

# Development of Frequency Domain Dynamic and Acoustic Capabilities in LS-DYNA®

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## Abstract

*A set of new features for frequency domain dynamic and acoustic computation have been implemented in LS-DYNA®. They include random vibration and high-cycle fatigue analysis, frequency response functions, steady state dynamics, response spectrum analysis, and acoustic analysis based on boundary element methods or finite element methods. The objective of introducing these new features is to add capabilities to LS-DYNA® to solve frequency domain vibration and noise radiation problems. This class of problems is very common in auto and aerospace industries and many other industries.*

*The paper provides a brief introduction of the new features. Keywords for the features are introduced. Areas of applications are discussed. Some examples are given to illustrate how to use these features.*

## 1. Introduction

A set of new features for frequency domain dynamic and acoustic computation have been implemented in LS-DYNA®. The features include random vibration and fatigue analysis, frequency response function (FRF), steady state dynamics (SSD), response spectrum analysis and BEM/FEM acoustics (see Table 1). They are important numerical tools for dynamic simulation and safety and reliability analysis of structures and parts. They have been extensively used in various fields, such as NVH (Noise, Vibration and Harshness) analysis in auto industry, aerodynamics in aircraft and aerospace industries, fatigue and lifespan prediction in machinery manufacturing, seismic analysis, and acoustic design for theatres and auditoriums.

	<i>Features</i>	<i>Applications</i>
<i>Frequency domain</i>	<i>Random vibration</i>	<i>Structural vibration</i>
	<i>Random fatigue</i>	<i>Fatigue analysis, structural lifespan prediction</i>
	<i>FRF</i>	<i>Structural dynamic property, transfer function</i>
	<i>SSD</i>	<i>Structural response for steady state harmonic load</i>
	<i>Response spectrum</i>	<i>Seismic analysis, peak response prediction</i>
	<i>Acoustics (BEM/FEM)</i>	<i>Noise, acoustic panel contribution, etc.</i>

Table 1. Frequency domain features and applications

Why do we need frequency domain analysis as time domain analysis has been developed to such a highly mature stage? While it is natural and efficient to run time domain analysis for transient

problems, such as impact and crashworthiness, in some cases, frequency domain analysis is more advantageous than the traditional time domain analysis. For example, for structures subjected to periodic or harmonic loading, it may be more efficient to approach the problem in frequency domain as there might be only a few frequencies involved. For some problems such as wheels running on rough road, ocean wave loads on offshore platforms, the nature of the loads is random. The loads are usually described in non-deterministic sense such as frequency spectrum. One has to resort to random analysis in frequency domain, which solves the problem in a statistical manner.

Frequency domain analysis is also suitable for problems with extremely long load history, such as wind turbine exposed to long-term wind load and parts operated in a high-cycle fatigue environment, where it is too expensive to run a time domain analysis. Meanwhile the frequency domain analysis can reveal the dependency of the structural response to the excitation frequencies so that the resonant frequencies can be avoided in the early design phase for new structures or systems.

With the addition of the new frequency domain features, LS-DYNA<sup>®</sup>, which has been renowned for its advanced capabilities in simulating complex transient real world problems, becomes more versatile and can serve as a competitive candidate for tackling even more challenging engineering problems in wider areas.

The frequency domain dynamic features (random vibration, random fatigue, FRF, SSD and response spectrum) are based on the results of modal analysis of the structures, e.g. the natural frequencies and modal shapes. They use either mode superposition method, or mode acceleration method or some other modal combination methods. Thus one needs to run implicit eigenvalue analysis preceding the frequency domain dynamic analysis. As usual, double precision executables are suggested to run the implicit analysis. The unknown variables in the equation system are modal coefficients instead of the physical variables. As the number of modes involved in the solution is usually much less than the number of physical degree of freedom, the frequency domain approach is more efficient than the direct time domain approach.

If stress results are requested in the analysis, modal stress output is required when running the implicit eigenvalue analysis. Linear element formulation is suggested to retrieve the modal stress output.

The frequency domain analysis results are given as binary plot files and ASCII database files, which are accessible by the post-processing software LS-PREPOST<sup>®</sup>.

The new keywords for the frequency domain dynamic and acoustic computation include

- \*FREQUENCY\_DOMAIN\_RANDOM\_VIBRATION\_{FATIGUE}**
- \*FREQUENCY\_DOMAIN\_FRF**
- \*FREQUENCY\_DOMAIN\_SSD**
- \*FREQUENCY\_DOMAIN\_RESPONSE\_SPECTRUM**
- \*FREQUENCY\_DOMAIN\_ACOUSTIC\_BEM\_{PANEL\_CONTRIBUTION}**
- \*FREQUENCY\_DOMAIN\_ACOUSTIC\_FEM**

They can be found in the Section \*FREQUENCY\_DOMAIN in the new release of LS-DYNA<sup>®</sup> Keyword User's Manual [1].

## **2. Random vibration and fatigue analysis**

The random vibration capability of LS-DYNA<sup>®</sup> originated from Boeing's in-house vibro-acoustic code N-FEARA. This feature computes the dynamic response of structures exposed to vibration or structural-acoustic coupling based on a known source. Various excitations and acoustic environments can be considered, including base excitations, correlated or non-correlated acoustic waves such as plane wave, progressive wave, reverberant wave, turbulent boundary layer, etc. The coupling between the structures (represented by the modal shapes) and the acoustic excitations is expressed through the concept of joint acceptance. The input spectrum can be given in terms of PSD for mechanical or acoustic pressure waves, or SPL for acoustic pressure waves. Here, PSD stands for Power Spectral Density and it displays the mean square amplitude of each sinusoidal wave with respect to its frequency. It is a function to describe how the energy or power of a signal is distributed across frequency. SPL stands for Sound Pressure Level and is the sound pressure measured in a decibel scale. The results include PSD of the nodal displacements, velocities, accelerations and element stresses, which are printed in the binary file d3psd, and RMS (Root Mean Square) of those variables, which are printed in the binary files d3rms. Both d3psd and d3rms are accessible by LS-PREPOST<sup>®</sup>.

The solution is based on modal superposition method or modal acceleration method. If a preload due to static pressure or temperature change is presumed, intermittent modal analysis is performed to incorporate the consideration of these preload effects on structural response. A restart option is provided in case the user has run modal analysis elsewhere and has the d3eigv family files in the working directory. In this case, the modal analysis is skipped and LS-DYNA<sup>®</sup> reads the d3eigv files directly to get the modal information. For the case of base acceleration, e.g. in the shaker table experiment, user can choose if absolute or relative results are requested. A unit conversion option is also provided as the acceleration load for many industry problems are defined in terms of "G" (gravity acceleration), instead of the compatible units ( $[\text{length}]/[\text{time}]^2$ ) used by LS-DYNA<sup>®</sup> by default.

This feature has been extended to random vibration or high-cycle fatigue analysis by LSTC, based on knowledge of material's S-N fatigue curve and Miner's cumulative fatigue damage rule. For random fatigue analysis, a binary plot file d3ftg, which is accessible by LS-PREPOST<sup>®</sup>, is created to show fringe level of cumulative damage ratio, or expected remaining life-cycle for the structure. User can choose parts or set of elements for running fatigue analysis, e.g. user may run fatigue analysis for only the "dangerous" elements which have high risk of failure.

The keyword to activate the random vibration (and fatigue) analysis is

**\* FREQUENCY\_DOMAIN\_RANDOM\_VIBRATION\_{FATIGUE}.**

A sample problem can be found in Figure 1. The structure is composed of 1972 nodes and 1865 shell elements. The material property of 1045 steel is adopted. The structure is subjected to base acceleration  $2G^2/\text{Hz}$  for the range of frequency 100-2000 Hz. Constant modal damping ratio 0.03 is adopted. The first 15 natural modes are employed in the modal superposition. Figure 1 (a) provides contour plot of the RMS of the Von-Mises stress; Figure 1 (b) provides the contour plot of the cumulative damage ratio for the structure with the exposure time of 4 hours.

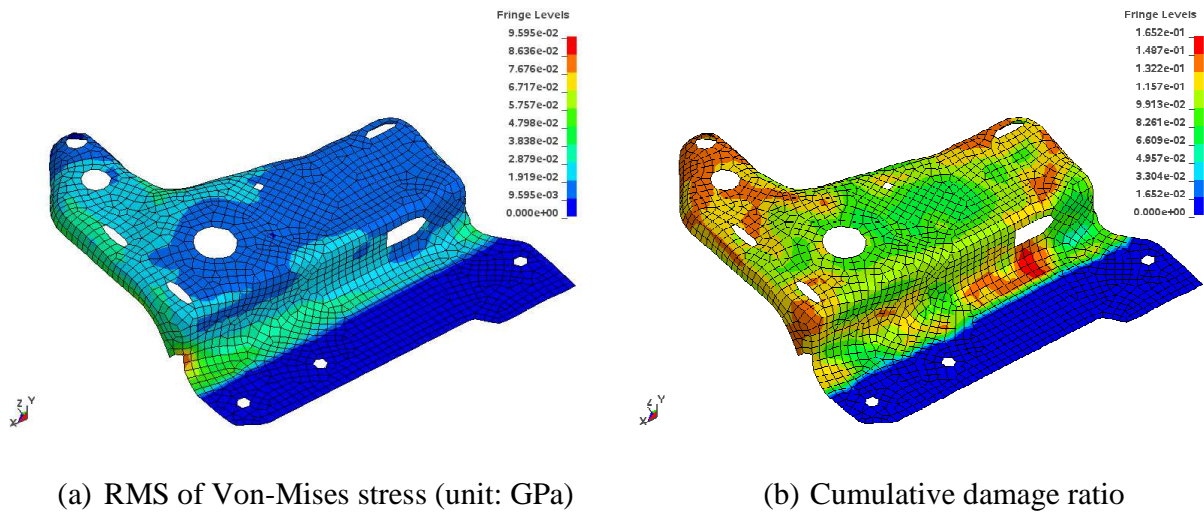


Figure 1. Random vibration and fatigue analysis of a panel structure

The S-N fatigue curve used in the analysis can be found in Figure 2.

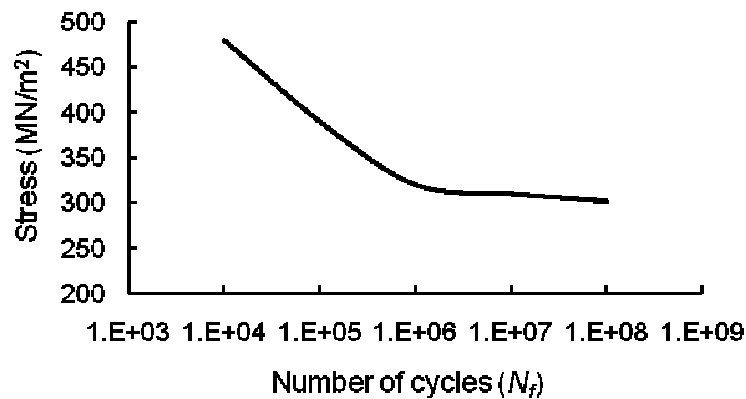


Figure 2. S-N fatigue curve for 1045 steel

The random vibration solver has been extended to MPP version and a good scalability can be achieved. The second example under consideration is a small satellite model that is required to pass a PSD analysis. The model is shown in Figure 3. It has 800k nodes and 660k elements. Rigid links are used to model bolted connections, transfer the base excitation into the satellite's launch vehicle adapter and to suspend a 150 kg instrumentation package. The total mass of the satellite is 270 kg. The panels of the model are built up using a combination of 8-node bricks for the interior ribs and shell elements for the exterior skins. The launch vehicle adapter at the base is all 8-node bricks. The satellite was given a standard PSD spectrum from 20 to 2,000 Hz. To study the scalability of the MPP solver, 1, 2, 4, 8, 16, 32, 48 and 64 processors were used in the computation. Two cases with 100 and 1000 vibration modes involved respectively were considered. The CPU times for the two cases are plotted in Figure 4. The tests were performed on clusters with Intel Xeon CPU (2.66GHz). This example shows that with the MPP implementation, LS-DYNA<sup>®</sup> has the capability to solve large scale random vibration problems with a large number of vibration modes, with a reasonable time cost.

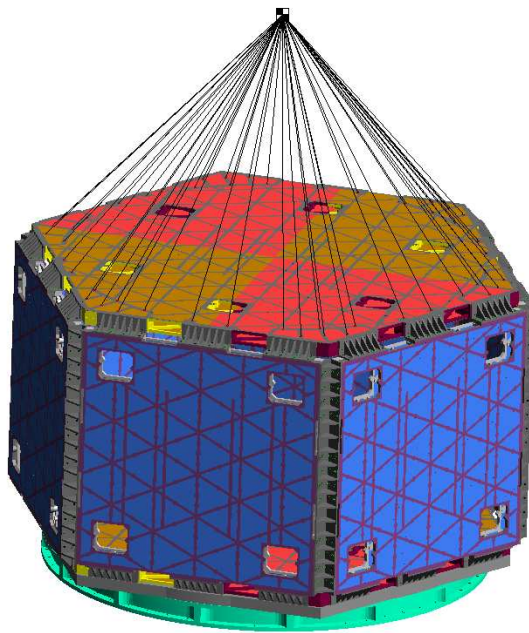


Figure 3. A satellite model

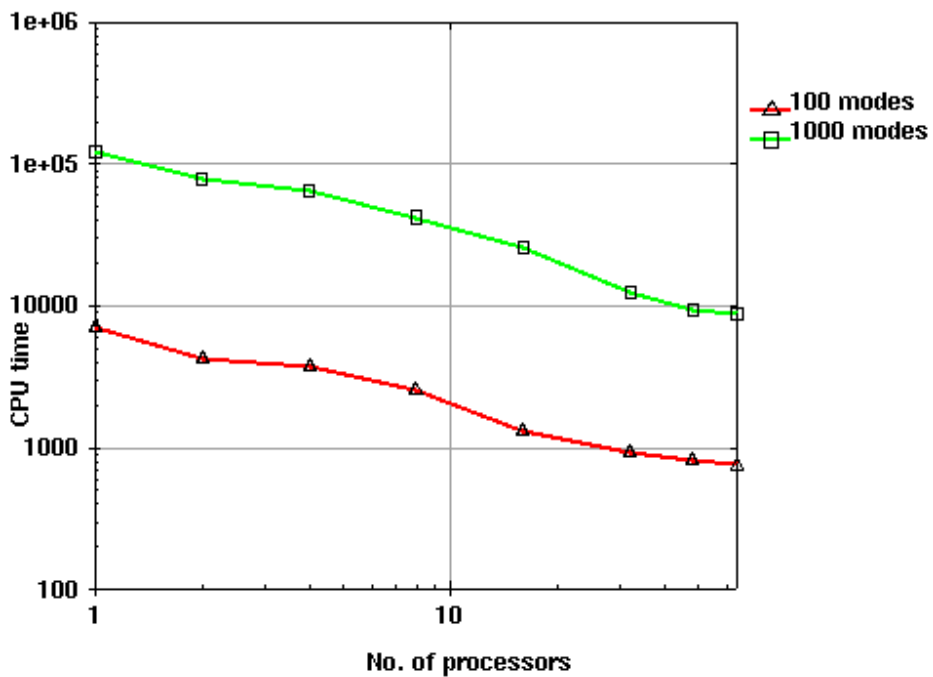


Figure 4. CPU time for different number of processors (unit: second)

For more information about the random vibration feature, please refer to the conference papers [2], [3].

### 3. Frequency response function

FRF is a characteristic of a structure that has a measured or computed response resulting from a known applied harmonic input. In other words, it is a transfer function between the excitation and response of a system. The basic formula for a FRF is

$$H(f) = \frac{X(f)}{F(f)} \quad (1)$$

Where  $F(f)$  is the input to the system in frequency domain and  $X(f)$  is the output of the system in frequency domain.

With the implementation of the FRF feature, LS-DYNA<sup>®</sup> provides user the opportunity to acquire a spectrum of structural response (displacement, velocity and acceleration) for applied unit harmonic excitations. The harmonic excitations are given in the form of nodal force, pressure or base acceleration, for a range of frequencies. The response can be given in terms of displacement, velocity, or acceleration. FRFs are complex functions, with real and imaginary components. They can also be expressed in the form of magnitude and phase angle pairs.

The FRF feature is activated by the keyword **\*FREQUENCY\_DOMAIN\_FRF**. Through the keyword, user provides information about the location, direction, range of frequencies for the harmonic excitation, and the location where the response is requested. Damping information is also provided in the keyword input. Damping can be given as constant or mode dependent damping ratio, or Rayleigh damping. The location of the excitation and response area can be given as node, or set of nodes, or set of segments. The direction of load can be in any of the x, y, z directions or given as a vector by using **\*DEFINE\_VECTOR**. The results are given as ASCII files `frf_amplitude` and `frf_angle`, which can be plotted as xy-curves with LS-PREPOST<sup>®</sup>.

For more information about the FRF and its implementation in LS-DYNA<sup>®</sup>, please refer to the papers [4], [5] and [6].

#### 4. Steady state dynamics

The SSD feature is an extension of FRF function. It calculates the steady state response of a structure subjected to known harmonic excitations. The excitation spectrum can be given as nodal force, pressure or base accelerations. The excitation spectrum takes complex variable input. In other words, both the amplitude and the phase angle of the excitation are considered.

The SSD feature can be activated by the keyword **\*FREQUENCY\_DOMAIN\_SSD**. The results are also complex and have both real and imaginary parts (or amplitude / phase angle pairs). The amplitudes of the response are given in a binary plot file `d3ssd`, which is accessible by LS-PREPOST<sup>®</sup>. A complete results including the amplitude and phase angle can be found in ASCII database `NODOUT_SSD` for nodes specified in keyword **\*DATABASE\_HISTORY\_NODE**, and database `ELOUT_SSD` for elements specified in the following keywords

- \*DATABASE\_HISTORY\_SOLID**
- \*DATABASE\_HISTORY\_BEAM**
- \*DATABASE\_HISTORY\_SHELL**
- \*DATABASE\_HISTORY\_TSHELL.**

An example of SSD analysis of a rectangular is provided in the paper. A rectangular plate is subjected to enforced nodal acceleration excitation in z-direction at one end, as shown in Figure 5. The response at the other end is desired.

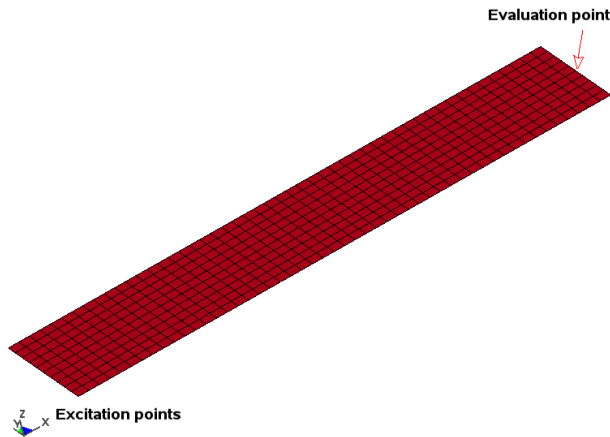


Figure 5. A rectangular plate subjected to enforced acceleration excitation

The problem was solved by two methods for the purpose of cross-validation: 1) a relative displacement method and 2) a large mass method. To use method 1), base acceleration load is assumed and body inertial force is computed and applied to the structure. To use method 2), a very large mass  $m_L$ , which is usually  $10^5$ - $10^7$  times ( $10^6$  is adopted in the paper) of the mass of the entire structure, is attached to the nodes with excitation; a very large nodal force  $p_L$  is applied to the excitation nodes to produce the desired enforced motion. The results can be found in Figure 6. It is shown that the two methods can provide almost identical results for this example.

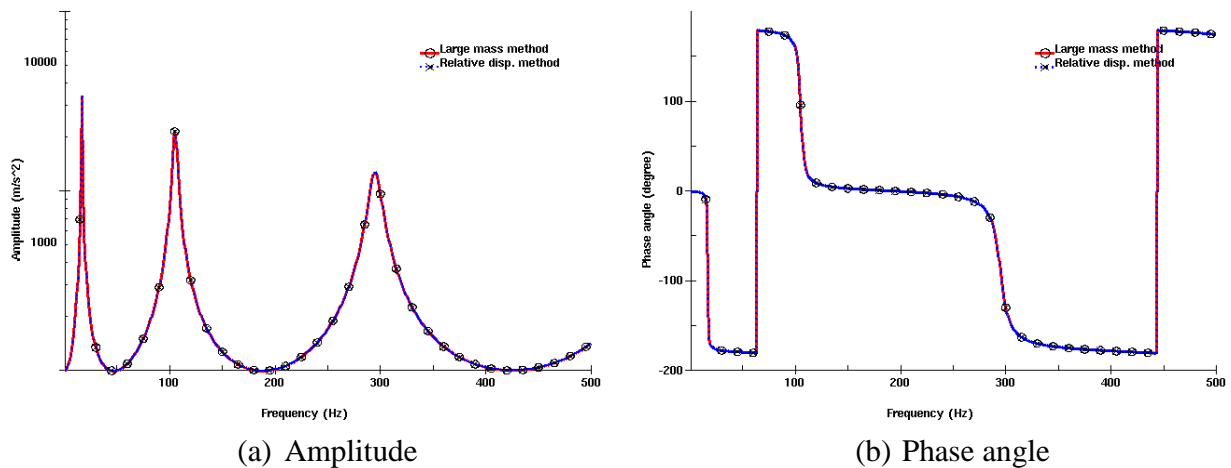


Figure 6. Response at the right end of the plate

For more information about the SSD, please refer to the conference paper [6].

## 5. Response spectrum analysis

This feature evaluates the maximum response of a structure subjected to input spectrum load, such as the acceleration, velocity or displacement spectrum load widely used in earthquake engineering. It is based on several different mode combination methods such as the Square Root

of Sum of Squares (SRSS) method, the United States Nuclear Regulatory Commission (NRC) grouping method, and the Complete Quadratic Combination (CQC) method. The results are written to a binary plot file d3spcm, which is accessible by LS-PREPOST<sup>®</sup>. Both nodal and elemental results are available. The input spectrum can be defined as a group of curves for displacement, velocity, acceleration, nodal force, or pressure spectrums, for different damping ratios.

This feature can be activated by the keyword

**\*FREQUENCY\_DOMAIN\_RESPONSE\_SPECTRUM.**

This feature can find applications in earthquake engineering and safety evaluation of buildings and constructions.

An example of response spectrum analysis of dam-foundation system is given below. The dam-foundation system is given in Figure 7. The foundation is assumed to be rigid for simplicity. The arch dam is 464.88 ft high. Elastic material is assumed for the concrete dam.

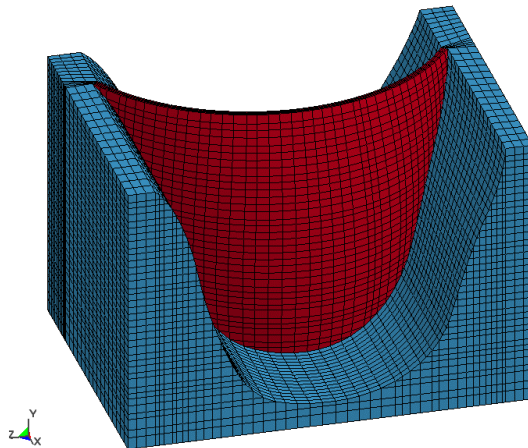


Figure 7. A dam-foundation system

The dam-foundation system is subjected to x-directional ground acceleration spectrum. The pseudo-acceleration spectrum (damping ratio  $\zeta=5\%$ ) of El Centro earthquake ground motion is used as input (see Figure 8) [7].



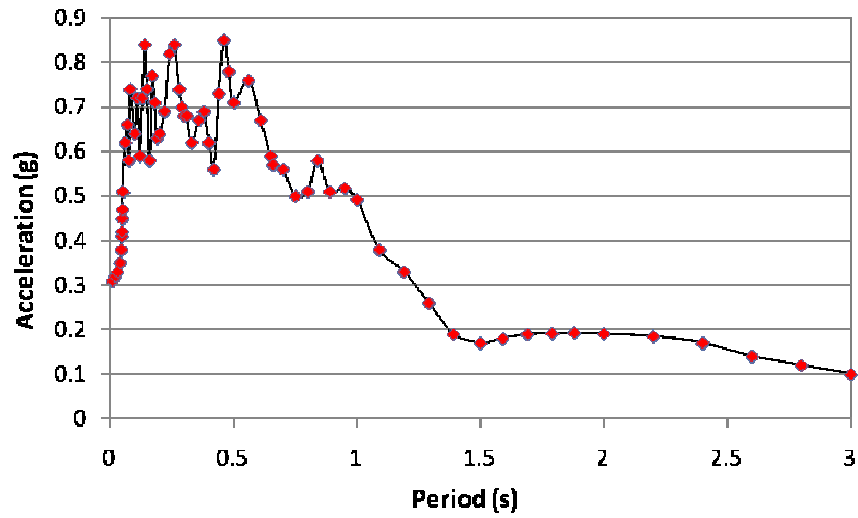


Figure 8. Pseudo-acceleration spectrum of El Centro earthquake record ( $\zeta=5\%$ )

The numerical results (see Figures 9, 10, 11) indicate that the upper and central part of the arch dam experiences larger deformation during an earthquake.

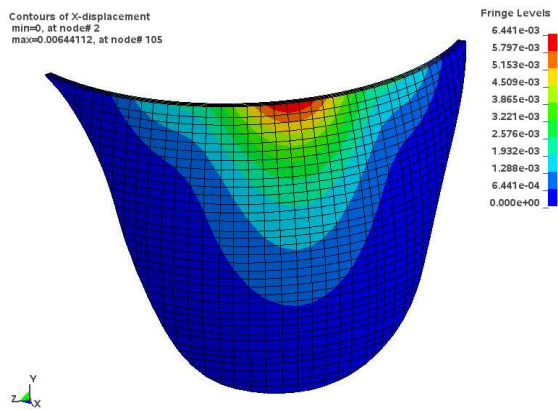


Figure 9. X-directional displacement (unit: ft)

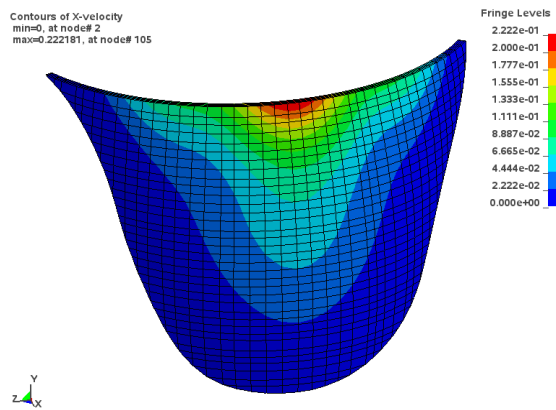


Figure 10. X-directional velocity (unit: ft/s)

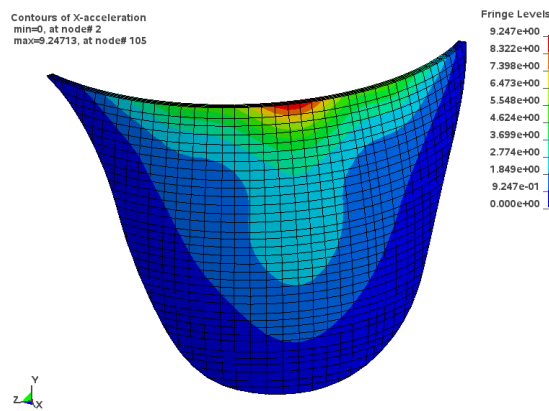


Figure 11. X-directional acceleration (Unit:  $\text{ft}^2/\text{s}^2$ )

## 6. Boundary element method for acoustics

The BEM acoustic solver is based on the solution of Helmholtz integral equation. It can be used to compute the radiated acoustic pressure (Pa) and sound pressure level (dB) for both interior and exterior problems. It has been coupled with the FEM dynamic analysis capability of LS-DYNA<sup>®</sup> to provide an integrated solution for vibro-acoustic problems. Two options are available to couple the BEM acoustic solver with the FEM dynamic analysis. For the first one, the traditional time domain FEM is performed and the time domain dynamic response of the structure is converted to frequency domain by using Fast Fourier Transform (FFT); for the second one, frequency domain steady state dynamics is performed (using **\*FREQUENCY\_DOMAIN\_SSD**) and it gives response in frequency domain directly. The obtained boundary velocities (accelerations) provide boundary condition for the subsequent BEM acoustic computation. Both the variational indirect BEM and collocation direct BEM are available in LS-DYNA<sup>®</sup>. The BEM-based acoustic solver adopts a domain decomposition technique and a low rank approximation method for solving the resulting system of equations [8]. Various preconditioners have been proposed to accelerate the iterative solution. Approximate methods such as the Rayleigh method and Kirchhoff method have also been developed to provide fast solution for cases with panel-like structures.

The BEM acoustic feature is activated by the keyword  
**\*FREQUENCY\_DOMAIN\_ACOUSTIC\_BEM.**

For the model given in Figure 5, the radiated noise at a field point which is 0.5 m above the right end of the plate is computed, using the variational BEM, based on the velocity results given by steady state dynamics computation as shown in Figure 6. The Sound Pressure Level (SPL) curve for the range of frequencies 1 Hz to 500 Hz is plotted in Figure 12. Reference pressure 20  $\mu\text{Pa}$  is adopted to convert the acoustic pressure to SPL.

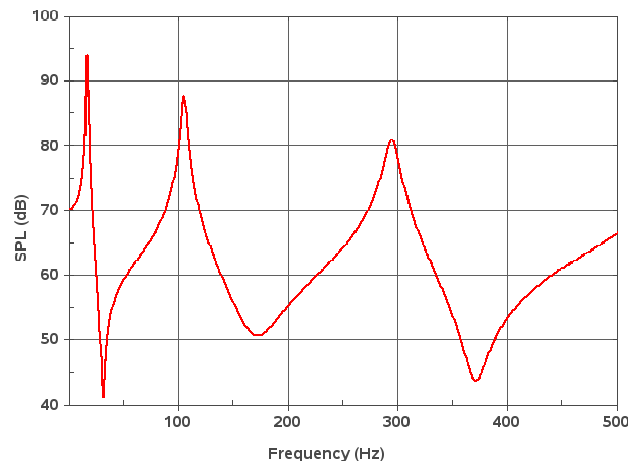


Figure 12. Sound Pressure Level at a field point above the plate

One can notice that the frequencies corresponding to the peak SPL (17 Hz, 105 Hz and 295 Hz) are also the frequencies corresponding to the peak acceleration response given by SSD (see Figure 6 (a)).

The BEM acoustic feature has been extended to provide the capability to study the acoustic panel contribution. This helps the designers to understand the noise contribution from each of the panels of a structure. Then remedies can be adopted to optimize the acoustic performance, to meet the requirements from clients, or from environmental regulations.

To study the acoustic panel contribution, the following keyword should be used

**\*FREQUENCY\_DOMAIN\_ACOUSTIC\_BEM\_PANEL\_CONTRIBUTION.**

For more information about the BEM acoustic feature, please refer to the conference papers [9] and [10].

## **7. Finite element method for acoustics**

This feature solves acoustic problems in frequency domain by finite elements. It can be used to compute the acoustic pressure (Pa) and sound pressure level (dB) for interior domain. The vibrating boundary condition can be obtained by steady state dynamics computation (**\*FREQUENCY\_DOMAIN\_SSD**), or by direct input (e.g. defining the amplitude and phase angle of the excitation spectrum by two **\*DEFINE\_CURVE**). This method is very efficient since there is only one unknown (pressure) for each node in the acoustic medium.

The keyword for running FEM for acoustics is

**\*FREQUENCY\_DOMAIN\_ACOUSTIC\_FEM.**

The possible extension of this feature is acoustic eigenvalue analysis, where the acoustic stiffness matrix is formed and eigenvalues are extracted from the stiffness matrix.

Currently only eight-node solid element is available for this method. For more information about the finite element method for acoustics, please refer to the conference paper [10].

## **8. Conclusion**

This paper introduces briefly a set of new features of LS-DYNA<sup>®</sup> for solving frequency domain vibration and acoustic problems. They include random vibration and fatigue analysis, frequency response function, steady state dynamics, response spectrum analysis and BEM/FEM acoustics. The keyword commands and application areas of the features are introduced. The input information and output files are discussed. Some examples are given to illustrate how to use these features. References are listed to provide more information about the features.

The objective of implementing these features is to provide users the capabilities to deal with frequency domain vibration and acoustic problems, which are very common in auto and aerospace industries and many other industries. The implemented features as well as upcoming developments establish LS-DYNA<sup>®</sup> as an attractive tool for this class of problems.

## **Acknowledgements**

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