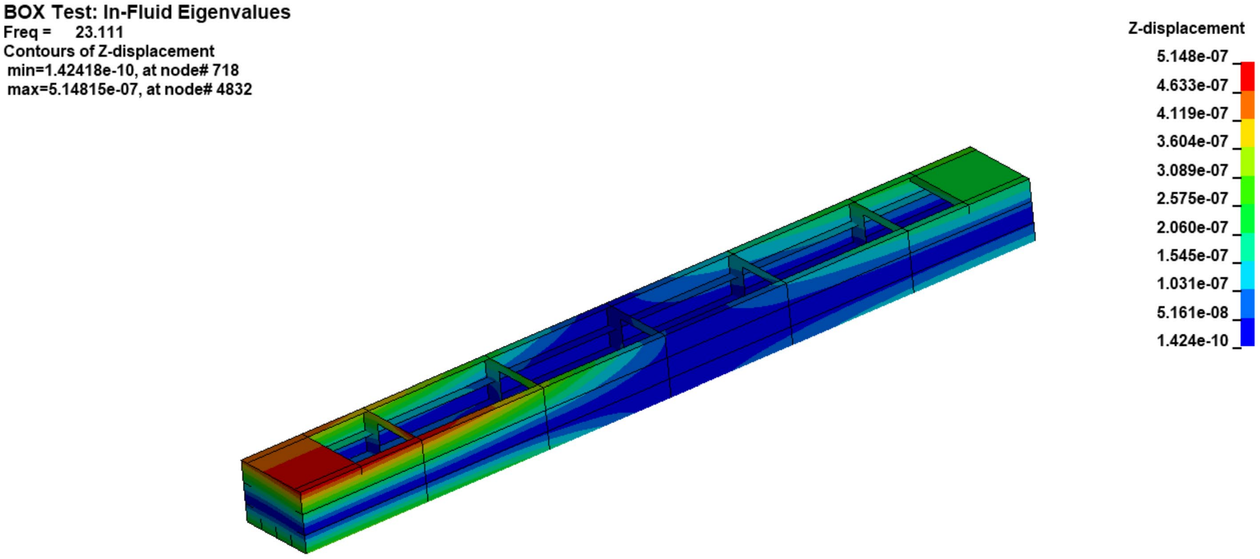
MODE	EIGENVALUE	RADIANS	CYCLES	PERIOD
1	-5.128816E-07	7.161575E-04	1.139800E-04	8.773469E+03
2	-3.068087E-07	5.539032E-04	8.815643E-05	1.134347E+04
3	-1.210808E-07	3.479667E-04	5.538062E-05	1.805686E+04
4	1.643634E-07	4.054176E-04	6.452421E-05	1.549806E+04
5	4.178696E-07	6.464284E-04	1.028823E-04	9.719848E+03
6	1.076729E-06	1.037655E-03	1.651480E-04	6.055175E+03
7	9.673690E+03	9.835492E+01	1.565367E+01	6.388278E-02
8	3.436295E+04	1.853725E+02	2.950294E+01	3.389492E-02
9	5.431060E+04	2.330464E+02	3.709048E+01	2.696110E-02
10	1.563009E+05	3.953491E+02	6.292176E+01	1.589275E-02
11	3.265953E+05	5.714852E+02	9.095469E+01	1.099449E-02
12	3.787937E+05	6.154621E+02	9.795384E+01	1.020889E-02
13	3.970136E+05	6.300901E+02	1.002820E+02	9.971883E-03
14	5.469931E+05	7.395898E+02	1.177094E+02	8.495500E-03
15	6.024808E+05	7.761963E+02	1.235355E+02	8.094840E-03
16	6.987029E+05	8.358845E+02	1.330352E+02	7.516810E-03
17	7.126830E+05	8.442055E+02	1.343595E+02	7.442720E-03
18	7.817662E+05	8.841755E+02	1.407209E+02	7.106265E-03
19	8.630807E+05	9.290214E+02	1.478583E+02	6.763230E-03
20	8.675547E+05	9.314261E+02	1.482411E+02	6.745769E-03

Wet modes

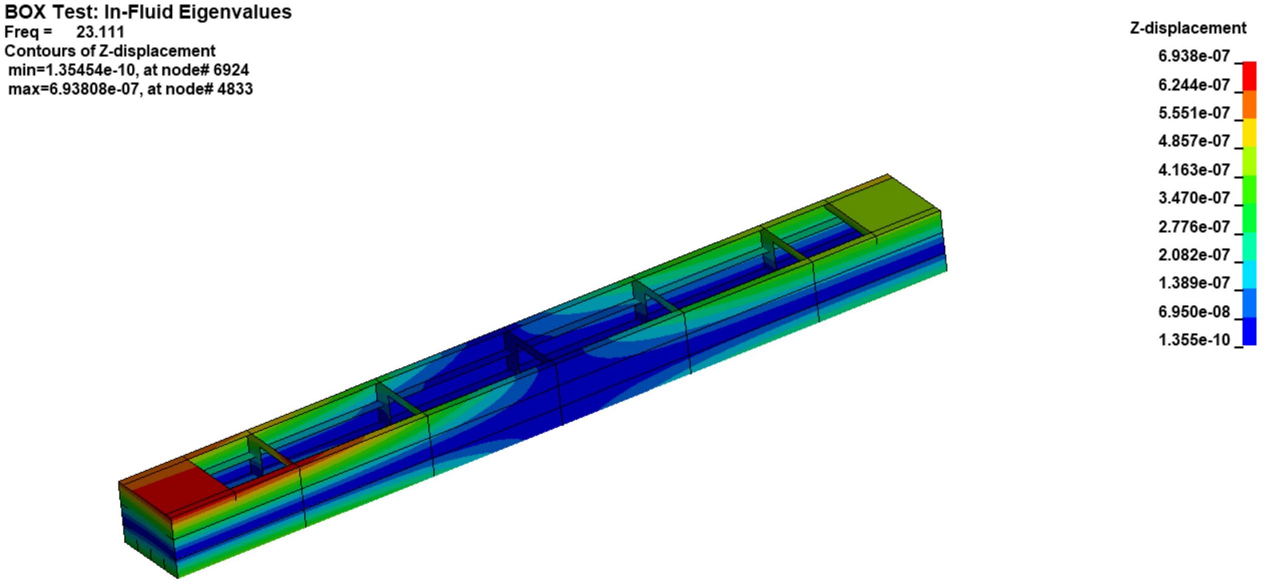
MODE	EIGENVALUE	RADIANS	CYCLES	PERIOD
1	-6.813531E-07	8.254412E-04	1.313730E-04	7.611912E+03
2	-5.080949E-07	7.128077E-04	1.134469E-04	8.814698E+03
3	-3.257459E-07	5.707415E-04	9.083633E-05	1.100881E+04
4	-1.624048E-07	4.029948E-04	6.413862E-05	1.559123E+04
5	2.267889E-08	1.505951E-04	2.396796E-05	4.172237E+04
6	2.021050E-07	4.495609E-04	7.154984E-05	1.397627E+04
7	8.639868E+03	9.295089E+01	1.479359E+01	6.759683E-02
8	2.569706E+04	1.603030E+02	2.551302E+01	3.919568E-02
9	3.217782E+04	1.793818E+02	2.854950E+01	3.502689E-02
10	1.150649E+05	3.392122E+02	5.398730E+01	1.852287E-02
11	1.710070E+05	4.135299E+02	6.581533E+01	1.519403E-02
12	2.772423E+05	5.265381E+02	8.380113E+01	1.193301E-02
13	3.117946E+05	5.583857E+02	8.886984E+01	1.125241E-02
14	3.271852E+05	5.720010E+02	9.103679E+01	1.098457E-02
15	3.378103E+05	5.812145E+02	9.250317E+01	1.081044E-02
16	4.087560E+05	6.393403E+02	1.017542E+02	9.827607E-03
17	4.658400E+05	6.825248E+02	1.086272E+02	9.205798E-03
18	5.537230E+05	7.441257E+02	1.184313E+02	8.443715E-03
19	5.595943E+05	7.480603E+02	1.190575E+02	8.399303E-03
20	6.100676E+05	7.810682E+02	1.243109E+02	8.044349E-03

Displacement response from SSD (d3ssd)

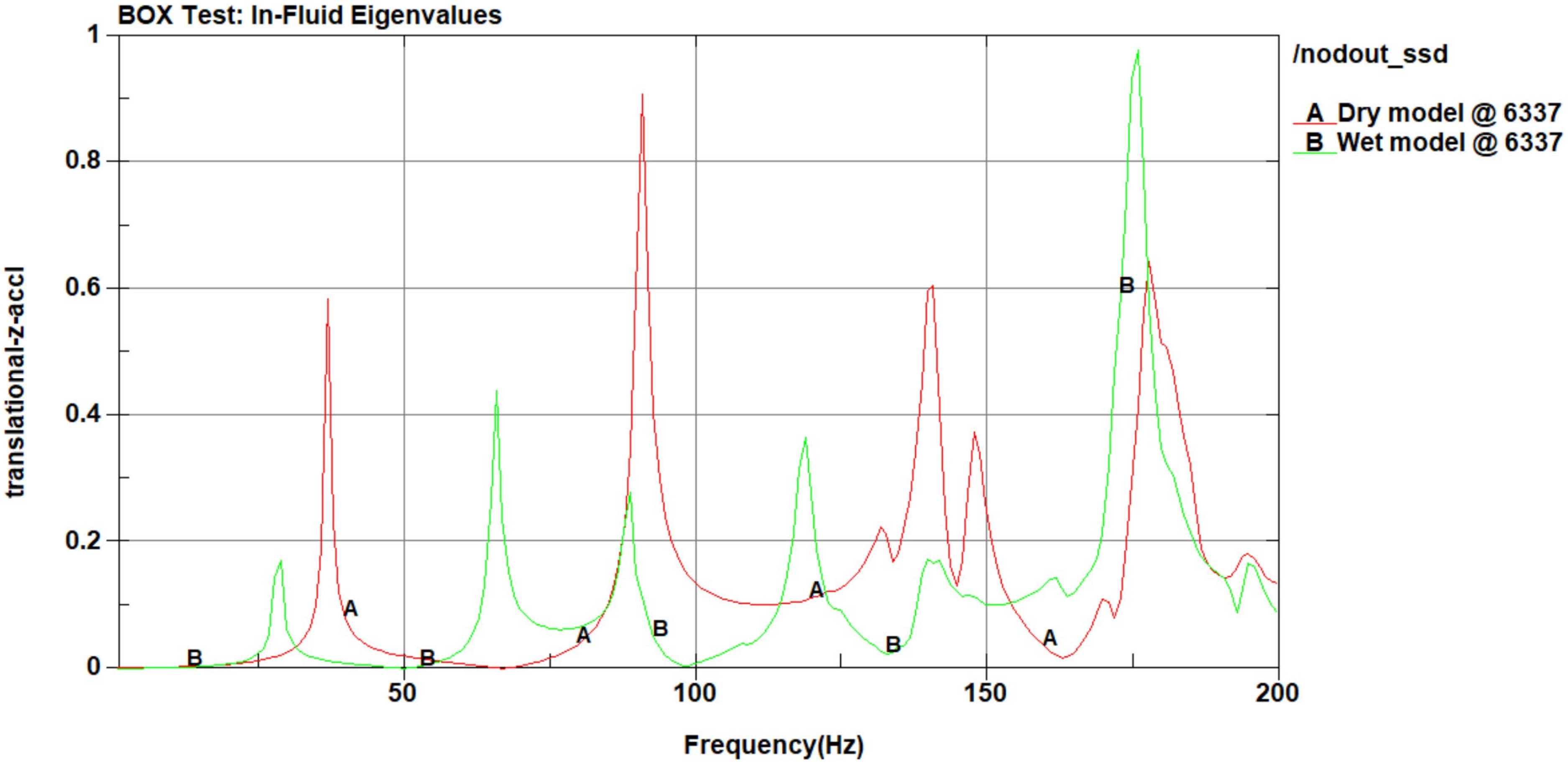
Dry mode model



Wet mode model



Displacement response from SSD (nodout_ssd)



Conclusion and future work

Conclusion and future work

- The strategy for the solution of structural vibration with incompressible fluids has been fully successful:
  - Boundary element (BE) modeling is inherently efficient, requiring a minimum of time and effort to develop the mesh – the mesh is simply the faces of the wetted surfaces;
  - The block low rank (BLR) implementation of the governing integral equation for incompressible fluid mass results in acceptable CPU time and memory resource usage;
  - The use of the LOBPCG eigen-solver and the inclusion of the added mass in expanded form leads to dramatic reductions in both the CPU time and the memory required for the eigen-solution.
  - Finally, the integration with existing time and frequency domain vibration solvers is smooth.
- The next steps in this effort are:
  - Complete the BE implementation for internal fluids, including very low frequency sloshing behavior;
  - Extend the BE added mass implementation to the HPC/MPP environment.
- The LOBPCG eigen-solver, especially in this context, is relatively new.
  - Additional models for testing would be helpful (especially realistic and large-scale models).

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