

ATV and MATV Techniques for BEM Acoustics in LS-DYNA[®]

Yun Huang, Zhe Cui

Livermore Software Technology Corporation
7374 Las Positas Road, Livermore CA 94551

Abstract

This paper presents the new ATV (Acoustic Transfer Vector) and MATV (Modal Acoustic Transfer Vector) techniques for BEM acoustics in LS-DYNA, which were implemented recently.

Acoustic Transfer Vector provides the transfer function between the normal nodal velocity on structural surface and the acoustic response at selected field points; Modal Acoustic Transfer Vector provides similar transfer function, but is based on the excitation from modal shape vibrations. ATV and MATV reveal the inherent properties of structures and acoustic volume, and can be used to predict radiated noise from vibrating structures when combined with vibration boundary conditions. Particularly they are useful for the acoustic analysis of structures subjected to multiple load cases.

Some examples are given to illustrate the application of the ATV and MATV techniques. For ATV, post-processing of the results in the form of binary plot database is also presented.

Introduction

Recently a bunch of acoustic boundary element methods (BEM) have been implemented to LS-DYNA [1]. These acoustic BEM can be used to predict the noise from a vibrating structure. They have wide application in auto NVH analysis, and other vibro-acoustic analysis.

To facilitate the acoustic analysis for the situation where multiple load cases are present, two new techniques ATV (Acoustic Transfer Vector) and MATV (Modal Acoustic Transfer Vector) have been implemented to the acoustic BEM.

ATV is defined as the transfer function between the normal nodal (elemental) velocity and the acoustic pressure at field points. Once all the ATV are obtained, the total acoustic pressure at field points can be computed by simple matrix – vector multiplication, as in equation (1)

$$\begin{Bmatrix} p_1 \\ p_2 \\ \vdots \\ p_i \\ \vdots \\ p_m \end{Bmatrix} = \begin{bmatrix} \Omega_{1,1} & \Omega_{1,2} & \cdots & \Omega_{1,j} & \cdots & \Omega_{1,n} \\ \Omega_{2,1} & \Omega_{2,2} & \cdots & \Omega_{2,j} & \cdots & \Omega_{2,n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \Omega_{i,1} & \Omega_{i,2} & \cdots & \Omega_{i,j} & \cdots & \Omega_{i,n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \Omega_{m,1} & \Omega_{m,2} & \cdots & \Omega_{m,j} & \cdots & \Omega_{m,n} \end{bmatrix}_{m \times n} \begin{Bmatrix} v_1 \\ v_2 \\ \vdots \\ v_j \\ \vdots \\ v_n \end{Bmatrix} \quad (1)$$

or equation (2) in short form

$$\{P\}_m = [ATV]_{m \times n} \{v\}_n \quad (2)$$

In equation (1), 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 in boundary elements. $\Omega_{i,j}$ represents the acoustic pressure at field point i , due to unit normal velocity at node j . Please note that all the variables in equations (1) and (2) are dependent on frequency $\omega=2\pi f$. Besides, the variables in both equations are complex.

As indicated by equation (2), 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 load cases have to be considered.

To get the velocity vector $\{v\}_n$, one can run lab testing, road testing, or numerical vibration analysis such like using the keyword *FREQUCNY_DOMAIN_SSD in LS-DYNA. The *FREQUCNY_DOMAIN_SSD keyword provides the solution for harmonic steady state vibration based on mode superposition method. For each vibration frequency, the structural response is composed of contribution from all the involved eigen modes. This suggests that one can first run acoustic computation for each eigen mode, to get acoustic contribution from each mode, and then do a modal superposition to get the total acoustic pressure, using the same modal coordinates obtained in SSD calculation. This brings us to the concept of modal ATV, or MATV, as illustrated by equation (3)

$$\begin{Bmatrix} p_1 \\ p_2 \\ \vdots \\ p_i \\ \vdots \\ p_m \end{Bmatrix} = \begin{bmatrix} \Psi_{1,1} & \Psi_{1,2} & \cdots & \Psi_{1,j} & \cdots & \Psi_{1,l} \\ \Psi_{2,1} & \Psi_{2,2} & \cdots & \Psi_{2,j} & \cdots & \Psi_{2,l} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \Psi_{i,1} & \Psi_{i,2} & \cdots & \Psi_{i,j} & \cdots & \Psi_{i,l} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \Psi_{m,1} & \Psi_{m,2} & \cdots & \Psi_{m,j} & \cdots & \Psi_{m,l} \end{bmatrix}_{m \times l} \begin{Bmatrix} q_1 \\ q_2 \\ \vdots \\ q_j \\ \vdots \\ q_l \end{Bmatrix} \quad (3)$$

Or equation (4) in short form

$$\{P\}_m = [MATV]_{m \times l} \{q\}_l \quad (4)$$

Where, $\Psi_{i,j}$ represents the acoustic pressure at field point i , due to the normal velocity boundary condition for eigen mode j . Once again p_i is the acoustic pressure at field point i . q_j is the modal coordinates for mode j . q_j is obtained from SSD (Steady State Dynamics) analysis. m is the number of field points and l is the number of modes involved in the mode superposition procedure. Once again all the variables in equation (1) are dependent on frequency $\omega=2\pi f$ and they are all complex.

Please note that ATV and MATV can be related by the following equation

$$\begin{aligned} \{P\}_m &= [ATV]_{m \times n} \{v\}_n \\ &= [ATV]_{m \times n} i\omega \{u\}_n \\ &= [ATV]_{m \times n} i\omega [\phi]_{n \times l}^T \{q\}_l \\ &= [MATV]_{m \times l} \{q\}_l \end{aligned} \quad (5)$$

Where i is the imaginary unit ($i = \sqrt{-1}$) and $\{u\}_n$ is the displacement vector. The matrix $[\phi]_{n \times l}$ is the modal shape matrix, provided by implicit eigenvalue analysis. $\{q\}_l$ is the modal coordinate vector.

One can see, for each load case, only the modal coordinates vector $\{q\}_l$ need to be updated and once it is ready, a simple matrix-vector multiplication can be performed and it provides the solution for acoustic pressure vector at the field points.

For a real practical problem, the number of eigen modes involved is usually much less than the number of nodes in the boundary elements ($n \ll l$), so the MATV approach represented by equation (3) or (4) is more efficient than the ATV approach, if the vibration simulation can be accomplished by SSD.

For ATV, a binary plot database d3atv is provided in LS-DYNA, to visualize the acoustic pressure due to unit normal velocity at each surface node. This helps to study the contribution to acoustic pressure from each surface node. To get d3atv database, the keyword *DATABASE_FREQUENCY_BINARY_D3ATV is needed in LS-DYNA keyword input deck. For more details about this keyword, please refer to LS-DYNA Keyword Users' Manual [2].

Several examples are given below to demonstrate the ATV and MATV capabilities.

ATV for a simplified engine model

Figure 1 shows a simplified engine model and the location of two field points. To run ATV analysis for this model, the keyword *FREQUENCY_DOMAIN_ACOUSTIC_BEM_{ATV} is employed. In this keyword, we set up the range of frequencies to compute, the number of excitation frequencies, the location of field points, and some other parameters for BEM Acoustic analysis. More details about this keyword can be found in reference [2].

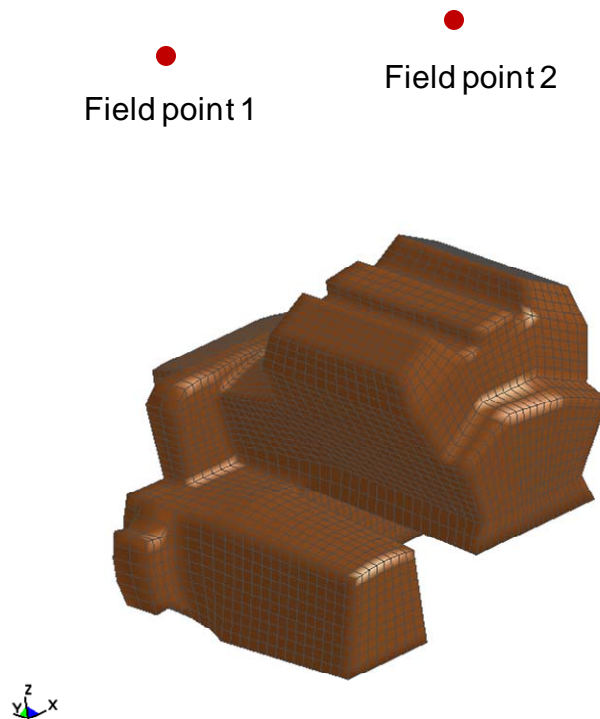


Figure 1: A simplified engine model for ATV computation

In LS-DYNA computation, we run BEM analysis for unit normal velocity from each of the surface nodes, and compute the acoustic pressure at the two field points. Please note that for each frequency, one does not need to reform the complex influence matrix for each surface node under consideration --- it is formed only once. We only need to update the R.H.S. of the equation system (see equation (6) below).

$$[C(\omega)]\{x(\omega)\} = \{y(\omega)\} \quad (6)$$

The results of the ATV computation are given in 1) ASCII files

ATV_FIELD_PT_ID

ATV_DB_FIELD_PT_ID

And 2) BINARY database d3atv.

In ATV_FIELD_PT_ID, the complex pressure for one field point (indicated by ID) for user specified excitation frequencies is given for each surface node. When multiple field points are present, LS-DYNA will generate multiple ATV_FIELD_PT_ID, with different ID.

In ATV_DB_FIELD_PT_ID, the SPL (Sound Pressure Level, or dB) for the field point ID for user specified excitation frequencies is given for each surface node.

D3atv is a binary plot database, and it is written in the same format as d3plot and other binary plot databases in LS-DYNA. It is accessible to LS-PrePost[®]. It shows the real part, imaginary part and dB values of the acoustic pressure, at each field point, at each frequency, due to unit normal velocity at each surface node. For this example, some of the results are given in Figure 2,

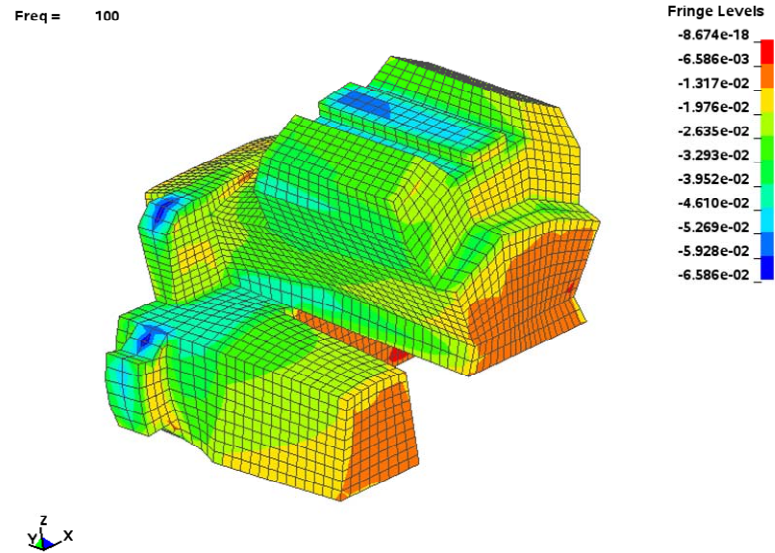


Figure 2: Real part of pressure ATV at field point 1

and Figure 3.

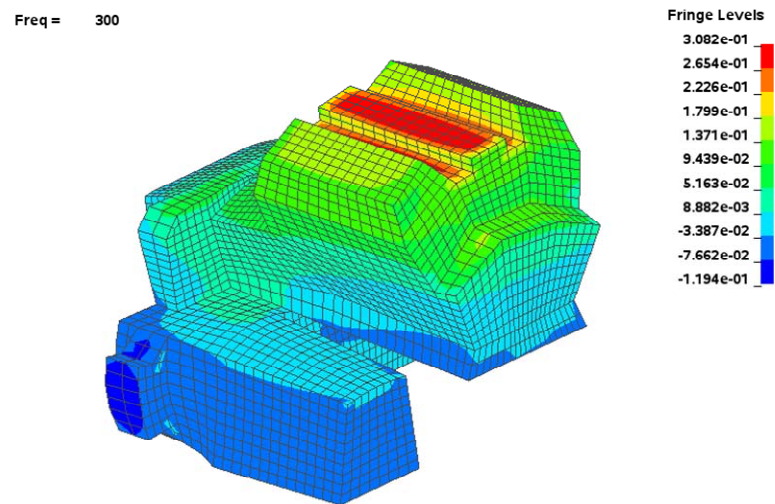


Figure 3: Imaginary part of pressure ATV at point 2

From d3atv, such as Figures 2 and 3, people can see easily that which part of the surface gives more contribution to the final acoustic pressure at field points.

MATV for a simplified engine model

Figure 4 shows a simplified door model. It is fixed at the upper edge and the 4 holes near the lower edge. It is subjected to 10 load cases. For each of the load case, a nodal force spectrum is given at one node on the door. The range of frequency is same for the 10 load cases. So this provides a good example for using the MATV technique in LS-DYNA.

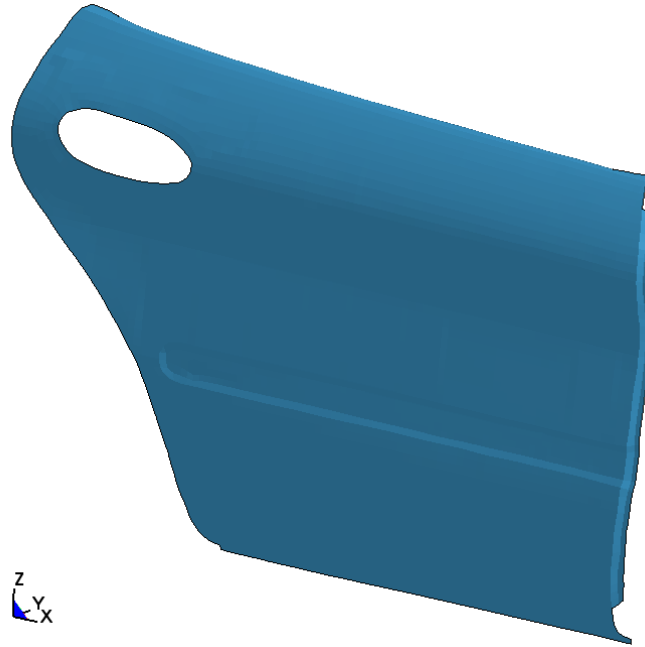


Figure 4: A door model for MATV computation

To using the MATV technique, the first thing to do is to generate the MATV matrices. The excitation frequency is 100-500 Hz, with 101 equally spaced frequencies. So for running implicit eigenvalue analysis, modes up to 600 Hz (which is 20% higher than the highest excitation frequency) is needed. Keyword `*FREQUENCY_DOMAIN_ACOUSTIC_BEM_{MATV}` is used, without specifying any loading or excitation conditions for acoustic computation. Keywords `*CONTROL_IMPLICIT_GENERAL`, `*CONTROL_IMPLICIT_EIGENVALUE` are set, to perform the implicit eigenvalue analysis, and generate d3eigv binary plot database. LS-DYNA will extract the eigen vectors $\{\phi\}_j$ from d3eigv. For each excitation frequency f , LS-DYNA will generate the psedo-velocity boundary condition $i\omega\{\phi\}_j$ ($\omega = 2\pi f$) and run BEM acoustic computation to get the MATV matrix.

For the second step, the keyword `*FREQUENCY_DOMAIN_SSD` is adopted, to run steady state dynamic computation for given nodal force loading. SSD will generate the modal coordinates $\{q\}_i$ for each excitation frequency. The keyword `*FREQUENCY_DOMAIN_ACOUSTIC_BEM_{MATV}` is also needed and we set `IREST=1`, which means that we are running restart BEM acoustic computation based on existing MATV.

To check the accuracy of the method, we run this problem also in the traditional way (SSD + BEM Acoustic computation) without using MATV. The results for one load case by the two different methods are plotted in Figure 5, and one can see that the two curves match very well.

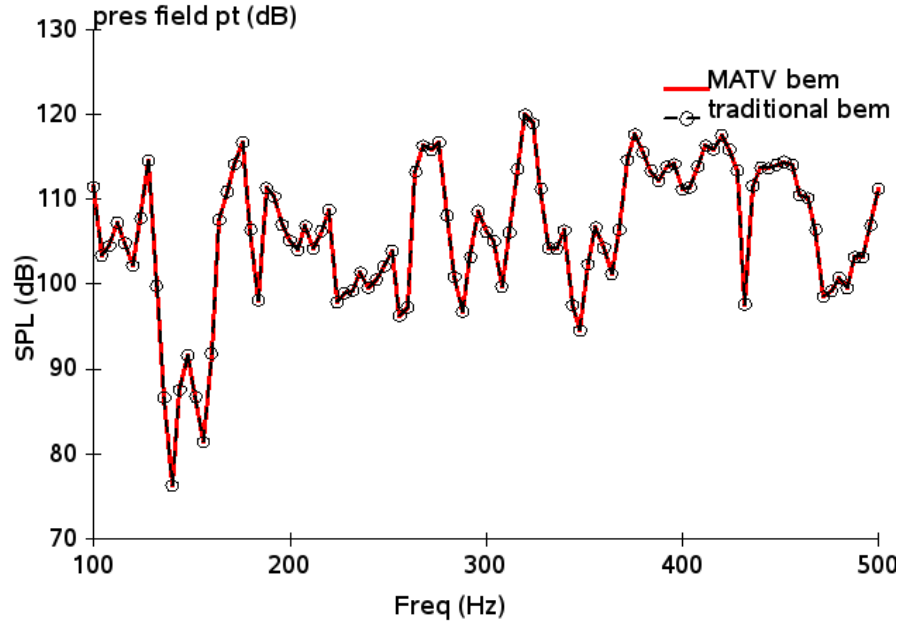


Figure 5: SPL at field point

The total CPU time for running 1 load case and 10 load cases is listed in Table 1. The computation is performed on Intel Xeron CPU E5504 @2.00 GHz (CPU MHz: 1596.00 cache size 4096 KB). Three different methods are used: 1) Direct SSD + traditional BEM, which means that we go through the whole procedures (Modal analysis, SSD and tradition BEM) for each load case; 2) Restart SSD + traditional BEM, which means that starting from the 2nd load case, we skip the modal analysis part, and run a restart SSD using existing d3eigv, and then the traditional BEM; and 3) Restart SSD + MATV BEM, which means that we skip the modal analysis part starting from the 2nd load case, and run a restart SSD and then use the MATV based BEM to get the acoustic pressure for all the load cases.

For 1) Direct SSD + traditional BEM method, the total CPU time for 10 load cases is simply 10 times of the CPU time for one load case. For 2) Restart SSD + traditional BEM, starting from the 2nd load case, LS-DYNA can make use of the existing d3eigv database, and run modal superposition to get SSD response directly. This way we can skip the time-consuming modal analysis step, and gain some CPU saving. The most CPU saving is observed in 3) Restart SSD + MATV BEM. For 3), the step 1 (generating the MATV matrices) is needed only once and the step2 (BEM acoustic calculation based on MATV) is repeated 10 times if 10 load cases are present. Since the CPU time for step 2 is so small one can expect that when more load cases are present, more CPU saving can be achieved by the MATV BEM, comparing to the traditional BEM.

Cases	1) Direct SSD + traditional BEM	2) Restart SSD + traditional BEM	3) Restart SSD + MATV BEM
1 load case	2 h 39 m 50 s	2 h 39 m 50 s	4 h 40 m 56 s
10 load cases	26 h 38 m 18 s	25 h 53 m 13 s	4 h 41 m 10 s

Table 1: CPU time for different methods (h: hour; m: minute; s: second)

For the “1 load case”, one always has to start from modal analysis and generate d3eigv binary database. So the CPU time for methods 1) and method 2) is same for the “1 load case”. Method 3) takes longer time to run for the “1 load case” but the extra time is well compensated by the huge saving in computation for additional load cases.

Conclusion

For BEM Acoustic solver in LS-DYNA, ATV and MATV techniques have been implemented. ATV provides the transfer function between the normal nodal velocity on structural surface and the acoustic response at selected field points; Modal Acoustic Transfer Vector provides similar transfer function, but is based on the excitation from modal shape vibrations. ATV and MATV are properties of the structure and they are not dependent on the loading conditions. Once computed, they can be used for many load cases. That is why they are useful and provide efficient tools when one needs to run acoustic computation for multiple load cases.

Another possible application of ATV and MATV is the inverse acoustic analysis. Based on the measured acoustic environment, and using the ATV / MATV techniques, one is able to locate the source of vibration excitation. This can be useful to solve the auto BSR (Buzz, Squeak and Rattle) problems.

References

1. Huang Y., Souli M., Development of acoustic and vibro acoustic solvers in LS-DYNA®. *Proceedings of the 10th International LS-DYNA® Users' Conference*, June 8-10, 2008, Dearborn, Michigan.
2. LS-DYNA Keyword User's Manual, Livermore Software Technology Corporation, January 14, 2014 (revision: 4571).