

Discussion on acoustic databases in LS-DYNA[®]

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Abstract: A bunch of acoustic solvers have been provided by LS-DYNA. They include the ones based on boundary element methods (keyword ***FREQUENCY_DOMAIN_ACOUSTIC_BEM**, including the approximate methods: Rayleigh method, Kirchhoff method), finite element methods (keyword ***FREQUENCY_DOMAIN_ACOUSTIC_FEM**, and vibration solvers (ERP, equivalent radiated power, based on Steady State Dynamics, keyword ***FREQUENCY_DOMAIN_SSD_ERP**).

The acoustic solvers have been widely used in NVH, vibro-acoustic analysis and many other areas where noise level or sound quality is a concern. To perform the post-processing of the acoustic analysis with LS-DYNA, a bunch of databases have been implemented.

For fringe plot of the results, the following binary databases have been provided: D3ACS, D3ACP, D3ACC, D3ATV, D3ERP and D3EIGV_AC;

For xyplot of the results, the following ASCII databases have been provided: Press_Pa, Press_dB, Press_Pa_real, Press_Pa_imag, Press_Pa_t, Press_dB_t, Press_Power, Press_radeF, Press_dB(A), Press_dB(B), Press_dB(C), Press_dB(D) and panel_contribution_NID.

These databases have different purposes and should be used under different circumstances.

1. Introduction

Since ls971 R6 version, a series of frequency domain features of acoustic simulation have been implemented to LS-DYNA. They include the ones based on boundary element methods (keyword ***FREQUENCY_DOMAIN_ACOUSTIC_BEM**, including the approximate methods: Rayleigh method, Kirchhoff method), finite element methods (keyword ***FREQUENCY_DOMAIN_ACOUSTIC_FEM**) and vibration solvers (ERP, equivalent radiated power, based on Steady State Dynamics, keyword ***FREQUENCY_DOMAIN_SSD_ERP**). They were developed to meet requirements from users of different industries, especially those from auto NVH analysis.

A bunch of databases have been provided for the post-processing of the acoustic analysis with LS-DYNA. All these database files can be accessed by LS-PrePost. This paper gives a brief review of these databases.

2. Binary database for fringe plot

2.1 D3ACS

The binary plot file D3ACS shows the solution of frequency domain FEM acoustic computation or collocation BEM acoustic computation. The acoustic computation is activated by the keyword ***FREQUENCY_DOMAIN_ACOUSTIC_FEM** or ***FREQUENCY_DOMAIN_ACOUSTIC_BEM**.

The solution of FEM or collocation BEM acoustic computation is given as complex acoustic pressure on the nodes. For FEM acoustic analysis, the user gets the acoustic pressure in the finite element acoustic volume (including the surface); for collocation BEM acoustic analysis, the user gets the acoustic pressure on the

surface (boundary elements) of the acoustic volume. The real and imaginary parts of the pressure, the magnitude of the pressure, the sound pressure level (dB), and the normal velocity on the surface nodes are provided in D3ACS as nodal state variables for each output frequency. For collocation BEM, the acoustic intensity ($\frac{1}{2} \text{Re}\{pv^*\}$) is computed based on acoustic pressure p and normal velocity v , and is also output to D3ACS.

A cylinder model is adopted to illustrate the D3ACS database for acoustic BEM solver (figure 1). For simplicity, the cylinder is assumed to be subjected to uniform normal velocity for the whole range of frequency. Figure 2 shows the contour of sound pressure level at frequency 211.92 Hz, which is from D3ACS file.

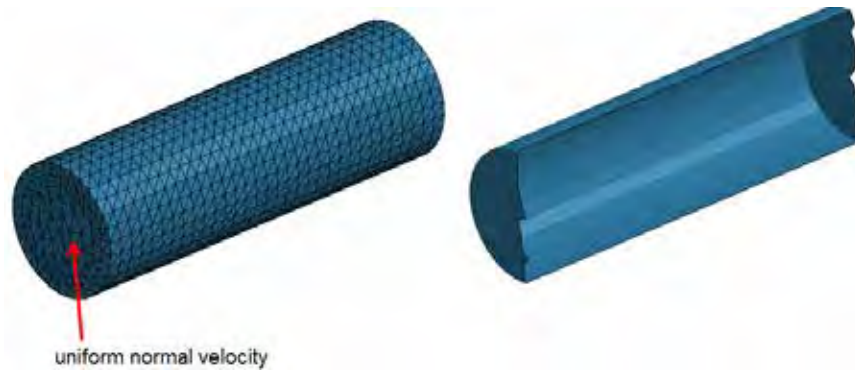


Figure 1. A cylinder BEM model



Figure 2. Sound pressure Level (dB) at frequency 211.92 Hz

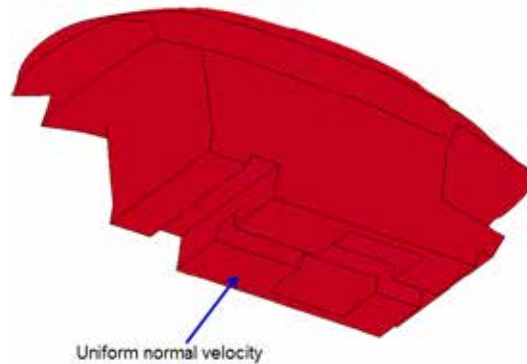


Figure 3. Simple compartment FEM model

A simple compartment model is used to illustrate the D3ACS database for acoustic FEM solver (figure 3). For simplicity, the compartment is assumed to be subjected to uniform normal velocity at the base for the whole range of frequency. Figures 4a and 4b show the contour of magnitude of sound pressure on the surface and in the acoustic volume at frequency 10 Hz, given by D3ACS file. One can see that the BEM solver gets the acoustic pressure on the surface, while the FEM solver gets acoustic pressure in the acoustic volume as well as on the surface.

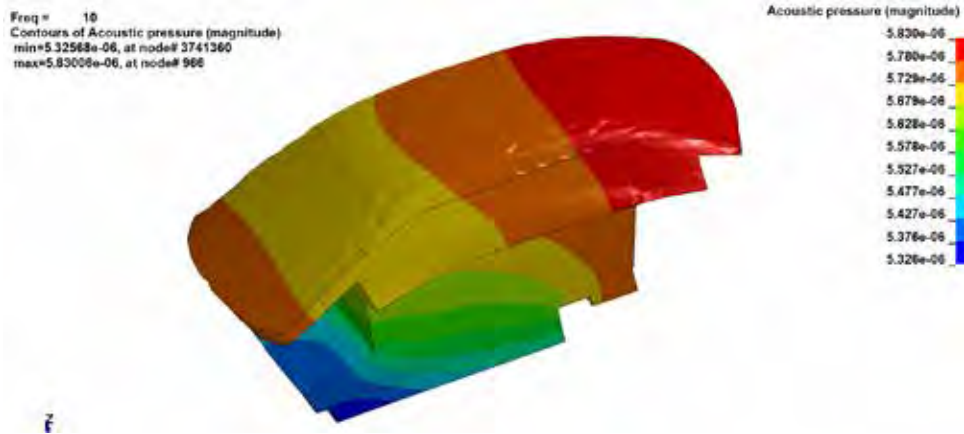


Figure 4a. Sound pressures (magnitude) on the surface at frequency 10 Hz

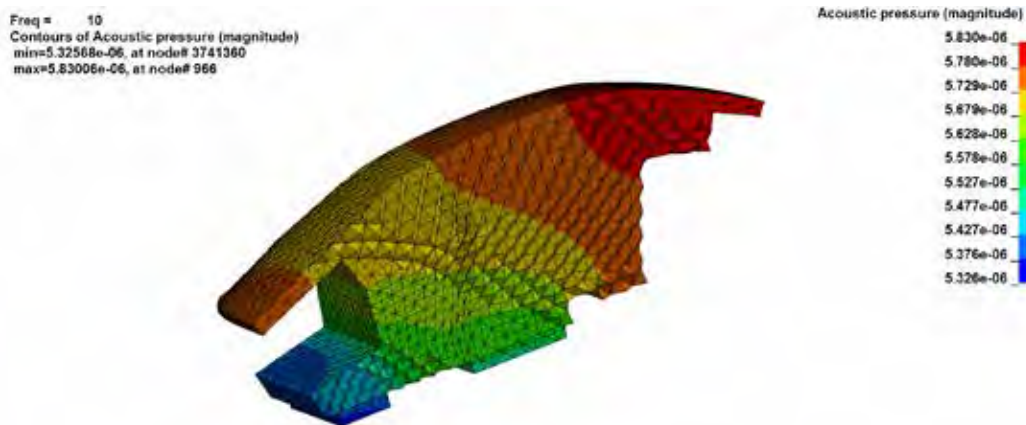


Figure 4b. Sound pressures (magnitude) in the acoustic volume at frequency 10 Hz

2.2 D3ACP

The binary plot file D3ACP shows the fringe plot of acoustic pressure at field points in BEM acoustic analysis. The field points are defined by the keyword ***FREQUENCY_DOMAIN_ACOUSTIC_FRINGE_PLOT**.

The results of acoustic analysis are given as complex acoustic pressure at the field points. The real and imaginary parts of the pressure, acoustic intensity, the magnitude of the pressure and the sound pressure level (dB) are written to D3ACP as nodal state variables for each output frequency. Acoustic intensity is computed by assuming a plane wave condition, as shown in equation (1).

$$I = \frac{1}{2} \operatorname{Re}\{pv_n^*\} = \frac{1}{2} \operatorname{Re}\left\{p \frac{p^*}{rc} \dot{y}\right\} = \frac{1}{2rc} \operatorname{Re}\{pp^*\} \quad (1)$$

Where p is the acoustic pressure (p^* is the conjugate of p), ρ is the density of acoustic medium, c is the sound speed and v_n is the normal velocity on the surface of the structure.

A simple car model is used to illustrate the D3ACP database. Figure 5 is the simple car model. Figure 6 shows the real and imaginary parts of the acoustic pressure contour at 71Hz.

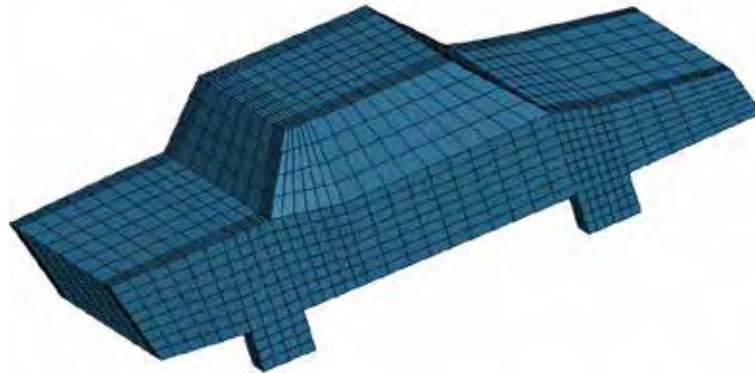


Figure 5. A simple car BEM model

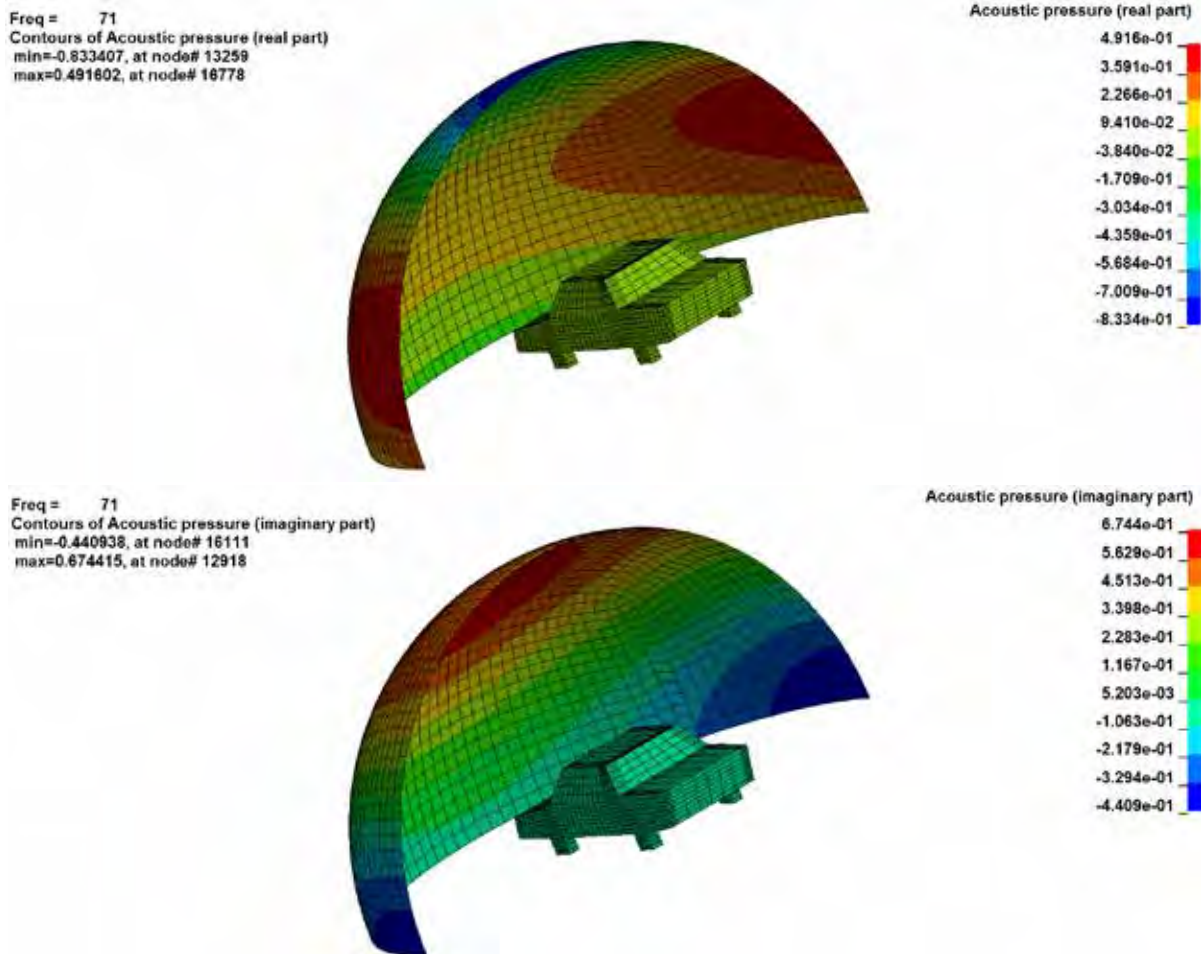


Figure 6. Real and imaginary parts of sound pressures at frequency 71 Hz

2.3 D3ACC

The binary plot file D3ACC saves element acoustic pressure contribution and contribution percentage on selected field points from a boundary element acoustic analysis. The acoustic analysis is activated by the keyword ***FREQUENCY_DOMAIN_ACOUSTIC_BEM**. The dump of this file is activated by the keyword ***DATABASE_FREQUENCY_BINARY_D3ACC**.

The idea of this contribution analysis is that according to equation (2), the acoustic pressure p at a field point P is given as a combination of the pressure p_j contributed by each of the boundary elements.

$$p(P) = \sum_{j=1}^N \frac{\partial G}{\partial n_j} \frac{\partial p_j}{\partial n_j} - p \frac{\partial G}{\partial n} = \sum_{j=1}^N p_j(P) \quad (2)$$

In equation (2), G is the acoustic fundamental solution in free space and n is the normal direction of the boundary elements.

To compute the contribution percentage of an element to the acoustic pressure at a field point, vector projection like the one shown in figure 7 is used. This is because the acoustic pressure, in frequency domain, is given as complex variables.

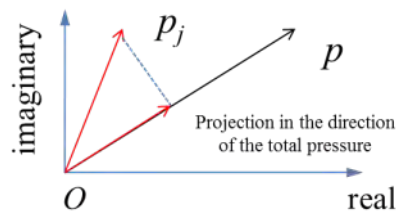


Figure 7. Computation of contribution percentage using vector projection

A simple car compartment model is used to illustrate the D3ACC database (figure 8). Figure 9 shows the real part of the element acoustic pressure contribution towards field point 100001 at frequency 300 Hz. Figure 10 shows the element contribution percentage for acoustic pressure at field point 100001 at 300 Hz. Please note, the element acoustic pressure contribution (and contribution percentage) not only vary with frequency, but also vary with field points.

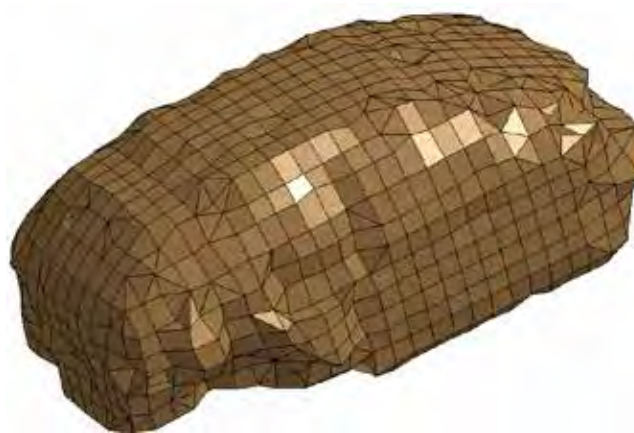


Figure 8. A simple car compartment BEM model

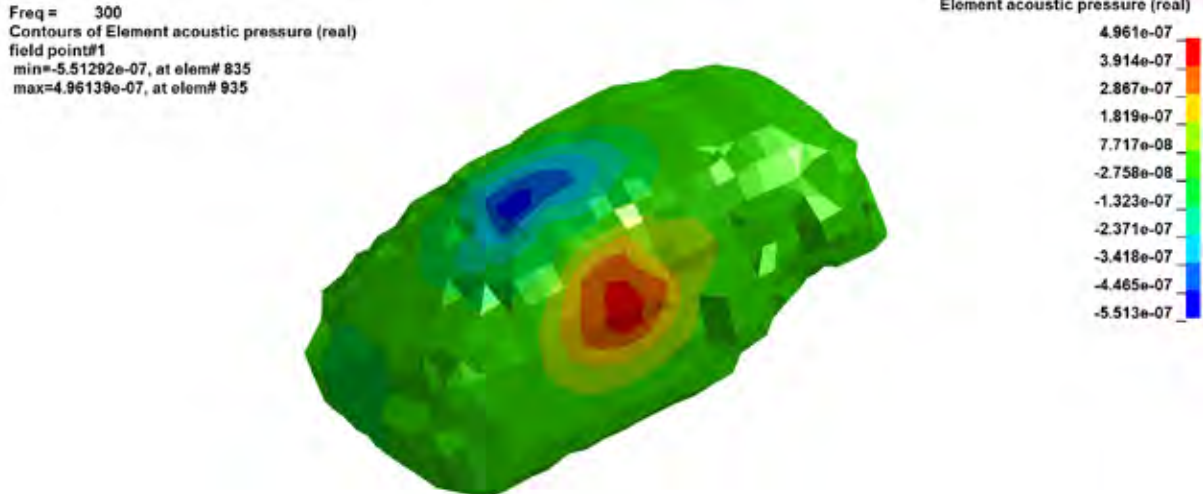


Figure 9. Real part of element acoustic pressure contribution for field point 100001 at 300 Hz

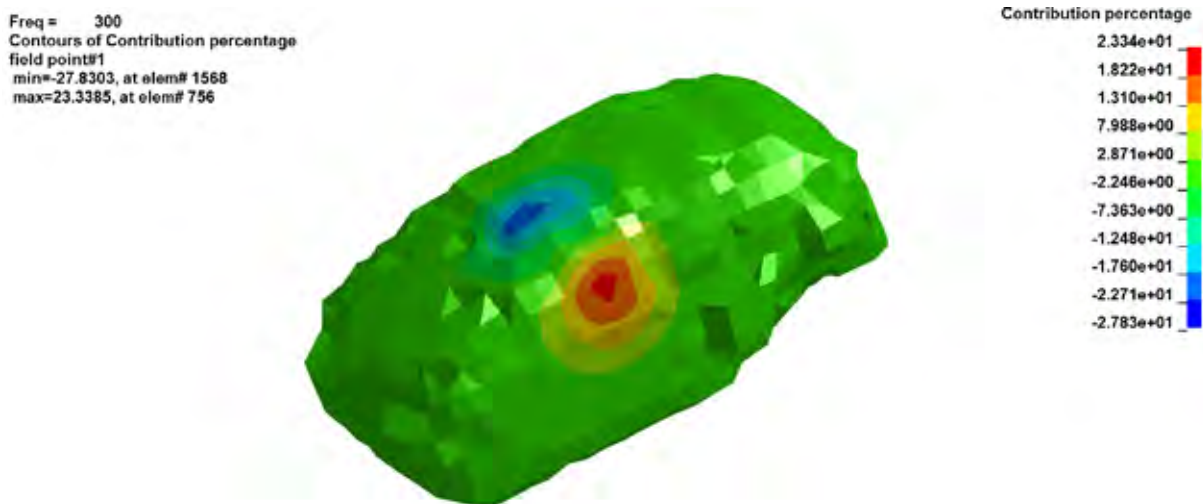


Figure 10. Element contribution percentages for acoustic pressure at field point 100001 at 300 Hz

2.4 D3ATV

The binary plot file `D3ATV` saves acoustic transfer vector results. The analysis is activated by the keyword `*FREQUENCY_DOMAIN_ACOUSTIC_BEM_ATV`.

ATV provides the acoustic pressure at field points due to unit normal velocity at each of the nodes (or elements) composing the acoustic domain surface. For each field point, for each frequency, the ATV is a complex vector with N components, where N is the total number of nodes (or elements) in acoustic boundary elements. `D3ATV` saves the real and imaginary parts of the complex pressure, and the sound pressure level (dB).

ATV is defined as the transfer function between the normal nodal (or elemental) velocity and the acoustic pressure at field points. Once all the ATV vectors are obtained, the total acoustic pressure at field points can be computed by a simple matrix – vector multiplication, as in equation (3),

$$\begin{matrix}
 \dot{p}_1 \\
 \dot{p}_2 \\
 \vdots \\
 \dot{p}_i \\
 \vdots \\
 \dot{p}_m
 \end{matrix}
 =
 \begin{matrix}
 \hat{W}_{1,1} & \hat{W}_{1,2} & \dots & \hat{W}_{1,j} & \dots & \hat{W}_{1,n} \\
 \hat{W}_{2,1} & \hat{W}_{2,2} & \dots & \hat{W}_{2,j} & \dots & \hat{W}_{2,n} \\
 \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
 \hat{W}_{i,1} & \hat{W}_{i,2} & \dots & \hat{W}_{i,j} & \dots & \hat{W}_{i,n} \\
 \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
 \hat{W}_{m,1} & \hat{W}_{m,2} & \dots & \hat{W}_{m,j} & \dots & \hat{W}_{m,n}
 \end{matrix}
 \begin{matrix}
 v_1 \\
 v_2 \\
 \vdots \\
 v_j \\
 \vdots \\
 v_n
 \end{matrix}
 \tag{3}$$

or equation (4) in short form

$$\{P\}_m = [ATV]_{m \times n} \{v\}_n \tag{4}$$

In equation (3), p_i is the acoustic pressure at field point i and v_j is the actual normal velocity at node j . m is the number of field points and n is the number of nodes (or elements) in boundary elements. $\hat{W}_{i,j}$ represents the acoustic pressure at field point i , due to unit normal velocity at node (or element) j . Please note that all the variables in equations (3) and (4) are dependent on round frequency $\omega=2\pi f$. Besides, the variables in both equations are complex.

As indicated by equation (4), for a given frequency and given geometry, the ATV matrix is constant and is not dependent on the loading condition. Once the ATV matrix is obtained, for any given normal velocity vector $\{v\}_n$, a simple matrix-vector multiplication can provide the total pressure $\{P\}_m$ quickly. That is why this method is very efficient and provides huge saving in CPU times if multiple loading cases have to be considered.



Figure 11. A trunk lid BEM model

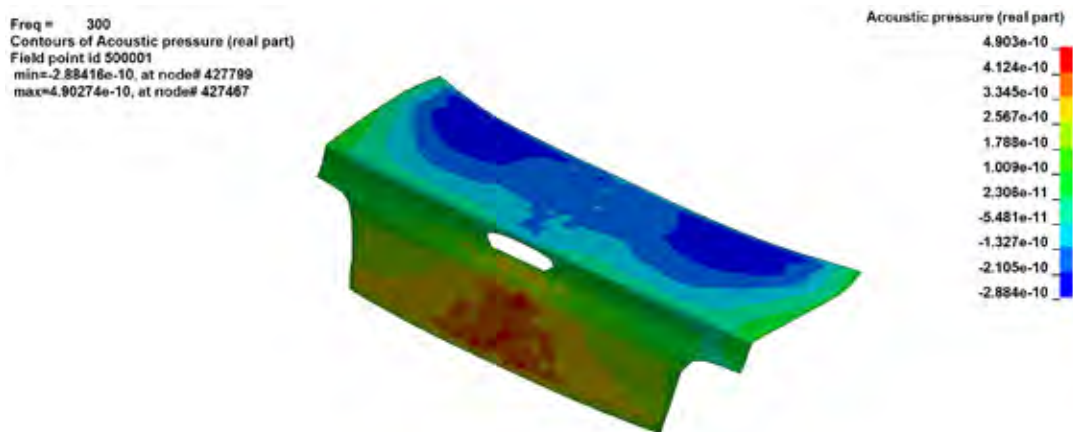


Figure 12. Real part of pressures ATV at point 500001

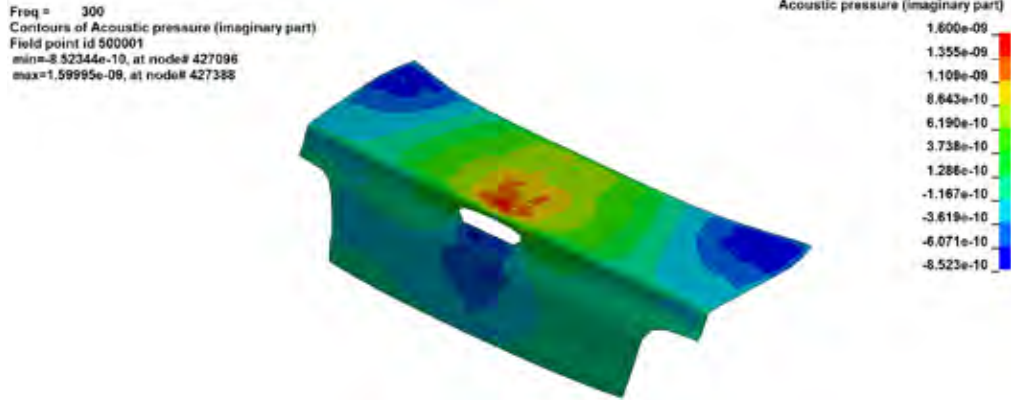


Figure 13. Imaginary part of pressure ATV at point 500001

A trunk lid model is used to illustrate the D3ATV database (figure 11). Figures 12 and 13 show the real and imaginary part of pressure ATV at point 500001.

2.5 D3ERP

The binary plot file D3ERP saves ERP (equivalent radiated power) analysis results. The analysis is activated by the keyword ***FREQUENCY_DOMAIN_SSD_ERP**.

The ERP calculation is based on plane wave assumption for the radiated acoustic waves. First we calculate the ERP density, which is defined as

$$ERP_r = \frac{1}{2} r c \operatorname{Re}[v_n \bar{\varphi}_n] \tag{5}$$

Where r is the density of acoustic medium, c is the sound speed and v_n is the normal velocity on the surface of the structure.

The ERP absolute value radiated from the vibrating panels is the integral of the ERP density over the whole surface and is given by

$$ERP_{abs} = \oint_S ERP_r dS = \frac{1}{2} r c \oint_S \operatorname{Re}[v_n \bar{\varphi}_n] dS \tag{6}$$

It can be converted to a dB value if a reference value ERP_{ref} is provided.

$$ERP_{dB} = 10 \log_{10} (ERP_{abs} / ERP_{ref}) \tag{7}$$

A simplified engine model is used to illustrate the D3ERP database (figure 14). The whole surface of the engine is defined as sound radiating panel, by a set of segments (***SET_SEGMENT**). Figure 15 shows the ERP density at frequency 100Hz.

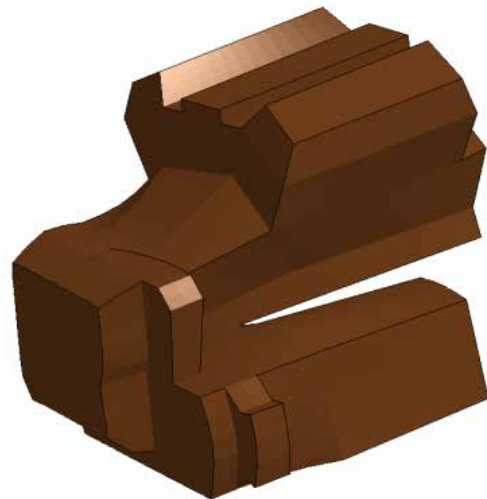


Figure 14. A simplified engine BEM model

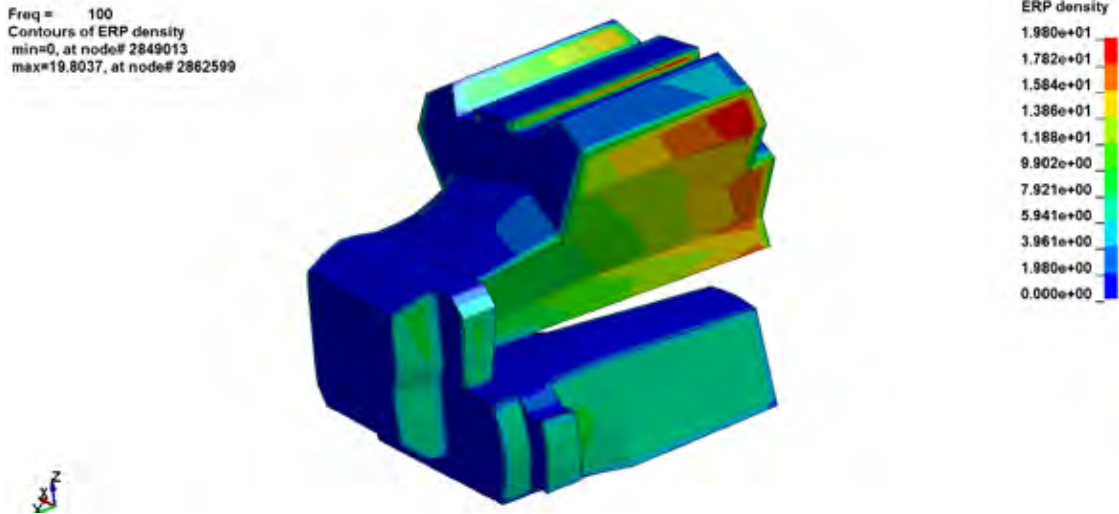


Figure 15. ERP density plot at frequency 100 Hz

2.6 D3EIGV_AC

The binary plot file D3EIGV_AC saves acoustic eigen frequencies and eigen vectors. The analysis is activated by the keyword ***FREQUENCY_DOMAIN_ACOUSTIC_FEM_EIGENVALUE**. The acoustic eigen vector is an array of acoustic pressure given at the nodes in the acoustic volume. Each node has one scalar acoustic pressure.

The acoustic eigenvalue analysis not only provides valuable characteristic information on the acoustic system itself, but also provides basis for modal solution method (comparing to direct solution method) for large scale problems.

An auto compartment model is used to illustrate the D3EIGV_AC database (figure 16). For acoustic eigenvalue analysis in LS-DYNA, various types of constraints on the boundary can be considered, like the prescribed pressure boundary condition. Figure 17 shows acoustic eigenvector for the 2nd mode. For this example, since no constraints are applied, the 1st mode is rigid body mode.



Figure 16. An auto compartment FEM model

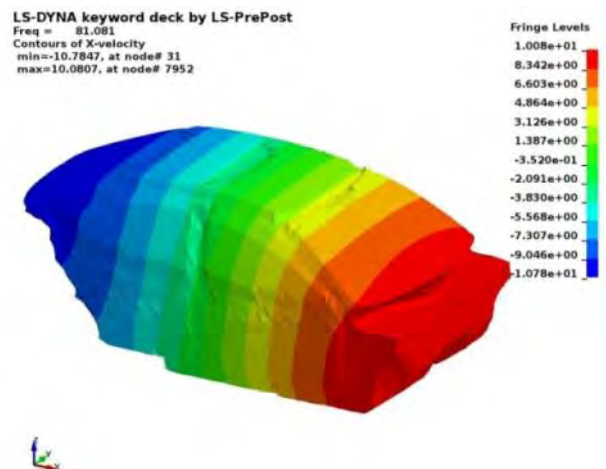


Figure 17. Acoustic eigenvector for the 2nd mode

Table 1 gives a summary of the acoustic binary databases, with their purpose and associated activating keywords in LS-DYNA.

Table 1. Acoustic binary databases

File name	Purpose	Activated by
D3ACS	Acoustic pressure on surface by BEM, in volume including surface by FEM	*DATABASE_FREQUENCY_BINARY_D3ACS by BEM or FEM
D3ACP	Acoustic pressure plot	*FREQUENCY_DOMAIN_ACOUSTIC_FRINGE_PLOT by BEM
D3ACC	Acoustic element contribution plot	*DATABASE_FREQUENCY_BINARY_D3ACC by BEM
D3ATV	Acoustic transfer vector	*FREQUENCY_DOMAIN_ACOUSTIC_BEM_ATV
D3ERP	Equivalent radiated power plot	*FREQUENCY_DOMAIN_SSD_ERP
D3EIGV_AC	Acoustic eigen vector	*FREQUENCY_DOMAIN_ACOUSTIC_FEM_EIGENVALUE

3. ASCII database for XY plot

Many ASCII databases have been provided in LS-DYNA's BEM and FEM acoustic solvers. The default acoustic ASCII databases are Press_Pa and Press_dB for both BEM and FEM acoustic solvers. The Sound Pressure is the force (N) of sound on a surface area (m²) perpendicular to the direction of the sound. The SI-units for the sound pressure are N/m² or Pa. Sound pressure level (SPL) is a logarithmic measure of the effective pressure of a sound relative to a reference value. Sound Pressure Level can be expressed as (8)

$$L_p = 20 \log_{10} \left(P / P_{ref} \right) \quad (8)$$

Where L_p is the sound pressure level (dB), P is the sound pressure (Pa) and P_{ref} is a reference pressure. Usually, in International Unit System the reference pressure is 2×10^{-5} Pa.

If the IPFILE is equal to 1 in BEM or FEM keywords, the real and imaginary parts of the sound pressure are output to ASCII files Press_Pa_real and Press_Pa_imag as the sound pressure is a complex variable.

If the TRSLT is great than zero in BEM, the time domain data of sound pressure and sound pressure level are calculated using inverse FFT and output to ASCII files Press_Pa_t and Press_dB_t.

Sound power or acoustic power is the rate at which sound energy is emitted, reflected, transmitted or received, per unit time. The SI unit of sound power is the watt(W). It is the power of the sound force on a surface of the medium of propagation of the sound wave. For a sound source, unlike sound pressure, sound power is neither room-dependent nor distance-dependent. Sound pressure is a measurement at a point in space near the source, while the sound power of a source is the total power emitted by that source in all directions. It is calculated by collocation BEM (methods 3 and 4) and output to Press_Power.

The radiation efficiency indicates how much sound power W a given structure radiates compared with the vibrating infinite flat surface for the same area. The radiation efficiency is thus given by equation (9). In general, the radiation efficiency is low meaning that structural vibrations have difficulty to produce noise. It is calculated by collocation BEM (methods 3 and 4) and output to Press_radeff.

$$s = \frac{W}{\frac{1}{2} r c S \langle |v|^2 \rangle} \quad (9)$$

where $\langle \dots \rangle$ denotes a spatial average and v is the amplitude of the velocity normal to the surface of the structure.

User can also request calculation for weighted sound pressure level A,B,C and D by setting different value of DBA in BEM or FEM. Below is the information about weighted sound pressure level [3].

- A-weighting: the A-weighting filter covers the full audio range - 20 Hz to 20 kHz and the shape is similar to the response of the human ear at the lower levels - see the equal loudness contours entry. A-weighted noise measurements are widely used and the meter class confirms the accuracy of the meter including the filters. A weighted measurements correlate well with the perceived loudness at low sound levels, as originally intended. However the current use for most noise applications, supported by regulations, does cause concern in some quarters.
- B-weighting: no longer in common use, was initially developed to cover the mid-range between the A and C-weighting networks. It was also more 'critical' of lower frequencies than the A-weighting network which probably accounts for its use by the motor industry for many years after its general decline in popularity.
- C-weighting: a standard frequency weighting for sound level meters, commonly used for higher level measurements and peak - sound pressure levels. The A-weighting curve is used extensively for general purpose noise measurements but the C-weighting correlates better with the human response to high noise levels.
- D-weighting: sound level meter frequency weighting developed for measuring aircraft noise especially non-bypass military engines. It is not in common use since IEC 61672 2003. More recent ISO standards recommend A-weighting for commercial aircraft noise.

A simple compartment FEM model is used to show the weighted sound pressure level (figure 3). Figure 18 shows the normal SPL and weighted SPL at field point 8106.

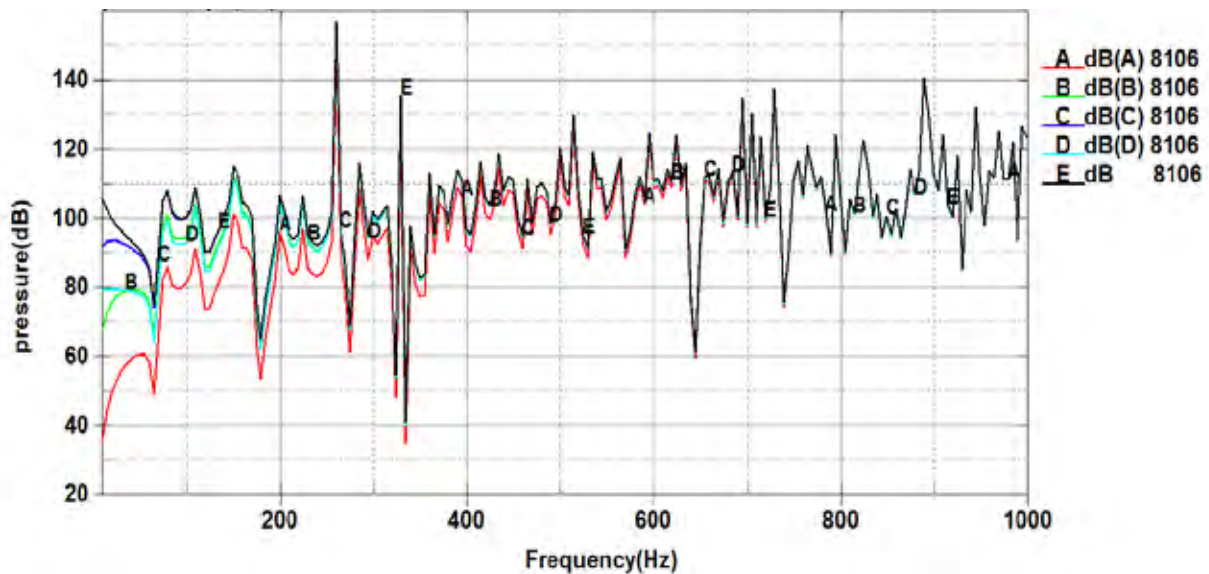


Figure 18. Normal SPL and weighted SPL at point 8106

Panel contribution analysis is conducted to identify the panels which have a high contribution on the acoustic response. It gives the contribution percentage of panels (given as part, set of parts or set of segments) on the acoustic results at observation points and output to ASCII file Panel_contribution_NID.

A simplified tunnel model is employed to illustrate the panel contribution analysis. The model is shown in figure 19. Figure 20 shows the panel contribution percentage of the four panels respectively. One can see that

the top panel (panel 3) makes the largest contribution for the noise for most frequencies. The contribution from panel 1 and panel 2 are almost identical due to the symmetry of the structure.

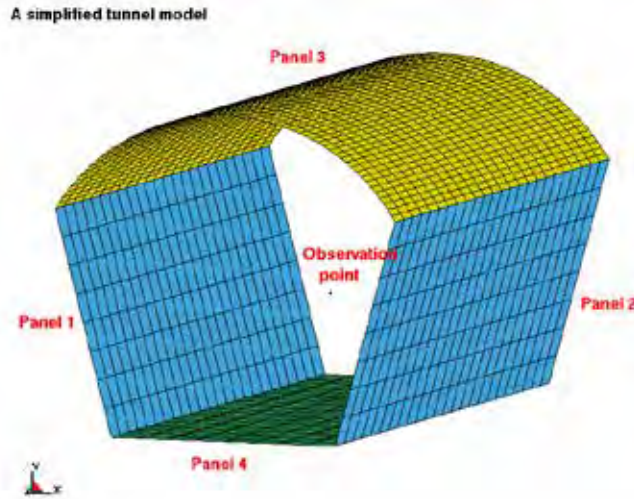


Figure 19. A simplified tunnel BEM model

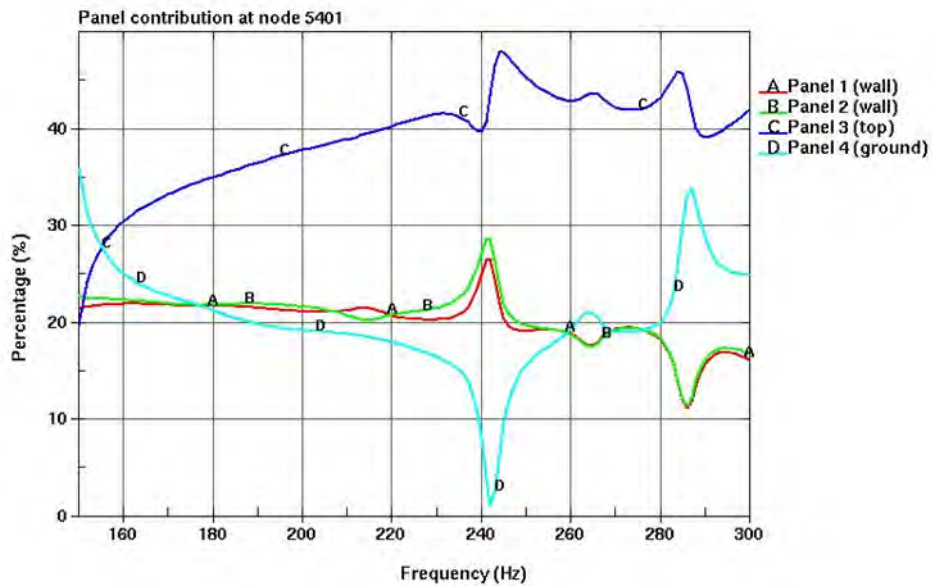


Figure 20. Different panel contributions at point 5401

Table 2 gives a summary of the acoustic ASCII databases, with their purpose and associated activating keyword in LS-DYNA.

Table 2. Acoustic ASCII databases

File name	Purpose	Activated by
Press_Pa	Pressure (abs) vs. Freq	BEM or FEM
Press_dB	SPL (dB) vs. Freq	BEM or FEM

Press_Pa_real	Pressure (real) vs. Freq	IPFILE=1 by BEM or FEM
Press_Pa_imag	Pressure (imag) vs. Freq	IPFILE=1 by BEM or FEM
Press_Pa_t	Pressure (abs) vs. Time	TRSLT>0 by BEM
Press_dB_t	SPL (dB) vs. Time	TRSLT>0 by BEM
Press_Power	Sound Power vs. Freq	BEM Method = 3 or 4
Press_radeff	Radiation efficiency vs. Freq	BEM Method = 3 or 4
Press_dB(A)	SPL (dB, A-weighting) vs. Freq	dBA=1 in BEM or FEM
Press_dB(B)	SPL (dB, B-weighting) vs. Freq	dBA=2 in BEM or FEM
Press_dB(C)	SPL (dB, C-weighting) vs. Freq	dBA=3 in BEM or FEM
Press_dB(D)	SPL (dB, D-weighting) vs. Freq	dBA=4 in BEM or FEM
Panel_contribution_NID	Panel contribution vs. Freq	Option: PANEL_CONTRIBUTION by BEM

4. Summary

The paper gives a review of the acoustic databases, which have different purposes and should be used in different circumstances. Users may get confused with these variety of binary and ASCII databases. With this paper, we give a detailed review of these acoustic databases, and explain the difference among them. Some examples are provided to demonstrate the application of these databases.

Some of the databases were implemented to answer the request from users or under the suggestion from users. The authors are grateful to the users for their suggestions and feedback.

References

- [1] Livermore Software Technology Corporation: "LS-DYNA Keyword User's Manual", 2016
- [2] F. J. Fahy and P. Gardonio, Sound and Structural Vibration: Radiation, Transmission and Response. Academic Press, London, 2nd edition, 2006
- [3] Source of information: <http://www.acoustic-glossary.co.uk/frequency-weighting.htm>