Evaluation of Equivalent Radiated Power with LS-DYNA®

Yun Huang, Zhe Cui

Livermore Software Technology Corporation

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Outline

1) Introduction
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3) Keywords
4) Examples and post-processing
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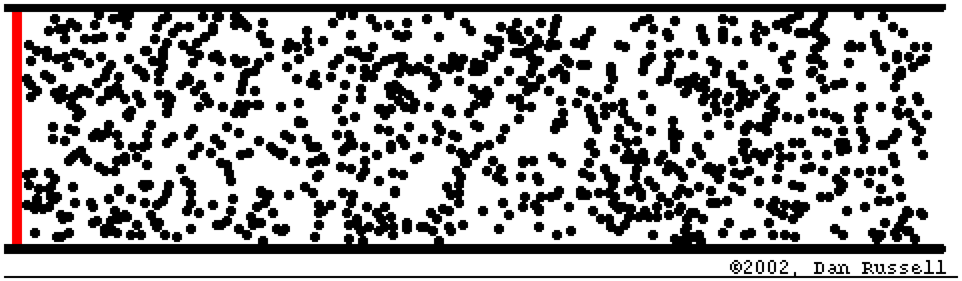
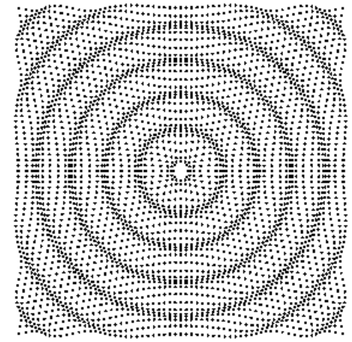
1) Introduction





Animation courtesy of Dr. Dan Russell, Grad. Prog. Acoustics, Penn State

Acoustic intensity

Sound pressure $P = p\, e^{i\omega t}$

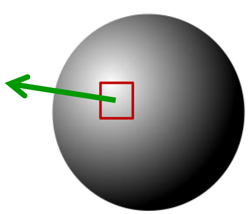
Particle velocity $V = v\, e^{i\omega t}$

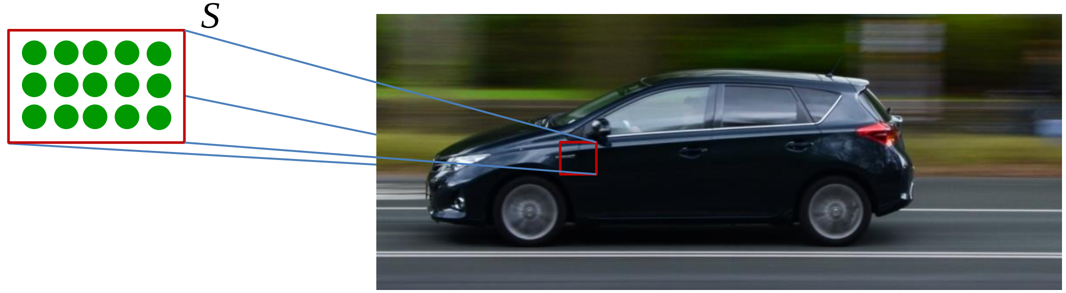
Acoustic intensity $I = \langle PV \rangle_t = \frac{1}{T}\int_0^T PV dt$ $\Rightarrow$ $I = \frac{1}{2}\mathrm{Re}\{p\, \bar{v}_n\}$

Time-harmonic wave

Acoustic power

$$W = \int_S I_n \, dS$$





Acoustic solvers in LS-DYNA

Time domain acoustics

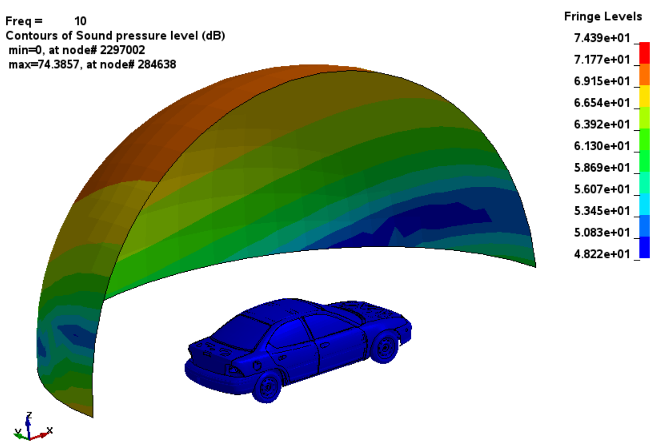
- using **MAT_ACOUSTIC** and **SOLID** formulation 8 and 14

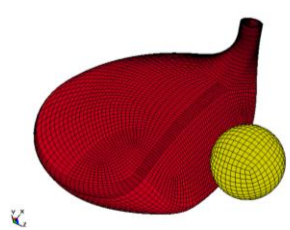
Frequency domain acoustics

- Boundary element method
  - ***FREQUENCY_DOMAIN_ACOUSTIC_BEM**
- Finite element method
  - ***FREQUENCY_DOMAIN_ACOUSTIC_FEM**

Application

- Vehicle NVH
- Acoustic design of sports products
- Transportation acoustics
- Noise control



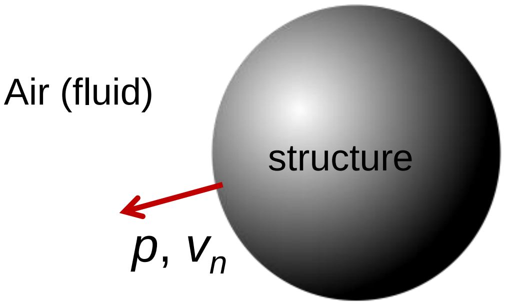




Why ERP is needed?

- Traditional methods, like FEM and BEM, are generally slow and memory intensive.
- ERP is a simple way to characterize structural borne noise
  - ✓ provide information about maximal possible acoustic radiation of panels for specific frequency domain excitation
  - ✓ No air modeling required
  - ✓ No equation systems to solve
  - ✓ good for acoustic optimization based on topology / geometry (direct surface integral)
  - ✓ damping in acoustic volume can be considered in terms of radiation loss factor
  - ✓ acoustic panel contribution analysis
  - ✓ in LS-DYNA, works as a post-processing of SSD

2) Brief theory about ERP

Acoustic intensity $$I = \frac{1}{2}\mathrm{Re}\left\{p\,\bar{v}_n\right\}$$



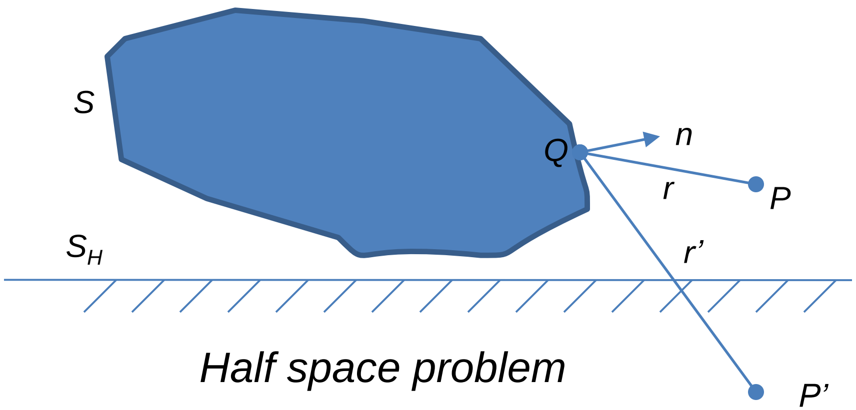
Usually, full fluid-structure coupling is needed, to compute the normal velocity and pressure

Equality of structure and particle velocity

In linear vibro-acoustics usually the coupling between structure and fluid assumes the equality of the normal velocity of structural surface and the particle velocity of the fluid on the structure surface

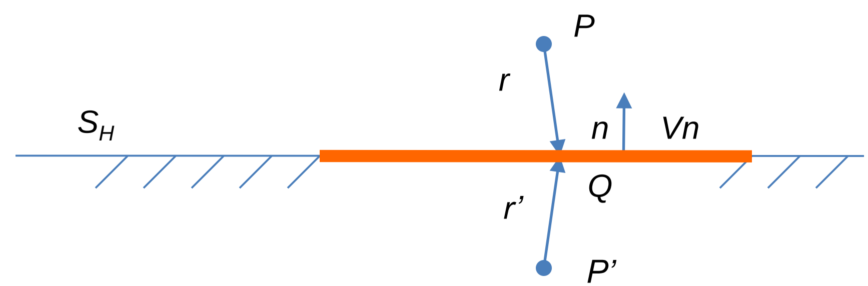
$$v_{S,n} = v_f$$

For rigid panels, one can get the acoustic pressure as follows.
(similar to the Rayleigh method)



Half space problem

Special case when the vibrating surface lies on the reflecting plane



Open space fundamental solution

$$G = \frac{e^{-ikr}}{4\pi r}$$

Half space fundamental solution

$$G_H = \frac{e^{-ikr}}{4\pi r} + \frac{e^{-ikr'}}{4\pi r'}$$

$$P(\omega) = -\int_S \left(i\rho\omega v_n(\omega) G_H + p(\omega)\frac{\partial G_H}{\partial n} \right) ds$$

$$G_H = 2G \qquad \partial G_H / \partial n = 0$$

$$P(\omega) = -\int_S 2 i\rho\omega v_n(\omega) G ds$$

Still too much efforts!

Pressure

$$p = \frac{i\omega\rho}{2\pi}\int_S v_n \frac{e^{-ikr}}{r} dS$$

$$k = \omega / c$$

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

$$I = \frac{1}{2}\mathrm{Re}\{p\,\bar{v}_n\} \qquad \frac{p}{v_n} = Z = \rho c$$

Plane wave:
- described by only one dimension
- sound pressure and particle velocity are in phase

ERP density

$$ERP_\rho = \frac{1}{2}\rho c\,\mathrm{Re}\left[v_n \cdot \bar{v}_n\right]$$

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 absolute

$$ERP_{abs} = \int_S ERP_\rho dS = \frac{1}{2}\rho c \int_S \mathrm{Re}\left[v_n \cdot \bar{v}_n\right] dS$$

ERP in dB

$$ERP_{dB} = 10\log_{10}\left(ERP_{abs} / ERP_{ref}\right)$$

Acoustic density

$$w = \frac{I}{c} = \frac{1}{2}\rho\,\mathrm{Re}\left[v_n \cdot \bar{v}_n\right]$$

Sound energy density (Pa)

FREQUENCY_DOMAIN_SSD_*ERP

Card 1	1	2	3	4	5	6	7	8
Variable	MDMIN	MDMAX	FNMIN	FNMAX	RESTMD	RESTDP	LCFLAG	RELATV
Type	I	I	F	F	I	I	I	I

Card 2	1	2	3	4	5	6	7	8
Variable	DAMPF	LCDAM	LCTYP	DMPMAS	DMPSTF	DMPFLG		
Type	I	I	I	I	I	I		

Card 3	1	2	3	4	5	6	7	8
Variable			MEMORY	NERP	STRTYP	NOUT	NOTYP	NOVA
Type			I	I	I	I	I	I

VARIABLE	**DESCRIPTION**
NERP	Number of ERP panels.

ERP Cards: additional Cards 3a and 3b are defined for ERP keyword option.

Card 3a	1	2	3	4				
Variable	RO	C	ERPRLF	ERPREF				
Type	F	F	F	F				

Repeat Card 3b NERP times (one card defines one ERP panel)

Card 3b	1	2						
Variable	PID	PTYP						
Type	I	I						

Card 4	1	2	3	4	5	6	7	8
Variable	NID	NTYP	DOF	VAD	LC1	LC2	LC3	VID
Type	I	I	F	F	I	I	I	I

VARIABLE	DESCRIPTION
RO	Fluid density
C	Sound speed of the fluid
ERPRLF	ERP radiation loss factor
ERPREF	ERP reference value. This is used to convert the absolute ERP value to ERP in decibels (dB)
PID	Part, part set, or segment set ID for ERP computation

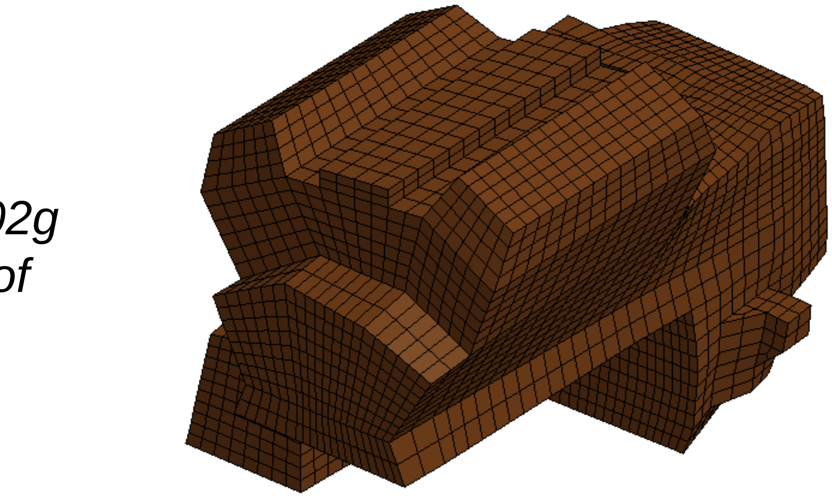
A typical keyword input

FREQUENCY_DOMAIN_SSD_*ERP

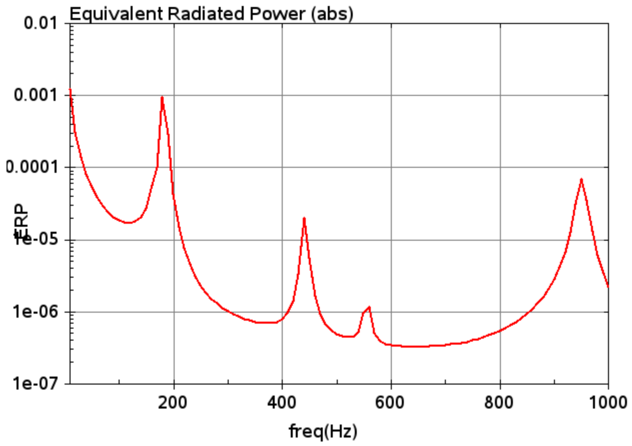
$#	MDMIN	MDMAX	FNMIN	FNMAX	RESTMD	RESTDP	LCFLAG	RELATV
	1	100	0.0	2000.0				
$#	DAMPF	LCDAM	LCTYP	DMPMAS	DMPSTF	DMPFLG		
	0.01							
$#			MEMORY	NERP	STRTYP	NOUT	NOTYP	NOVA
				1				
$#	RO	C	ERPRLF	ERPREF				
	1.21	340.0	1.	5.E-13				
$#	PID	PTYP						
	1							
$#	NID	NTYP	DOF	VAD	LC1	LC2	LC3	VID
	131	0	3	0	100	200		

4) Examples and post-processing

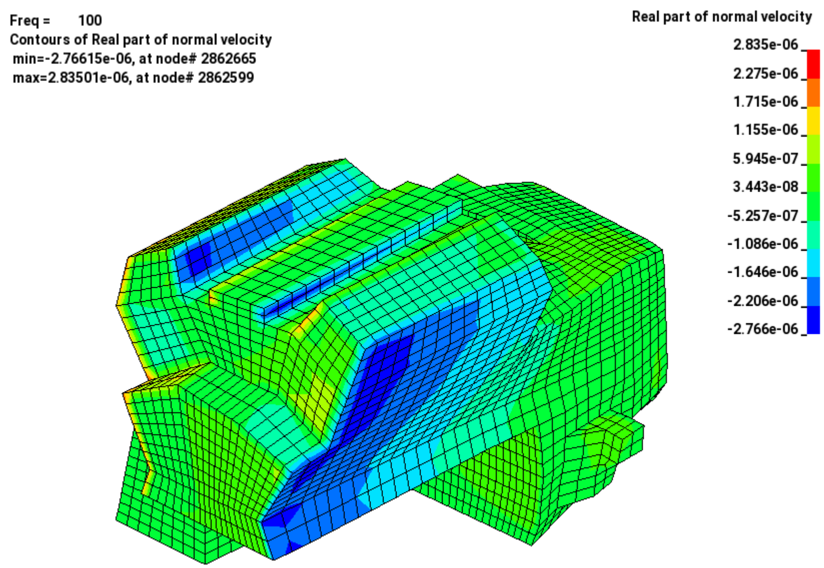
For a simplified engine model, a constant horizontal acceleration 0.02g is given on the base, for the range of frequency 10-1000 Hz.

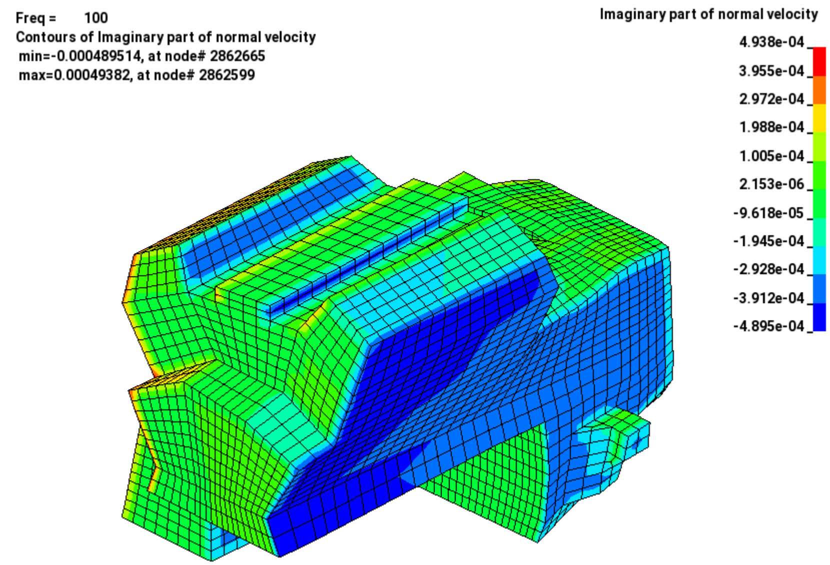


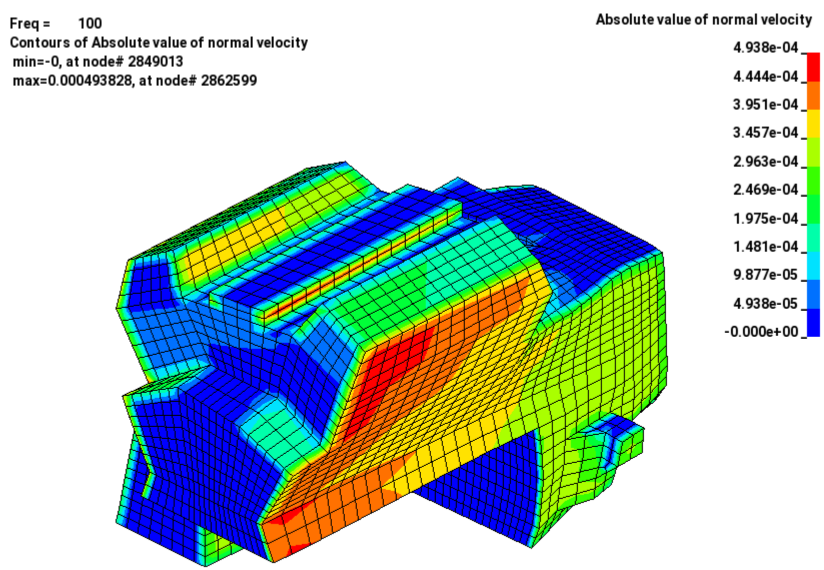
No. of solids: 13484
No. of nodes: 16041
No. of surface segments: 4880

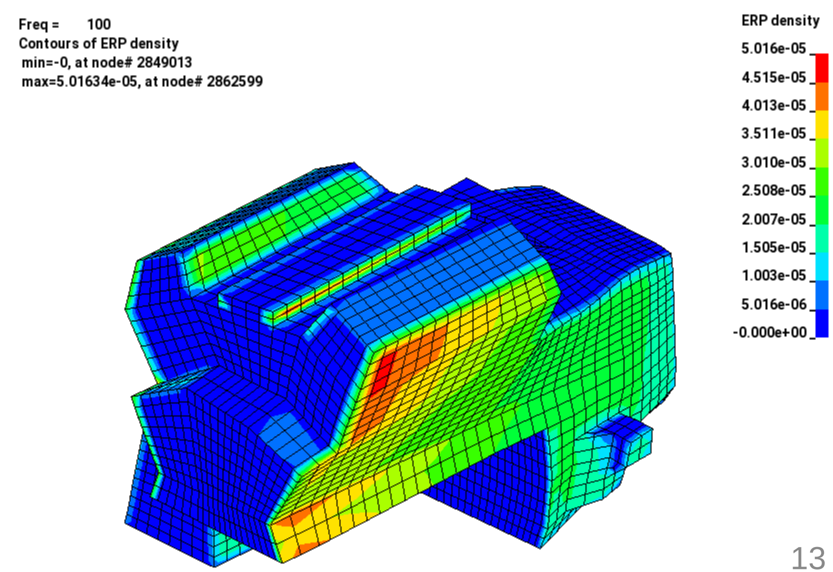


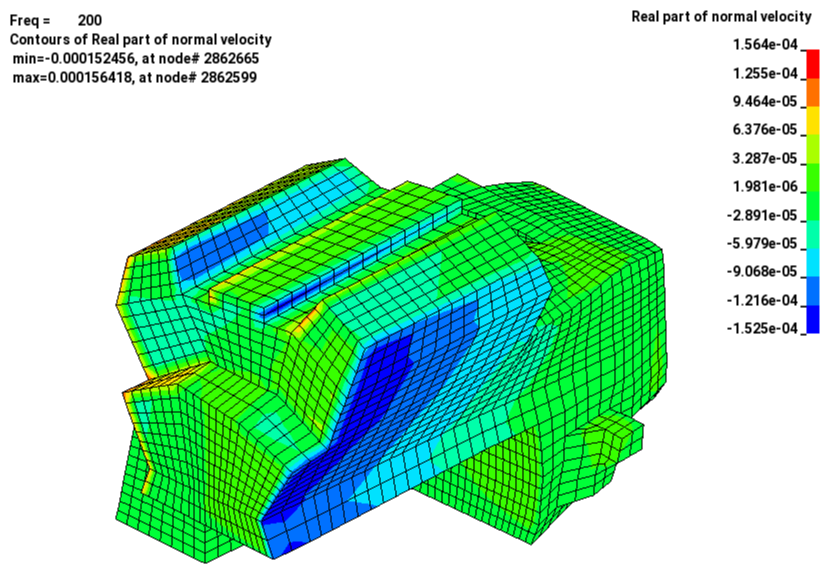
ERP_abs

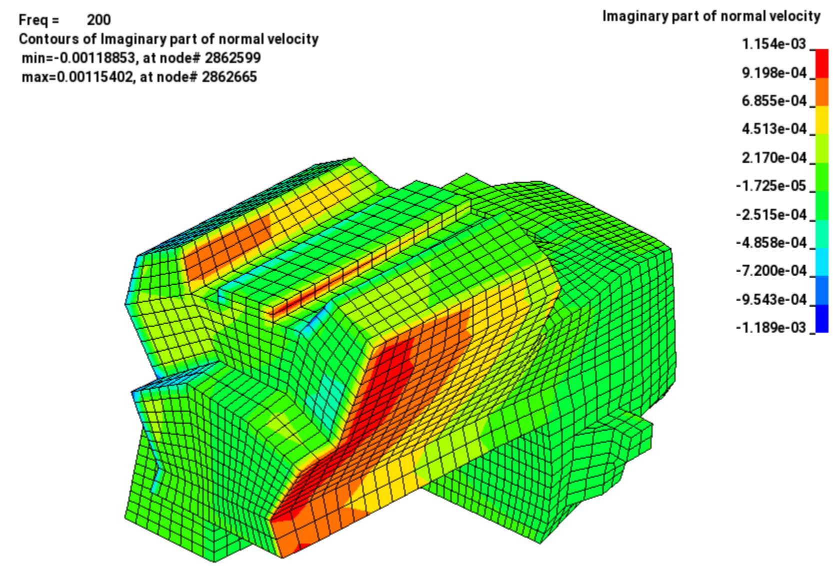

Freq = 100
Contours of Real part of normal velocity
min=-2.76615e-06, at node# 2862665
max=2.83501e-06, at node# 2862599
Real part of normal velocity
2.835e-06
2.275e-06
1.715e-06
1.155e-06
5.945e-07
3.443e-08
-5.257e-07
-1.086e-06
-1.646e-06
-2.206e-06
-2.766e-06

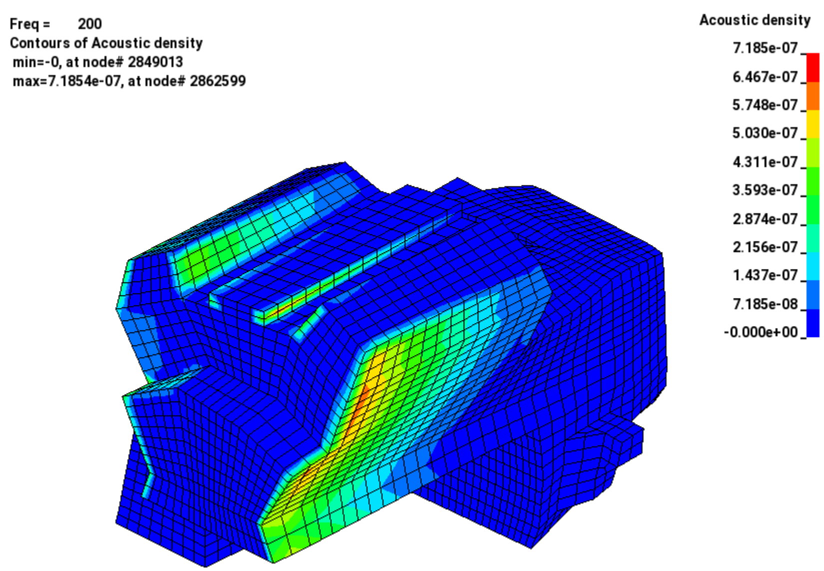

Freq = 100
Contours of Imaginary part of normal velocity
min=-0.000489514, at node# 2862665
max=0.00049382, at node# 2862599
Imaginary part of normal velocity
4.938e-04
3.955e-04
2.972e-04
1.988e-04
1.005e-04
2.153e-06
-9.618e-05
-1.945e-04
-2.928e-04
-3.912e-04
-4.895e-04

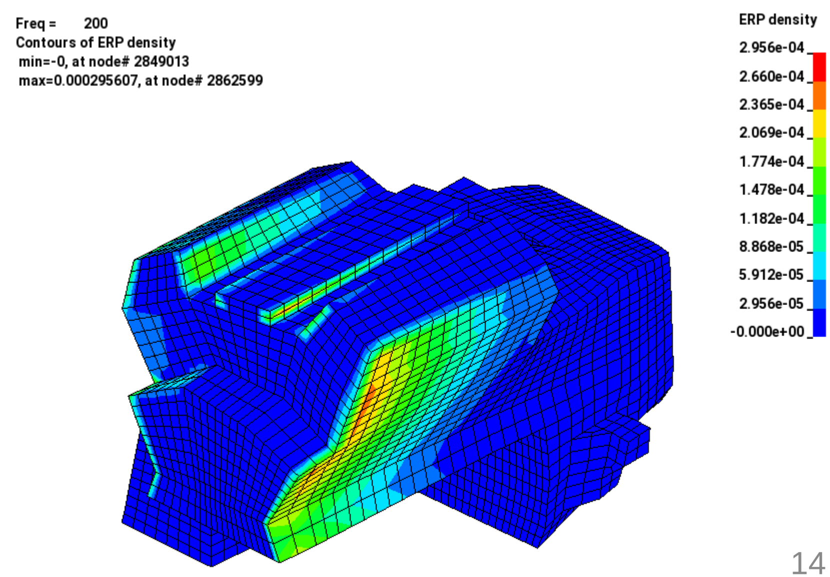

Freq = 100
Contours of Absolute value of normal velocity
min=-0, at node# 2849013
max=0.000493828, at node# 2862599
Absolute value of normal velocity
4.938e-04
4.444e-04
3.951e-04
3.457e-04
2.963e-04
2.469e-04
1.975e-04
1.481e-04
9.877e-05
4.938e-05
-0.000e+00


Freq = 100
Contours of ERP density
min=-0, at node# 2849013
max=5.01634e-05, at node# 2862599
ERP density
5.016e-05
4.515e-05
4.013e-05
3.511e-05
3.010e-05
2.508e-05
2.007e-05
1.505e-05
1.003e-05
5.016e-06
-0.000e+00

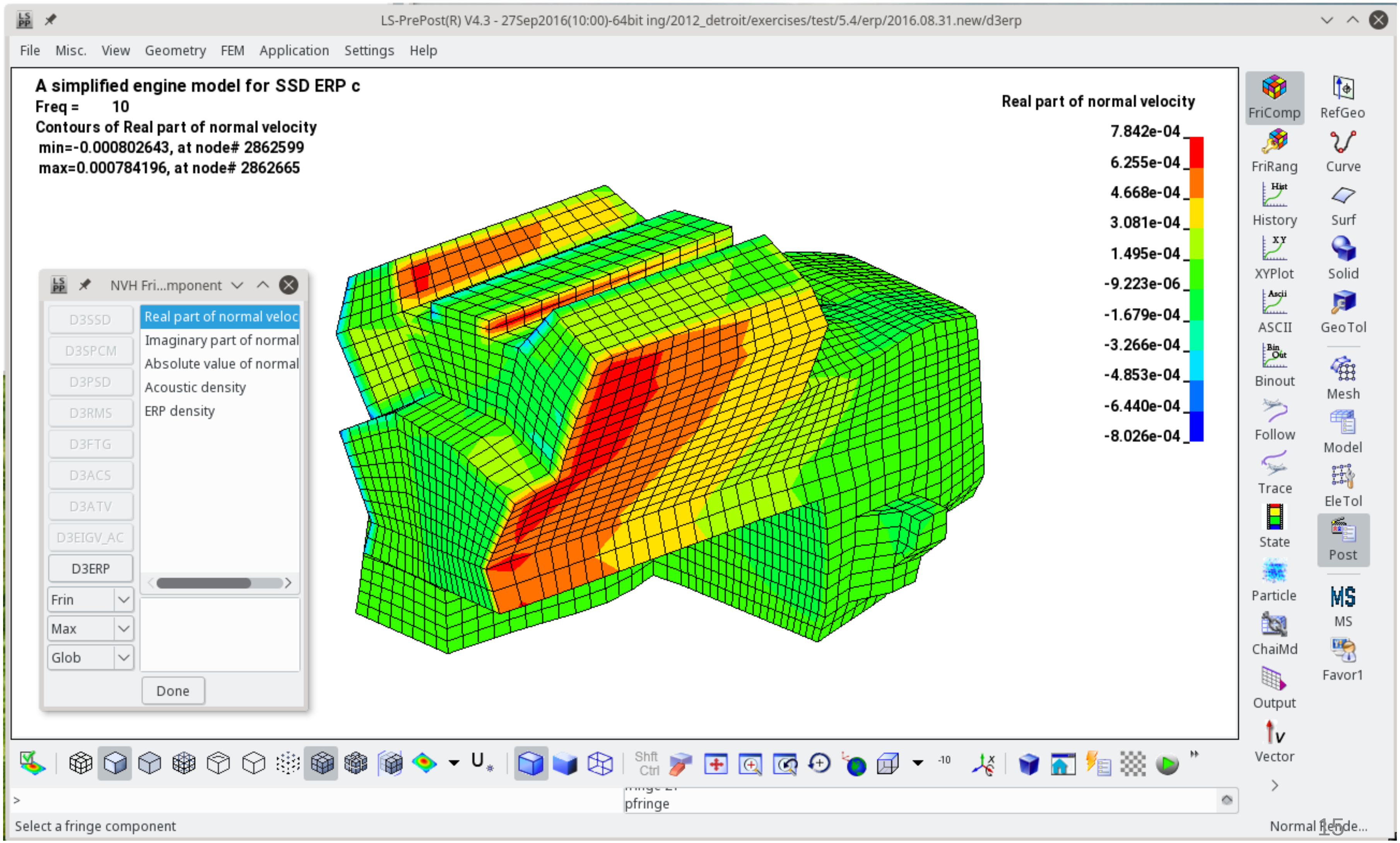

Freq = 200
Contours of Real part of normal velocity
min=-0.000152456, at node# 2862665
max=0.000156418, at node# 2862599
Real part of normal velocity
1.564e-04
1.255e-04
9.464e-05
6.376e-05
3.287e-05
1.981e-06
-2.891e-05
-5.979e-05
-9.068e-05
-1.216e-04
-1.525e-04

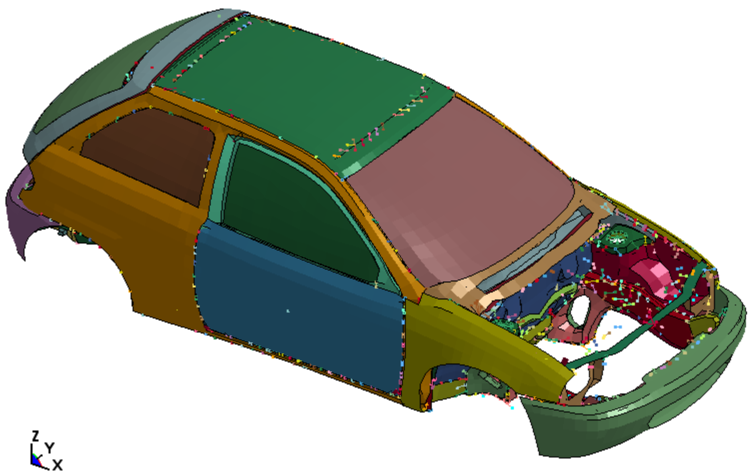

Freq = 200
Contours of Imaginary part of normal velocity
min=-0.00118853, at node# 2862599
max=0.00115402, at node# 2862665
Imaginary part of normal velocity
1.154e-03
9.198e-04
6.855e-04
4.513e-04
2.170e-04
-1.725e-05
-2.515e-04
-4.858e-04
-7.200e-04
-9.543e-04
-1.189e-03


Freq = 200
Contours of Acoustic density
min=-0, at node# 2849013
max=7.1854e-07, at node# 2862599
Acoustic density
7.185e-07
6.467e-07
5.748e-07
5.030e-07
4.311e-07
3.593e-07
2.874e-07
2.156e-07
1.437e-07
7.185e-08
-0.000e+00

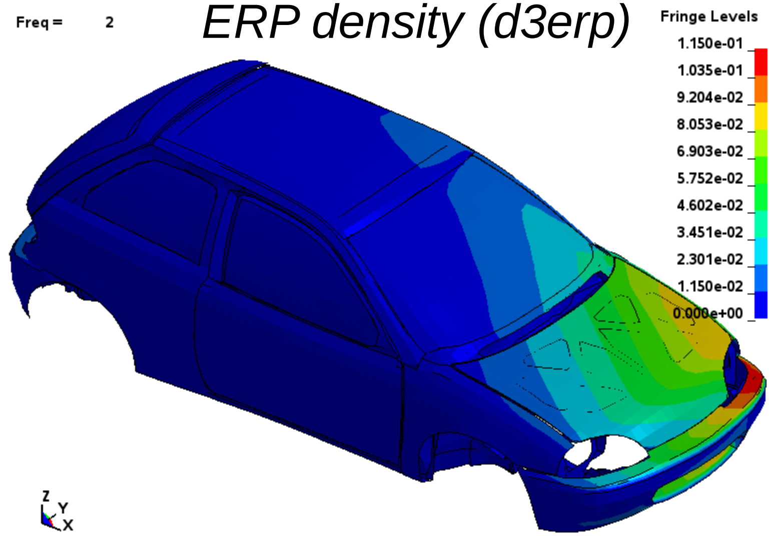

Freq = 200
Contours of ERP density
min=-0, at node# 2849013
max=0.000295607, at node# 2862599
ERP density
2.956e-04
2.660e-04
2.365e-04
2.069e-04
1.774e-04
1.478e-04
1.182e-04
8.868e-05
5.912e-05
2.956e-05
-0.000e+00

GUI for post-processing of d3erp

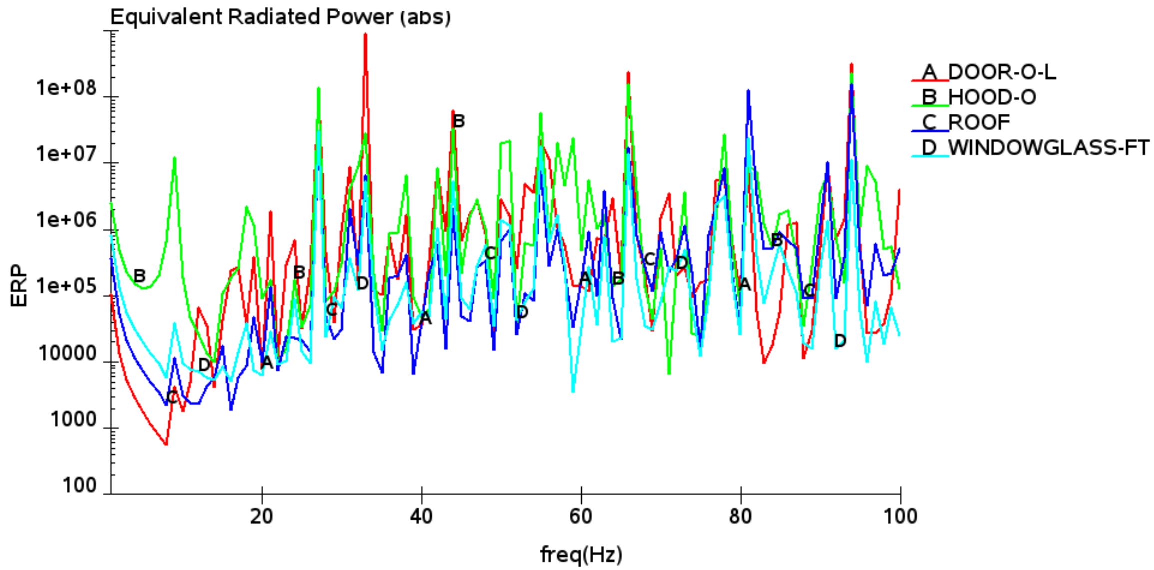




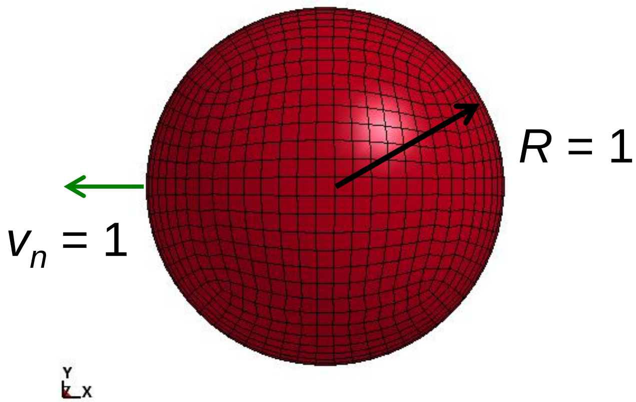
ERP density (d3erp)



With ERP, one can study the contribution to the radiated noise from each panel.



Pulsating sphere



$$\rho = 1.21; \quad c = 343.0$$

$$W = \frac{1}{2}\rho c \int_S \mathrm{Re}\left[v_n \cdot \bar{v}_n\right] dS$$

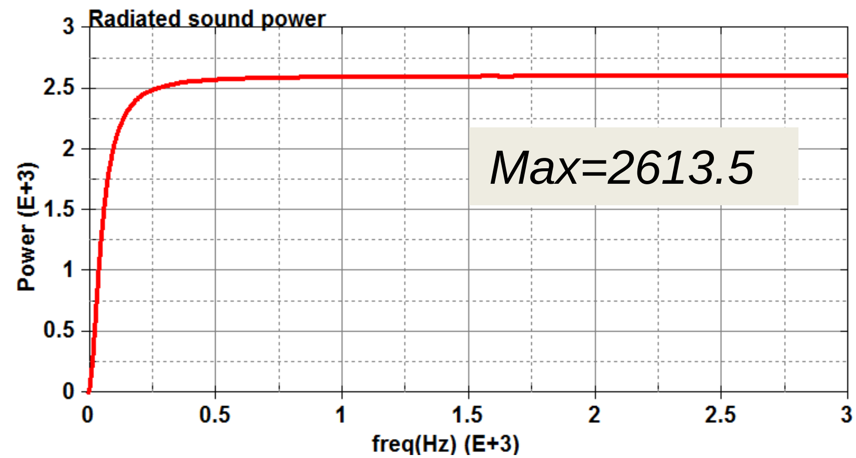
$$= \frac{1}{2}\rho c \int_S dS$$

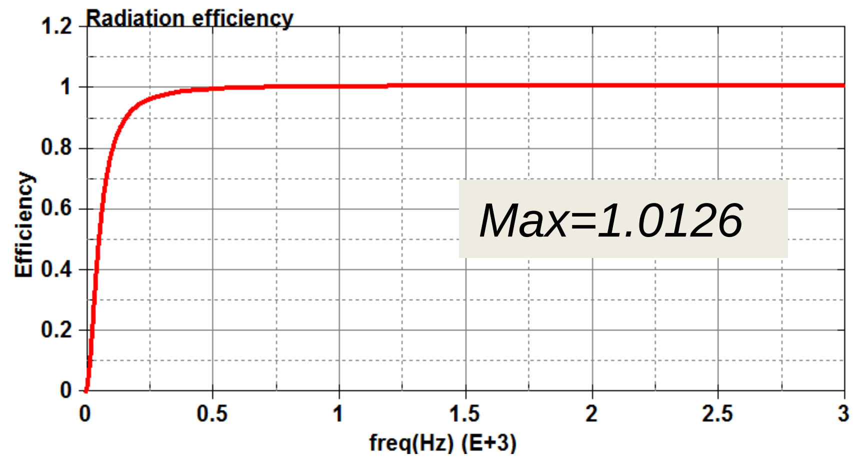
$$= 2\pi \rho c R^2$$

$$= 2607.7$$

* FREQUENCY_DOMAIN_ACOUSTIC_BEM

Press_Power
Press_radef





5) Conclusions

- A feature for ERP calculation is implemented
- Post-processing of the calculation results is provided
- Need to add element ERP absolute to d3erp
- More validation / testing
- Optimization based on ERP?

THANK YOU!

for your attention

Yun Huang huang@lstc.com
Zhe Cui czhe@lstc.com