

Response Spectrum Analysis and DDAM Analysis in LS-DYNA[®]

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Abstract

*Response spectrum analysis (keyword *FREQUENCY_DOMAIN_RESPONSE_SPECTRUM) evaluates the peak response of structures subjected to various loads like ground motions in an earthquake. It combines contribution from each vibration mode of the structures. This feature has important application in Civil and hydraulic engineering, where seismic analysis is critical to the design and safety evaluation of the large scale buildings.*

*DDAM (Dynamic Design Analysis Method) is a U.S. Navy-developed analytical procedure for shock design. It helps validate the design of onboard equipment and structures subject to dynamic loading caused by underwater explosions (UNDEX). It is a widely accepted procedure for safety evaluation for civil and military ship building. The keyword for response spectrum analysis (*FREQUENCY_DOMAIN_RESPONSE_SPECTRUM) in LS-DYNA has been extended to run DDAM analysis for shipboard components, with the option _DDAM.*

This paper first gives a brief review of the theory for response spectrum analysis and DDAM analysis. Then, with several examples, this paper shows how to run response spectrum analysis and DDAM analysis with LS-DYNA and how to perform post-processing of the results. For purpose of cross-validation, the results of DDAM analysis with LS-DYNA are compared with that given by other commercial code.

Introduction

Response spectrum analysis (*FREQUENCY_DOMAIN_RESPONSE_SPECTRUM) has been implemented to LS-DYNA since R7 of LS971. It was extended to Dynamic Design Analysis Method since R10. DDAM Dynamic Design Analysis Method (DDAM) is a U.S. Navy standard procedure that has been used for over 30 years for shock design. One can use DDAM to analyze the response of the shipboard equipment, such as antenna, radar, engines, and other critical structures, due to underwater explosions. All mission-essential equipment on board surface ships and submarines must be designed to operate under severe conditions of shock loading, such as from depth charges, explosion of mines, missiles, and torpedoes.

With the fixed structure moving in water, the shock spectrum experienced by the shipboard equipment is higher than that the same equipment fixed on ground would experience. This change in spectrum is called as the spectrum-dip effect, which is similar to soil-structure interaction under earthquake excitation. The interaction between the equipment under shock loading and its fixed structure can be modeled by DDAM. The coefficients included in the load spectrum equation for DDAM analysis allow also for the influence of equipment mounting location and shock direction.

To run DDAM analysis, the first step is to extract natural frequencies and normal modes of the equipment. Then the modal effective mass in each direction (x, y and z) are calculated. After that, DDAM analysis is performed using an input acceleration spectrum of shock design values. The input spectrum values are provided based on equations provided in unclassified U.S. Navy standard documents (NRL Report 1396), for pre-determined mounting location / load direction / material type, etc., together with the modal weight of the equipment.

Alternatively, engineers can use customized equations to define the input shock spectrum, based on user-defined coefficients. Those coefficients can be defined for an alternate unit system or obtained from field testing. NRL (Naval Research Laboratories) sum method is then used to combine the peak responses from all modes into overall response which includes displacements, velocities, accelerations, stresses and strains. After that, evaluation of the DDAM results, in correlation to design standards, or material failure criterion etc., is performed.

There are some limitations on DDAM analysis. First, it is a linear analysis. In other words, some nonlinear behavior or deformation cannot be captured explicitly. Secondly, the available DDAM-NRL coefficients are old and not convenient for new type of the ships and warfare. In addition, those coefficients don't consider the size variation of ships. For example, response of the same device on an aircraft carrier and on a small frigate under same shock load should be different. Understanding the limitations of DDAM analysis is necessary for engineers who need to run shock analysis. However, up to today, DDAM is still the most convenient and efficient method for shock analysis of onboard equipment.

Since the implementation of response spectrum analysis into LS-DYNA, LS-DYNA has been used to run the DDAM analysis, based on users' in house script [1] or pre-defined load spectrum. To make the DDAM analysis more convenient, a `_DDAM` option is added to the keyword `*FREQUENCY_DOMAIN_RESPONSE_SPECTRUM`. With this new option, users can run DDAM analysis with LS-DYNA directly.

Shock spectrum definition

The DDAM SDV (Shock Design Values) is an acceleration spectrum defined in terms of g (gravity acceleration). According to NRL-1396 standard, the following factors are considered to define the SDV

- Type of Ship
 - Surface
 - Submarine
- Mounting location
 - Hull mounted system
 - Deck mounted system
 - shell plating mounted system
- Direction of shock load or attack
 - Vertical
 - Athwartship
 - Fore and aft
- Material type
 - Elastic
 - Elastic-plastic

For example, for a hull mounted device on a surface ship, NRL-1396 [2] provides the following reference equations:

$$A_0 = 20 \left[\frac{(37.5 + \bar{W}_a)(12 + \bar{W}_a)}{(6 + \bar{W}_a)^2} \right] \quad (g) \quad (1)$$

$$V_0 = 60 \left[\frac{12 + \bar{W}_a}{6 + \bar{W}_a} \right] \quad (\text{in/sec}) \quad (2)$$

And design values

	Elastic		Elastic-Plastic	
	A _a	V _a	A _a	V _a
Vertical	1.0 A ₀	1.0 V ₀	1.0 A ₀	0.5 V ₀
Athwartship	0.4 A ₀	0.4 V ₀	0.4 A ₀	0.2 V ₀
Fore and aft	0.2 A ₀	0.2 V ₀	0.2 A ₀	0.1 V ₀

Table 1: Shock spectrum design values for surface ship, hull mounted system

Where,

$$\bar{W}_a = \frac{M_{eff} g}{1000} \quad (\text{kips}) \quad (3)$$

is the modal weight. M_{eff} is the effective modal mass, provided by implicit modal analysis (using keyword *CONTROL_IMPLICIT_EIGENVALUE in LS-DYNA).

So, one can use the modal weight (kips) computed for the mode under consideration, calculate the proper A_0 and V_0 from the reference equations (1) and (2); and then find the appropriate design values A_a and V_a using Table 1; and then multiply A_a by g (386 in/sec²) and V_a by ω_a (round frequency, $=2\pi f$); the SDV is the lesser of these two values. If a value of SDV < 2316 in/sec² (6 g) is determined by this method, the SDV of 2316 in/sec² should be used.

More reference equations and design values, for different ship types and mounting types, can be found in NRL Memorandum Report 1396 [2].

This procedure is repeated for all modes included in DDAM analysis.

LS-DYNA provides also the option to define the SDV by user directly.

For acceleration input spectrum, it is defined by

$$A = \begin{cases} A_f \times A_a \frac{(A_b + \bar{W}_a) \times (A_c + \bar{W}_a)}{(A_d + \bar{W}_a)^2} & \text{if } A_d \neq 0 \\ A_f \times A_a \frac{(A_b + \bar{W}_a)}{(A_c + \bar{W}_a)} & \text{if } A_d = 0 \end{cases} \quad (4)$$

The user defined velocity input spectrum is defined as

$$V = V_f \times V_a \frac{(V_b + \overline{W}_a)}{(V_c + \overline{W}_a)} \quad (5)$$

The parameters A_f , A_a , A_b , A_c , A_d and V_f , V_a , V_b , V_c are defined in Cards 4b.1 and 4b.2 in LS-DYNA keyword *FREQUENCY_DOMAIN_RESPONSE_SPECTRUM_DDAM.

NRL Sum method

A series of modal combination methods are available in LS-DYNA, for running response spectrum analysis with *FREQUENCY_DOMAIN_RESPONSE_SPECTRUM. They include SRSS, CQC, NRC grouping, etc. For DDAM, the standard modal combination method is NRL-sum, given as

$$R = |R_1| + \left[\sum_{i=2}^N (R_i)^2 \right]^{1/2} \quad (6)$$

The NRL-sum is a statistical estimate of the maximum response created by taking the response for the mode that exhibits the largest response and adding the SRSS response of other modes. The calculated response could be nodal displacement, velocity or acceleration or element stress / strain components, or forces. With this equation, the contribution on overall response from the mode that exhibits the largest response is emphasized.

Though R_1 is used in equation (6) for the response for the mode that exhibits the largest response, it does not suggest that that mode has to be the first mode.

Mode selection

Modal analysis is the first step for running DDAM. A careful selection of modes is critical to the application of DDAM. A well accepted criterion is that the cumulative modal weight (cumulative modal effective mass) of all modes involved in the shock spectrum must be greater than 80%, in each direction. If not, more normal modes should be included.

Closely spaced modes

Modes are close if their frequencies are within 10% of the mean frequency. Once each CSM pair combination is determined, it is used in the NRL-sum as a single effective mode.

LS-DYNA can identify the closely spaced modes automatically. Alternatively, user can pre-define the closely spaced modes pairs using the keyword *SET_MODE. If the closely spaced modes are defined by a set ID, additional card (Card 5) is required to input the set ID (sid) for the series of closely spaced mode pairs. For more details about the keyword, please refer to LS-DYNA Keyword Users' Manual [3].

LS-DYNA keywords

To run DDAM analysis, the keyword `*FREQUENCY_DOMAIN_RESPONSE_SPECTRUM_DDAM` is used. Besides, to get the binary plot database `d3spcm` from DDAM, user needs to define the keyword `*DATABASE_FREQUENCY_BINARY_D3SPCM` and set `binary=1` in this keyword. A sample for these keywords is given in Figure 1.

```

*CONTROL_IMPLICIT_GENERAL
$#  imflag      dt0      imform      nsbs      igs      cnstn      form      zero_v
      1      1.0000      0
*CONTROL_IMPLICIT_EIGENVALUE
$#  neig      center      lflag      lftend      rflag      rhtend      eigmth      shfscl
      30      .0
$#  isolid      ibeam      ishell      itshell      mstres      evdump
      1
*FREQUENCY_DOMAIN_RESPONSE_SPECTRUM_DDAM
$#  mdmin      mdmax      fnmin      fnmax      restrt      mcomb      relatv
      1      30      0.      5000.      4
$#  dampf      lcdamp      ldtyp      dmpmas      dmpstf
$#  std      unit      amin      vid      xc      yc      zc
      1      4      6      1
$#  shptyp      mount      movemt      mattyp
      2      1      3      1
*DATABASE_FREQUENCY_BINARY_D3SPCM
$#  binary
      1

```

Figure 1: Sample keyword setting for running DDAM

Additional keyword `*CONTROL_IMPLICIT_EIGENVALUE` is also needed, to provide natural frequencies and modal shape vectors for the structure under study. The natural frequencies and modal shape vectors are saved in `d3eigv` binary database, which can be accessed by LS-PrePost®. Another keyword `*CONTROL_IMPLICIT_GENERAL` is also needed to activate implicit analysis in LS-DYNA.

As shown in Figure 1, the parameters `mdmin` and `mdmax` pair (or `fnmin` and `fnmax` pair) in card 1 in `*FREQUENCY_DOMAIN_RESPONSE_SPECTRUM_DDAM` define the range of modes to be used in DDAM analysis. The parameter `restrt` defines restart option. When modal analysis was already done before, and `eigout` and `d3eigv` files are available, one can set `restrt = 1` to skip modal analysis in current DDAM computation. LS-DYNA can read `eigout` and `d3eigv` to extract the cumulative effective mass data, and eigen frequencies and eigenvectors. The card for damping (card 2) is not needed for DDAM analysis and should be blank. In card 3, `unit = 4` means that the unit system [lb, inch, second, lbf and psi] is used. When other units are used, user needs to tell LS-DYNA which set of unit system is used by setting `unit` appropriately (please refer to LS-DYNA Keyword Users' Manual [3] for more details). The equations (1) and (2) for defining the SDV are based on using [g] as unit for acceleration and [inch/s] as unit for velocity. So some unit conversion is needed and carried out in LS-DYNA to convert the SDV to values using acceleration or velocity units consistent with other variables.

With this keyword, we are running DDAM analysis using NRL-1396 design spectrum standard for shock load (`std = 1`). The DDAM analysis is performed on an elastic (`mattyp = 1`) part which is constrained in a surface ship (`shptyp = 2`) using Hull mounted system (`mount = 1`). The shock load is in Fore and Aft direction (`movemt = 3`).

This setting is equivalent to the following setting using user defined spectrum option (`std = -1`).

```

*CONTROL_IMPLICIT_GENERAL
$#  imflag      dt0      imform      nsbs      igs      cnstn      form      zero_v
      1      1.0000      0
*CONTROL_IMPLICIT_EIGENVALUE
$#  neig      center      lflag      lftend      rflag      rhtend      eigmth      shfscl
      30      .0
$#  isolid      ibeam      ishell      itshell      mstres      evdump
      1
*FREQUENCY_DOMAIN_RESPONSE_SPECTRUM_DDAM
$#  mdmin      mdmax      fnmin      fnmax      restrt      mcomb      relatv
      1      30      0.      5000.
$#  dampf      lcdamp      ldtyp      dmpmas      dmpstf
      1
$#  std      unit      amin      vid      xc      yc      zc
      -1      4      6      1
$#  af      aa      ab      ac      ad
      0.2      20.      37.5      12.      6.
$#  vf      va      vb      vc
      0.2      60.      12.      6.
*DATABASE_FREQUENCY_BINARY_D3SPCM
$#  binary
      1

```

Figure 2: Sample keyword setting for running DDAM with user defined constants for SDV

The parameters af, aa, ab, ac, ad, vf, va, vb, and vc come from equations (1) and (2) and table 1. More details about the parameters of the keywords can be found in LS-DYNA Users' Keyword Manual [2].

Postprocessing of DDAM results

The results of DDAM analysis are saved in binary plot database d3spcm, as other response spectrum analysis (*FREQUENCY_DOMAIN_RESPONSE_SPECTRUM). To get d3spcm, one needs to set binary = 1 in *DATABASE_FREQUENCY_BINARY_D3SPCM.

This database is accessible to LS-PrePost (version 4.0 and above). There is only one state in this database, which shows the peak values of response due to the shock loading. The response includes nodal displacement, velocity, acceleration, and elements' stresses and strains, as shown in Figure 3.

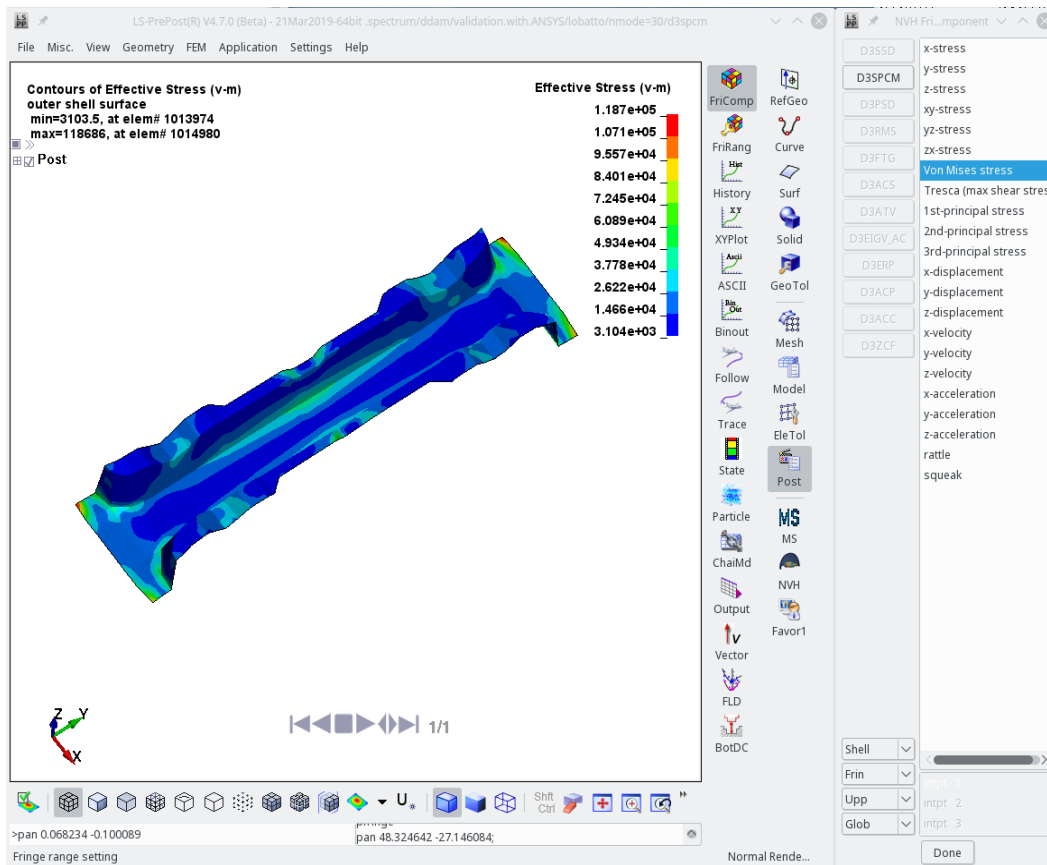


Figure 3: Fringe components of d3spsm, as shown in LS-PrePost

Examples

A benchmark example for a bracket model

A bracket model shown in Figure 4 is adopted for cross-validation of DDAM analysis by LS-DYNA and by third party commercial software - ANSYS. The ANSYS DDAM results were provided by a customer.

The LS-DYNA keyword setting for this model is shown in Figure 1. For this example, the SDV comes from NRL-1396 design spectrum standard ($\text{std} = 1$). The bracket model is elastic ($\text{mattyp} = 1$), and it is fixed on a surface ship ($\text{shptyp} = 2$) using Hull mounted system ($\text{mount} = 1$). The shock load is in Fore and Aft direction ($\text{movemt} = 3$). 30 normal modes are used in DDAM analysis, both in ANSYS and LS-DYNA.

The x-displacement results are shown in Figures 4 and 5. The Von Mises stress results are shown in Figures 6 and 7. One can see that the results given by ANSYS and by LS-DYNA not only match well in numbers, but also match in the fringe plot of the response.

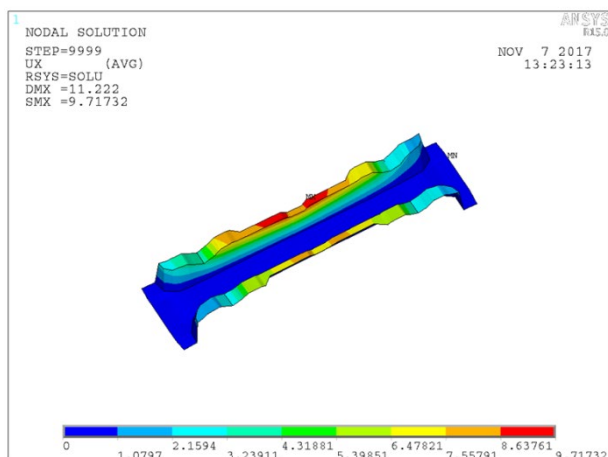


Figure 4: X-displacement by ANSYS

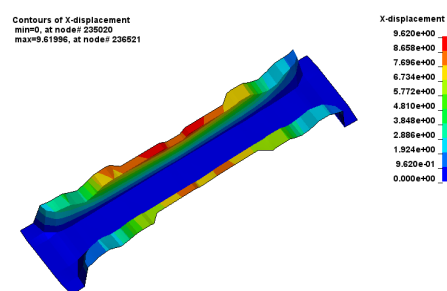


Figure 5: X-displacement by LS-DYNA

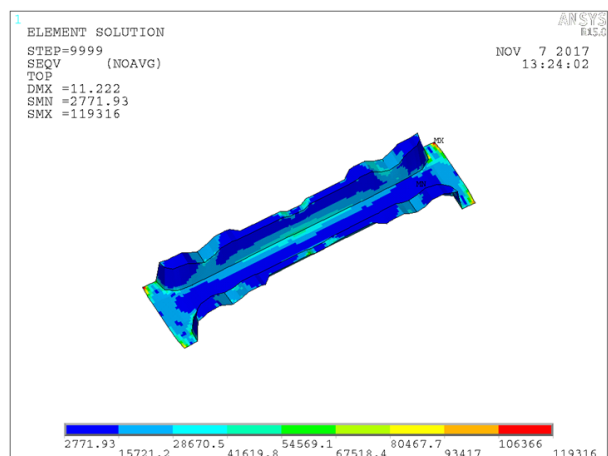


Figure 6: Von Mises stress by ANSYS

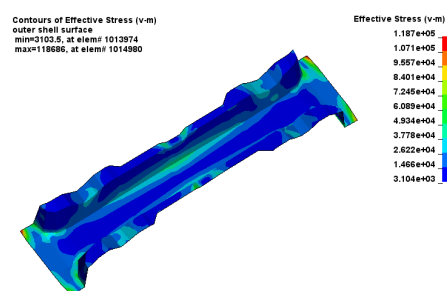


Figure 7: Von Mises stress by LS-DYNA

Table 2 below compares the maximum values of response, by ANSYS and LS-DYNA. For most items in Table 2 there is a good match between ANSYS results and LS-DYNA results.

		ANSYS	LS-DYNA	Diff (%)
Displacement (inch)	x	9.717	9.620	1.00%
	y	1.835	1.856	1.14%
	z	6.304	6.375	1.13%
Velocity (inch/s)	x	206.393	204.265	1.03%
	y	45.884	46.440	1.21%
	z	154.401	156.737	1.51%
Acceleration (inch/s ²)	x	5592.22	5571.59	0.37%
	y	2303.57	2438.19	5.84%
	z	6056.48	6306.27	4.12%
Von Mises stress (psi)		119316	118686	0.53%

Table 2: Maximum response values by ANSYS and LS-DYNA

An example of a simplified engine model

For the second example, a simplified engine model as shown in Figure 8 is considered. The engine model is deck-mounted on a surface ship (shptyp = 2, mount = 2). The shock load is in vertical direction (movemt = 1). Elastic material is used (mattyp = 1). 35 normal modes are used in DDAM analysis.

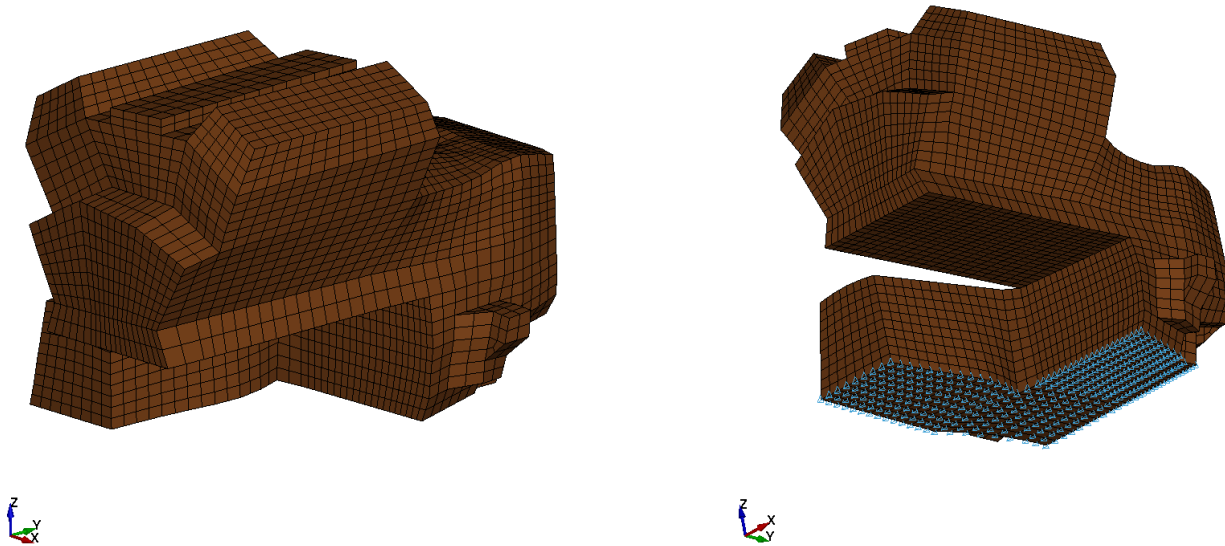
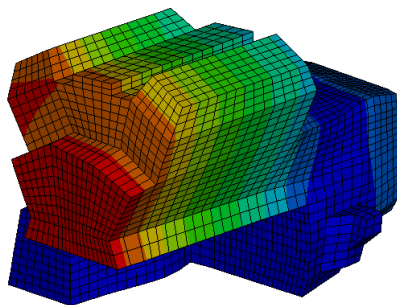


Figure 8: An engine model deck mounted on a surface ship

The DDAM analysis results on this model are given in Figures 9-12 for velocity and Von Mises stress. To study the effect of CSM (closed spaced modes), two sets of results are given. The first set of results are obtained without considering closed spaced modes and the second set of results are obtained with consideration of closed spaced modes. The pairs of closed spaced modes are identified by LS-DYNA automatically, based on the rule that two modes are close if their frequencies are within 10% of the mean frequency.

Contours of Z-velocity
min=0, at node# 2845533
max=1.34702, at node# 2846026



Z-velocity
1.347e+00
1.212e+00
1.078e+00
9.429e-01
8.082e-01
6.735e-01
5.388e-01
4.041e-01
2.694e-01
1.347e-01
0.000e+00

Contours of Z-velocity
min=0, at node# 2845533
max=1.34608, at node# 2846026

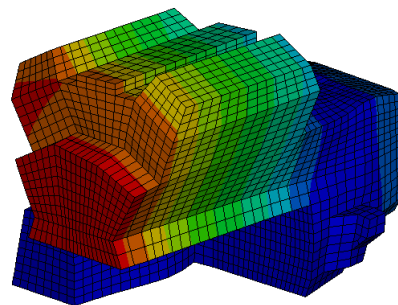
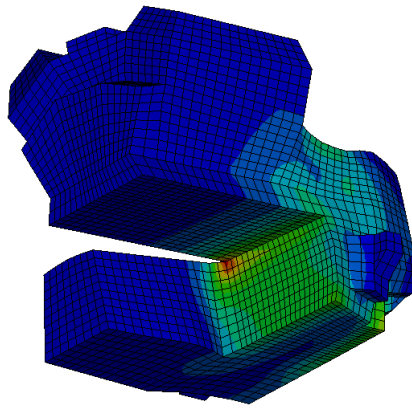


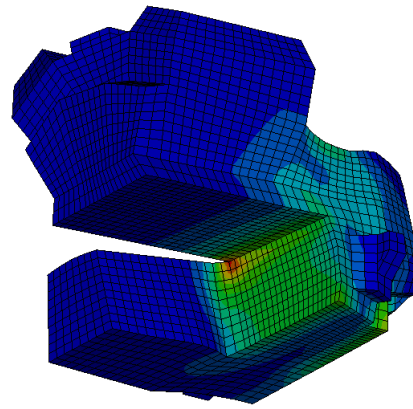
Figure 9: Z-velocity response without considering CSM Figure 10: Z-velocity response with considering CSM

Contours of Effective Stress (v-m)
min=199823, at elem# 2106780
max=1.27519e+08, at elem# 2104000



Effective Stress (v-m)
1.275e+08
1.148e+08
1.021e+08
8.932e+07
7.659e+07
6.386e+07
5.113e+07
3.840e+07
2.566e+07
1.293e+07
1.998e+05

Contours of Effective Stress (v-m)
min=141607, at elem# 2106701
max=1.21623e+08, at elem# 2104000



Effective Stress (v-m)
1.216e+08
1.095e+08
9.733e+07
8.518e+07
7.303e+07
6.088e+07
4.873e+07
3.659e+07
2.444e+07
1.229e+07
1.416e+05



Figure 11: Von Mises stress response without considering CSM



Figure 12: Von Mises stress response with considering CSM

Mode 1	Mode 2	Frequency 1 (Hz)	Frequency 2 (Hz)	closeness
1	2	161.916	183.585	6.27%
8	9	2154.123	2388.604	5.16%
10	11	2514.085	2568.140	1.06%
13	14	2900.369	2978.841	1.33%
15	16	3109.892	3235.419	1.98%
17	18	3440.616	3518.140	1.11%
20	21	3755.087	3769.748	0.19%
23	24	3998.838	4030.054	0.39%
25	26	4119.330	4185.419	0.80%
27	28	4337.447	4368.439	0.36%
29	30	4440.072	4477.796	0.42%
34	35	4885.955	4925.765	0.41%

Table 3: Closed spaced modes pairs identified by LS-DYNA

In Table 3, the values in closeness column (to show how close the two modes are in relation to their mean frequency) are computed as

$$\frac{f_2 - f_1}{f_2 + f_1} \times 100\% \quad (7)$$

For this example, it seems that there is no big difference in the response with or without considering closed spaced modes (of course, this does not have to be true for other cases). Generally speaking, without considering closed spaced modes effect, the total response could be larger.

Summary

DDAM is a standard procedure to validate the design of onboard equipment and structures subject to dynamic loading caused by underwater explosions (UNDEX). Up to today, it is still a convenient and efficient method for shock analysis.

This paper introduces the DDAM analysis feature of LS-DYNA, as an extended option for response spectrum analysis (`*FREQUENCY_DOMAIN_RESPONSE_SPECTRUM`). LS-DYNA provides flexible ways to run DDAM analysis. User can run DDAM analysis with NRL-1396 standard shock spectrum, or with customized shock spectrum with self-defined constants. Closed spaced modes can be considered in DDAM analysis.

Benchmark examples were given in the paper, to show the accuracy and reliability of the DDAM solver. Post-processing of the results by using LSTC's LS-PrePost software, is also reviewed.

References

- [1] Koehler M, McCoy W, Patel M: "Dynamic Design Analysis Method to Evaluate Shipboard Shock in LS-DYNA", Proceedings of the 15th International LS-DYNA Users' Conference, June 10-12, 2018, Dearborn, MI, USA.
- [2] O'Hara, G, Belsheim, R: "Interim design values for shock design of shipboard equipment", National Technical Information Service, 1963.
- [3] Hallquist, J. "LS-DYNA Keyword User's Manual, Volume I". LSTC, Livermore, CA, USA, 2017.