

## EVALUATION AND VISUALIZATION OF EQUIVALENT RADIATED POWER IN $\mu$ ETA

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ABSTRACT – Noise and vibration control is a demanding task in many engineering applications such as automotive engineering. Computation of the equivalent radiated power (ERP) is a simplified method to gaining information about maximal possible dynamic radiation of components and panels for specific excitations in frequency response analysis. ERP is well established and widely used. Integrated ERP computation with commercial solvers as a downstream process to evaluation of velocity responses is still limited. Only a limited number of commercial NVH postprocessing tools offer the possibility to compute and visualize ERPs from velocity results. Recent releases of  $\mu$ ETA do not have this feature. The authors have implemented and tested a new toolbar for ERP computation and visualization in  $\mu$ ETA taking advantage of the improved scripting functionality and the toolbar designer in recent releases of  $\mu$ ETA. Implementation, functionality, limitations and possible extensions of the ERP toolbar are explained and discussed in detail. Examples from automotive applications like validation and optimization of a gearbox are presented. Results derived with the ERP toolbar are compared with those derived with the ERP functionality of MD Nastran 2010. There is a good agreement of the results.

TECHNICAL PAPER –

### 1. INTRODUCTION

Noise control has become of great importance in many engineering applications like automotive engineering over the last years. Computation of acoustic responses requires the solution of expensive and time consuming coupled fluid/structure interaction problems. Design optimization processes with objective functions based on acoustic results become prohibitively costly.

In many practical engineering applications the noise radiated from a structure must be reduced. Thus, it is important to identify those parts of the structure which contribute most and to identify those frequencies where the radiation becomes maximal. A simplified access to gaining information about maximal possible dynamic radiation of components and panels for specific excitations in frequency response analysis is the computation of the equivalent radiated power (ERP) of those parts. Its computation is primarily dependent on the evaluation of velocity responses on the radiating surface which can be computed with all commercial FEM solvers. Requirements on computing power and computing time of optimization processes based on ERP information are significantly smaller than those based on acoustic responses.

The proposed formulation depends on the computation of the velocity distribution on the surface of the model with the finite element method. Based on these finite element results the ERPs on the surface of the structure can be computed as a postprocessing step. Thus, the necessary formulations must be implemented into a postprocessor.

Recent  $\mu$ ETA versions offer improved scripting functions and a Script Editor which enable the user to extend the postprocessing functionalities. The Toolbar Designer offers the necessary functionality for building user defined toolbars with which the implemented scripts can be accessed and controlled. These two tools have been used to implement the proposed formulation into  $\mu$ ETA.

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## 2. EQUIVALENT RADIATED POWER

### Element Area

The first step in computing ERPs is the computation of the area of the surface elements. As can be seen by identification of any arbitrary shell element in μETA the area of this element is known but cannot be visualized. To visualize the element area a new resultset must be created. This can easily be done with the μETA function 'AreaOfElement' for all shell elements.

### Normal Velocity

The normal of an element can be evaluated from the μETA post function 'ShellNormalOfElement'. The element normal velocity can then be evaluated by computing the magnitude of the scalar product of normal and velocity

$$(1) \quad abs(v_n) = abs(v_x \cdot n_x + v_y \cdot n_y + v_z \cdot n_z).$$

The normal velocity of a complete property (PID) is computed as the sum over all normal element velocities of that property.

### Pressure

The pressure  $p$  on an arbitrary point  $r_p$  is defined as

$$(2) \quad p(r_p) = \frac{i\omega\rho}{2\pi} \int_S v_n(r_s) \frac{e^{-ikR}}{R} dS$$

where  $k=\omega/v_F$  denotes the wave number and  $R=|r_s-r_p|$  is the distance between an arbitrary field point and the evaluation point.

### Intensity

The acoustic intensity of any point  $r_p$  can be computed from the product of pressure and normal velocity and is defined as

$$(3) \quad I(r_p) = \frac{1}{2} \text{Re}[p(r_p) \cdot v_n(r_p)^*]$$

where  $p$  is the pressure at  $r_p$ ,  $v_n$  is the normal velocity and \* denotes the complex conjugate.

### Acoustic Power

The acoustic power  $W$  radiated from the surface is the integral of the intensity over that surface and is thus given by

$$(4) \quad W = \int_S I(r_s) dS.$$

### ERP density

The equivalent radiated power density is defined as

$$(5) \quad ERP_\rho = \frac{1}{2} \rho_F v_F \text{Re}[v_n(r_p) \cdot v_n(r_p)^*].$$

The equivalent radiated power density can thus be computed from the normal velocities locally at each point of the surface.

### ERP absolute

The absolute value of equivalent radiated power radiated from the surface of a plate is the integral of the ERP density over that surface and is given by

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$$(6) \quad ERP_{abs} = \frac{1}{2} \rho_F v_F \int_S \operatorname{Re}[v_n(r_P) \cdot v_n(r_P)^*] dS.$$

### ERP in dB

Usually, the computed ERP is expressed in dB values. The underlying relation for transforming ERP absolute to ERP in dB is

$$(7) \quad ERP_{dB} = 10 \log_{10} \left( ERP_{abs} / ERP_{ref} \right)$$

where  $ERP_{ref}$  is a reference value.

### 3. FUNCTIONALITY OF THE ERP TOOLBAR

The ERP toolbar that has been implemented offers the necessary functionality for calculating the ERP values from computed surface velocity distributions.

Firstly, a surface mesh of shell elements of the considered structure must be imported and from this model the area of each surface shell element will be computed, see Figure 1 (ComputeElementArea). These quantities are stored as a new resultset and can be visualized as a fringe plot, see Figure 2 (Element area at state 1).

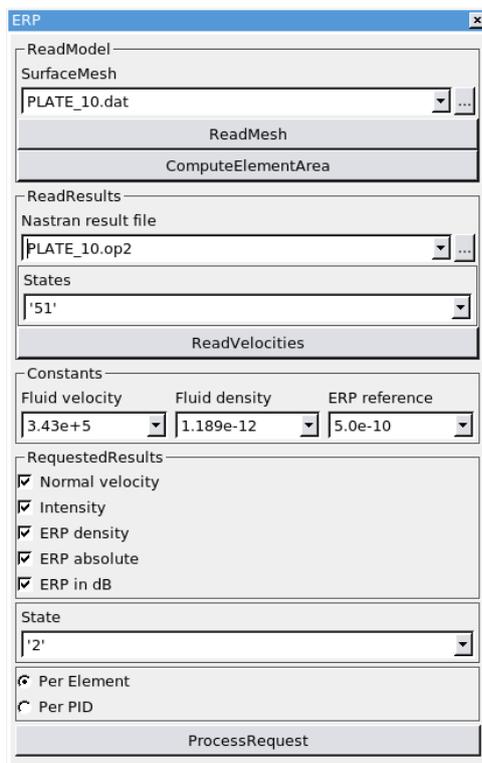


Figure 1: ERP toolbar

The next step is the import of computed velocity distributions from a Nastran result file. Velocities can be imported in binary (OP2) or ASCII (PCH) format. For each relevant frequency the computed magnitude of translational velocity must be read as a vector-valued function from a file which can be selected with the 'Nastran result file' entry widget. The corresponding states must be specified in the 'States' entry widget, cf. Figure 1 ('51'). Here, a list of requested states can be specified as a comma-separated list or a range of states can be entered with a hyphen. Afterwards the button 'ReadVelocities' must be pressed to start the import process. Now, for each selected result state a new resultset of the translational magnitude of the velocities is created, cf. Figure 2 (SUBCASE 100:: ...). For now the proposed ERP toolbar is limited to Nastran result files only. This can easily be extended to other solvers by some simple modifications in the toolbar import interface.

The computation of the ERP values requires the specification of some constants to evaluate the equations (5) – (7). These quantities can be specified in the entry widgets ‘Fluid velocity’, ‘Fluid density’ and ‘ERP reference’. The user has to make sure that the values entered are suitable for the considered fluid and are in correct units. In some formulations for ERP evaluation in dB like in MD Nastran an additional scaling factor is introduced (MD Nastran: 2.0). This can be accounted for in the proposed formulation by suitable scaling of the entered value for the ERP reference.

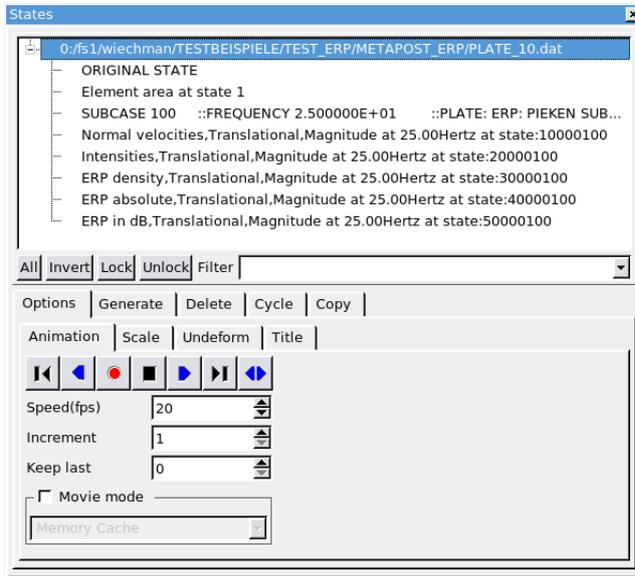


Figure 2: States created with the ERP toolbar

In the frame entitled ‘RequestedResults’ the requested quantities are specified. There are five checkbuttons for ‘Normal velocity’, ‘Intensity’, ‘ERP density’, ‘ERP absolute’ and ‘ERP in dB’. At least one of these quantities must be selected.

The states for which the selected quantities are evaluated must be specified in the ‘State’ entry widget, cf. Figure 1 (‘2’). Here, the same specifications as in the import states entry widget are allowed.

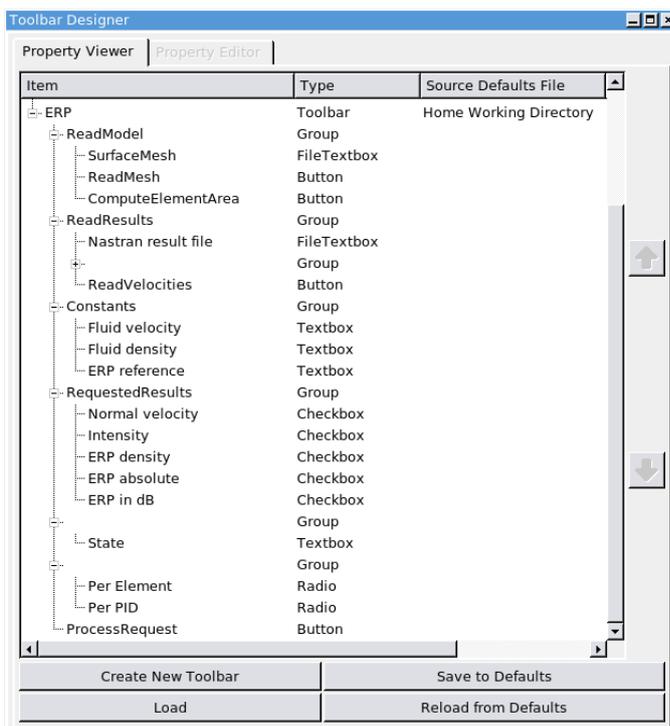


Figure 3: Toolbar Designer with ERP toolbar definition

Finally, the type of evaluation either for each element or for a complete property (PID) must be specified with the radio buttons 'Per Element' and 'Per PID', respectively.

Correspondingly, the requested results are evaluated element-wise or for each property specified in the model.

Pressing the button 'ProcessRequest' will then start the evaluation of the requested quantities. New states for the requested results are created and can be visualized as 3D fringe plots, see Figure 2 (Normal velocities..., Intensity..., ERP density..., ERP absolute... and ERP in dB...).

The ERP toolbar was developed with the improved scripting functionality and the Toolbar Designer available in  $\mu$ ETA postprocessor. In Figure 3 the definitions for the ERP toolbar in the Toolbar Designer can be seen.

## 2. VERIFICATION EXAMPLE

A small test problem has been considered in order to verify the presented implementation of ERP in  $\mu$ ETA. As depicted in Figure 5 a square plate simply supported at all edges have been meshed with 50x50 QUAD4 elements. It is loaded with a uniform vertical load  $p=1e-6$ N/mm<sup>2</sup>.

```
SOL 111
DIAG 5,8,13
CEND
TITLE = PLATE
SUBTITLE = ERP
SPC =1
METHOD =100
SUBCASE 100
  LABEL =PLATE
  DLOAD=610
  FREQUENCY=600
  VELOCITY(PLOT)=ALL
  SET 22=PANEL
  ERP(PUNCH,SOLUTION=ALL,KEY=FREQ)=22
BEGIN BULK
SET3      1  ELEM      1  THRU   2500
ERPPNL PANEL      1
PARAM,COUPMASS,1
PARAM,GRDPNT,0
PARAM,POST,-1
PARAM,PRGPST,NO
PARAM,NASPRT,1
PARAM,MECHPRT,YES
PARAM,ERPRHO,1.189e-12
PARAM,ERPC,3.43e5
PARAM,ERPRLF,1.0
PARAM,RHOCP,1.0
PARAM,ERPREFDB,1.0e-9
RLOAD2,610, 610,0.,0.,999,,0
PLOAD2,610,1.-6,1,THRU,2500
TABLED1  999LINEAR LINEAR
+      0.  1. 1000.  1.ENDT
FREQ1,600,15.,0.2,50
EIGRL,100,,100.,0,,MAX
MAT1,1,210000.,0.3,7.85-9
INCLUDE 'PLATE_01.bdf'
ENDDATA
```

Figure 4: Listing of the MD Nastran input file

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As can be seen in Figure 4 parameters for the MD Nastran ERP computation have been set to  $\rho_F=1.189\text{e-}12$  (PARAM,ERPRHO),  $\nu_F=3.43\text{e}5$  (PARAM,ERPC) and  $ERP_{ref}=1.0\text{e-}9$  (PARAM,ERPREFDB). In order to account for the additional scaling operation for computation of ERP in dB in MD Nastran (factor 2.0) the ERP reference value in  $\mu$ ETA was divided by 2.0 and was thus set to  $5.0\text{e-}10$ , see Figure 1.

A frequency response analysis for the low frequency range from 15Hz to 25Hz has been computed. The complete plate was defined as one panel. The velocity and the ERP have been computed. Velocities have been written to the OP2-file (VELOCITY(PLOT)=ALL). The ERP was computed with default parameter settings and output to the PCH-file (ERP(PUNCH,SOLUTION=ALL,KEY=FREQ)=22). Here, set 22 is an element set of all QUAD elements of the plate (SET 22=ANEL).

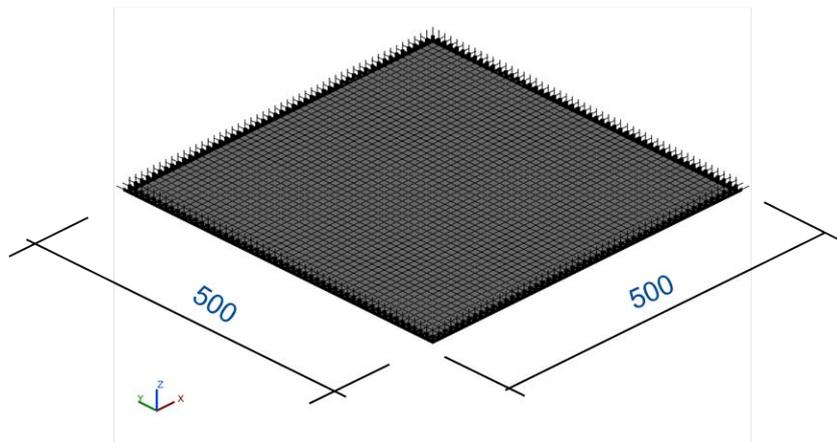


Figure 5: Simply supported quadrilateral plate with dimensions 500x500mm

Due to the applied loading in vertical z-direction only all velocity components perpendicular to that direction are zero. Thus, plots of velocity magnitude and normal velocity are identical as can be seen in Figure 6.

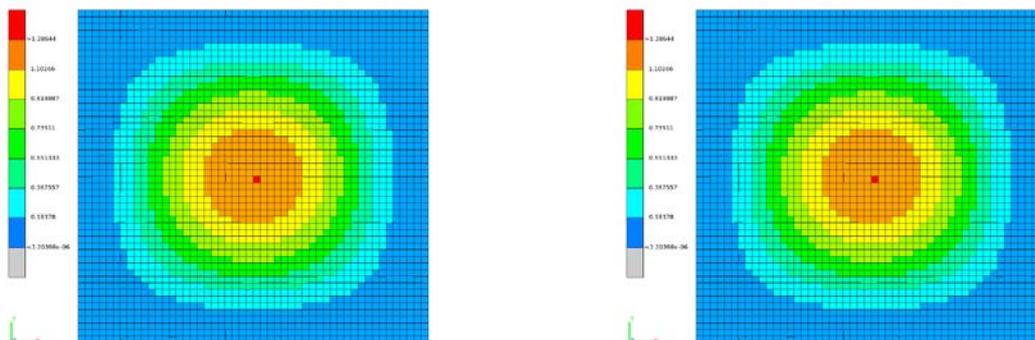


Figure 6: Velocity, Translational, Magnitude at 25Hz; Normal velocity at 25Hz

Based upon the computed normal velocities of the plate elements the corresponding distributions of intensity, ERP density, ERP absolute and ERP in dB have been evaluated. The corresponding fringe plots of the created states are shown in Figure 7.

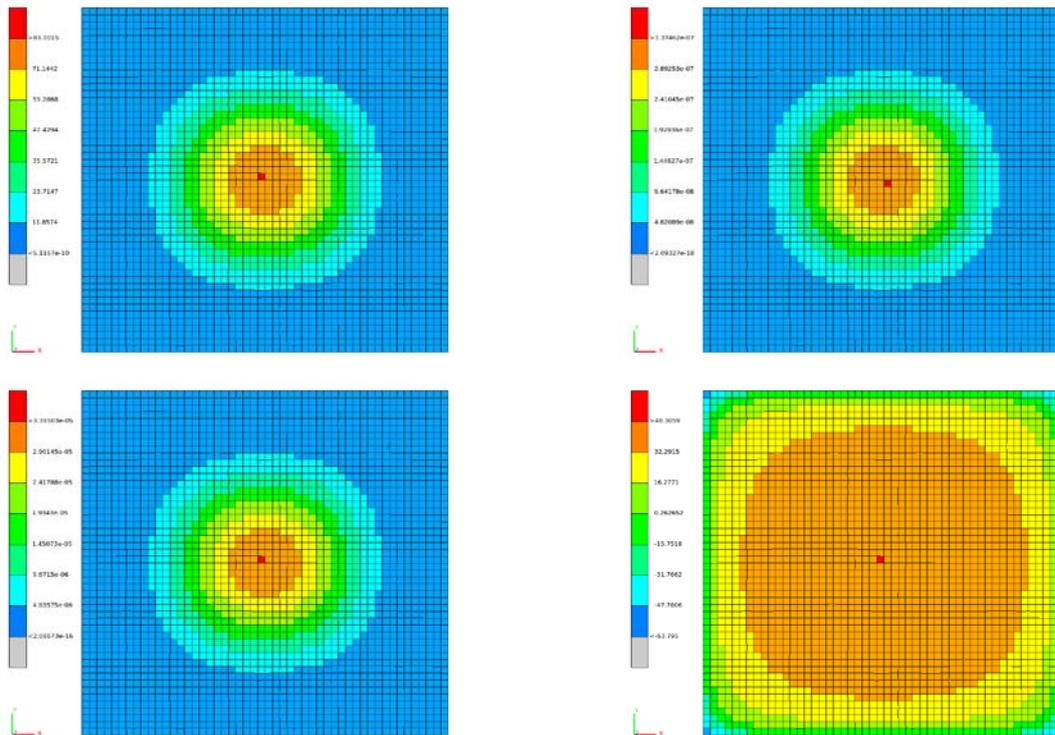


Figure 7: Intensity, ERP density, ERP absolute and ERP in dB at 25Hz

Finally, the ERP of the complete panel has been computed and it was compared with the results derived from the MD Nastran ERP computation.

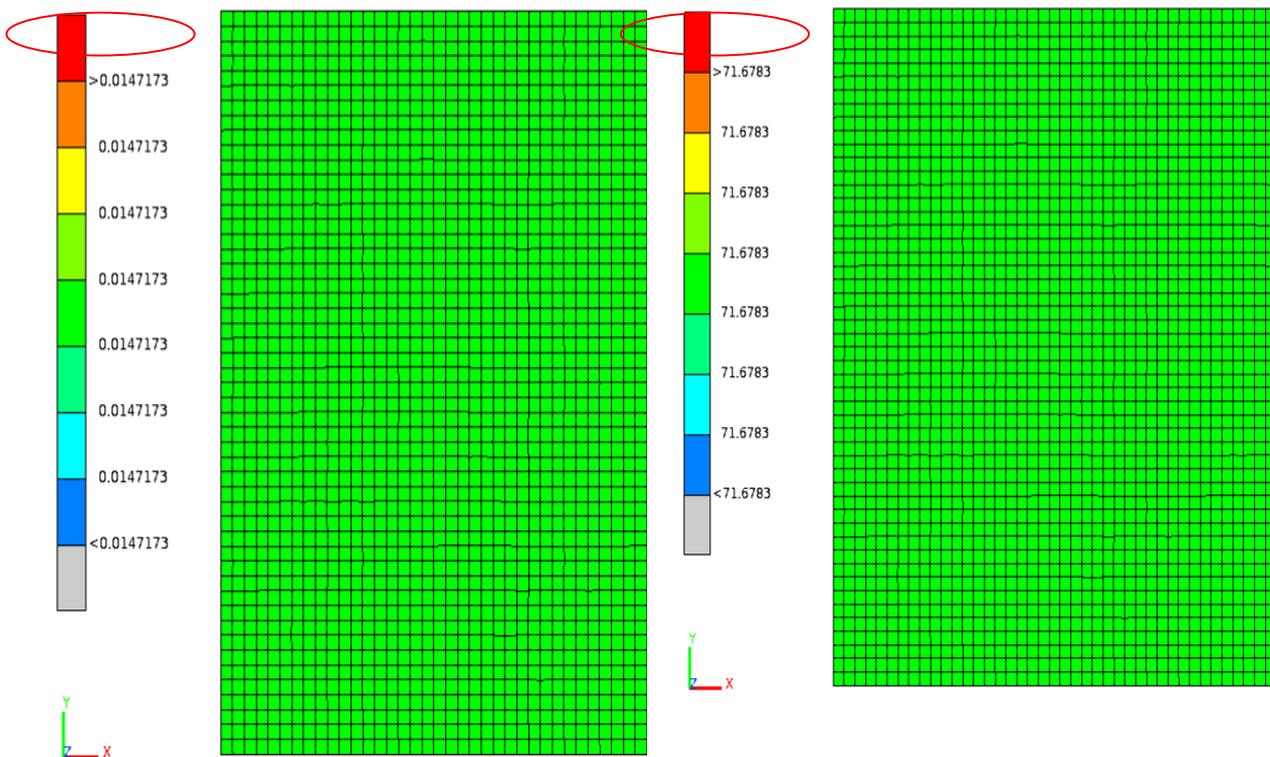


Figure 8: ERP absolute and ERP in dB per panel at 25Hz

As can be seen in Figure 8 and Figure 9 results from MD Nastran and those derived with the ERP toolbar are in good agreement. The difference in some decimal units might be due to some rounding errors.

\$ERP*	2.400000E+01	1.177332E-02	7.986679E-01	7.070899E+01
\$ERP*	2.420000E+01	1.230247E-02	8.345636E-01	7.089992E+01
\$ERP*	2.440000E+01	1.286152E-02	8.724877E-01	7.109292E+01
\$ERP*	2.460000E+01	1.345267E-02	9.125900E-01	7.128809E+01
\$ERP*	2.480000E+01	1.407835E-02	9.550342E-01	7.148552E+01
\$ERP*	2.500000E+01	1.474120E-02	1.000000E+00	7.168533E+01
\$ERP*ERP MAX		1.474120E-02		

Figure 9: Extract from the MD Nastran punch file

### 3. OPTIMIZATION OF A GEARBOX

The proposed implementation has been used to optimize a gearbox design with respect to radiated power. The initial design of a gearbox is shown in Figure 10. Eight panels have been defined (upper front right, lower front right, upper front left, lower front left, upper rear right, lower rear right, upper rear left, lower rear left).

For this model a unit load was applied to simulate contact of the gear wheel flanks. For this load case a frequency response analysis in the frequency range from 1000Hz to 2000Hz was performed. The purpose of the investigation was the identification of critical frequencies within the specified range and the identification and subsequent optimization of the maximal contributing panels.

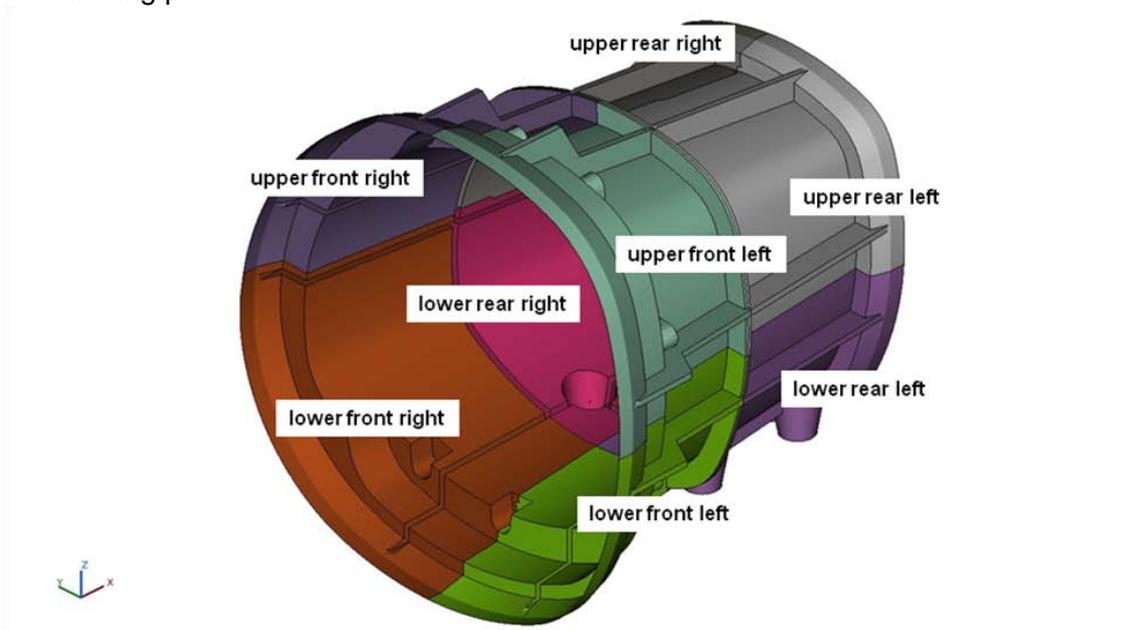


Figure 10: Panel definition for the gearbox

In Figure 11 the computed element area (right side of the gearbox) can be seen. Element sizes are varying approximately from 3mm<sup>2</sup> to 6mm<sup>2</sup>.

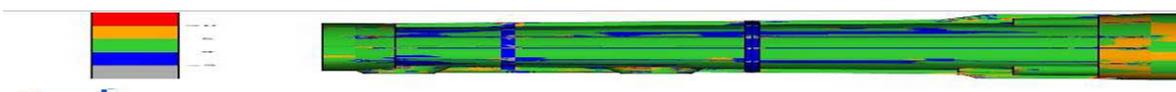


Figure 11: Element area

The panel contributions of the gearbox panels in the considered frequency range have been computed. The results derived from MD Nastran ERP computations can be seen in Figure 12 for the front of the gearbox and in Figure 13 for the rear panels of the gearbox. The critical frequency is at 1700Hz where the curves have a maximal value. The most contributing panel at that frequency is the lower rear right panel as can be seen in Figure 14. The contribution of the lower front right panel is almost as high as that of the lower rear right panel at critical frequency 1700Hz.

Based upon these findings an optimization of the ribs of the gearbox has been performed in order to reduce the contribution of the lower rear right and the lower front right panel and thus reduce the peak at 1700Hz.

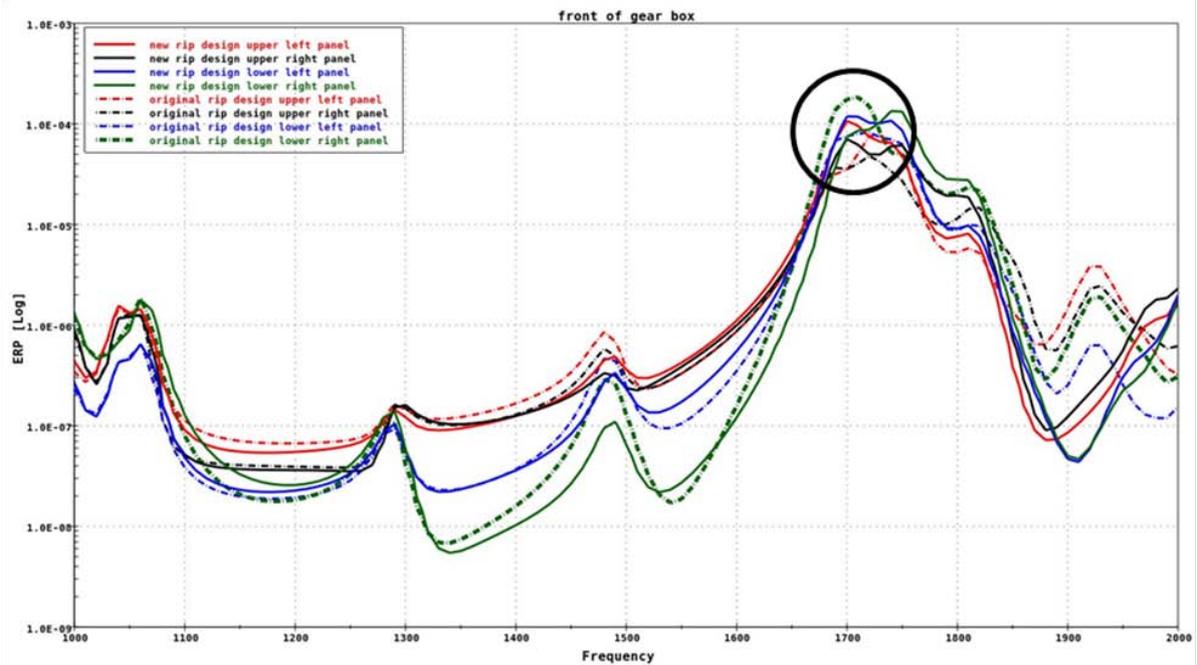


Figure 12: Comparison of ERP results for front panels of the initial design (dotted lines) and the improved design (solid lines)

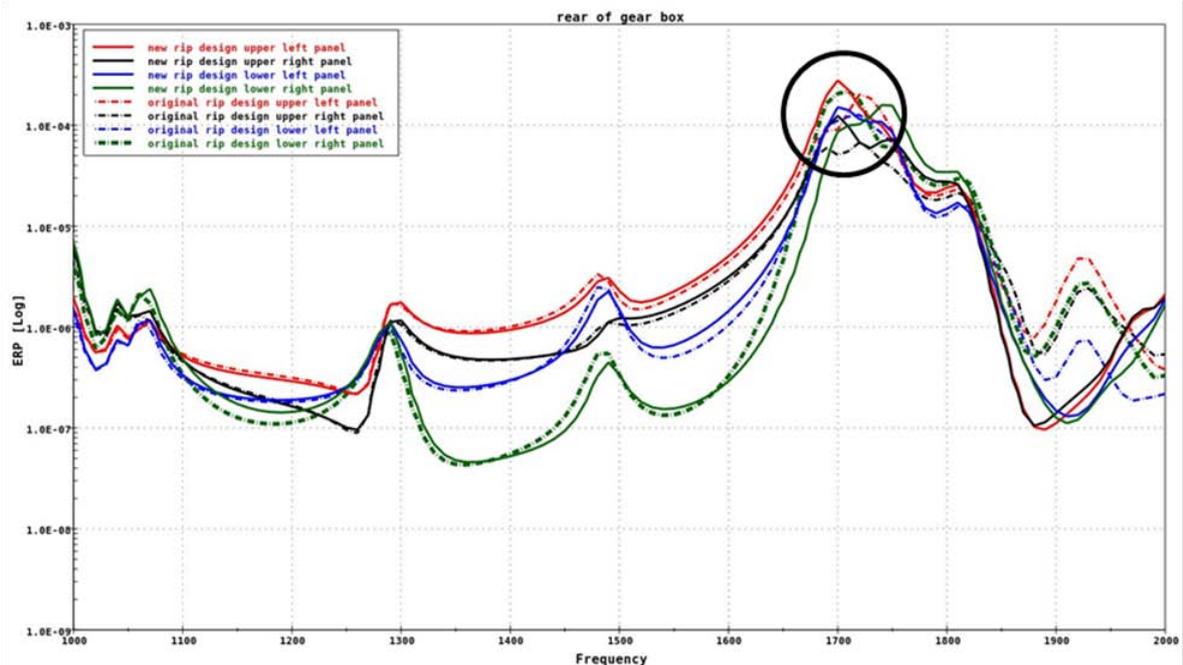


Figure 13: Comparison of ERP results for rear panels of the initial design (dotted lines) and the improved design (solid lines)

The resulting rib design can be seen in Figure 15 and Figure 16.

As can be seen from Figure 12 and Figure 13 with the new rib design the reduction of the contribution of the lower front right panel could be reduced by 57% and the contribution of the lower rear panel could be reduced by 58%.

For the new design the contributions of the upper and lower rear left panel now become significantly increased.

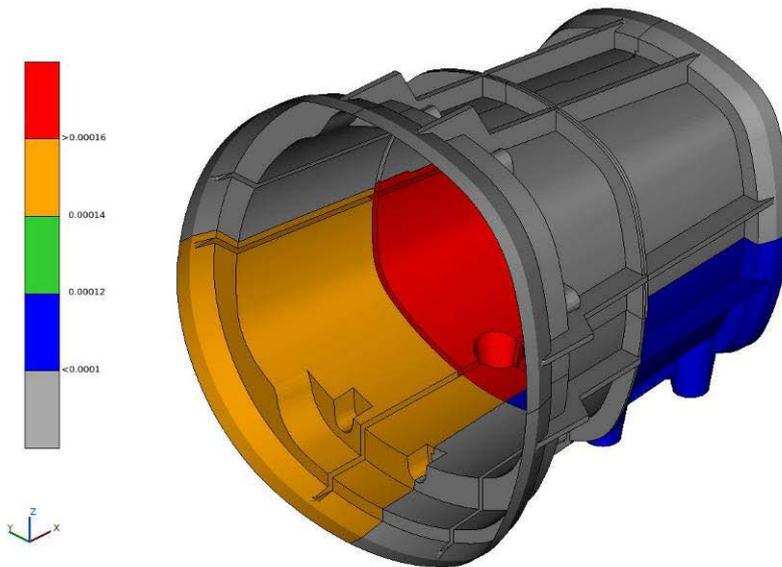


Figure 14: ERP density plot per panel (PID) of original design at 1700Hz

In Figure 15 and Figure 16 distribution of intensities and ERP results in dB are compared for the original and the improved design. The findings for the upper and lower rear left panels derived from the curves in Figure 12 and Figure 13 are confirmed by these plots.

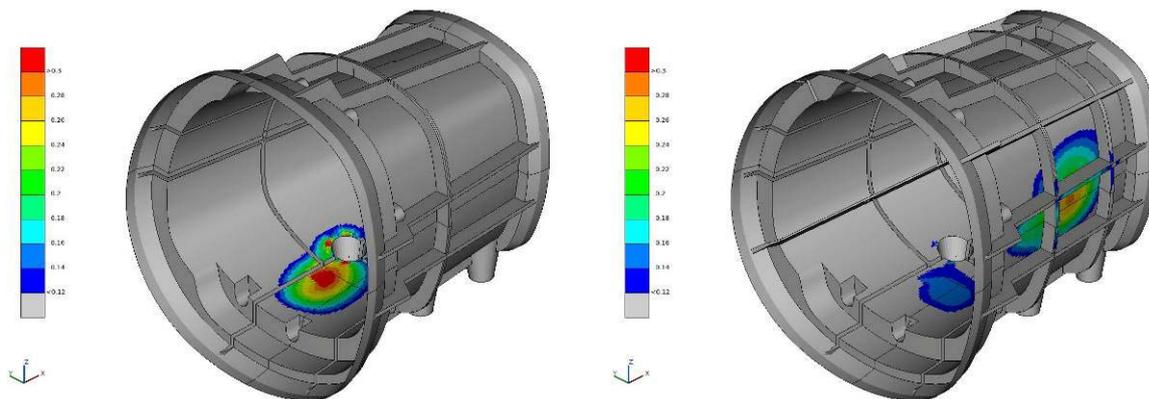


Figure 15: Intensity plot per element of original and improved design at 1700Hz

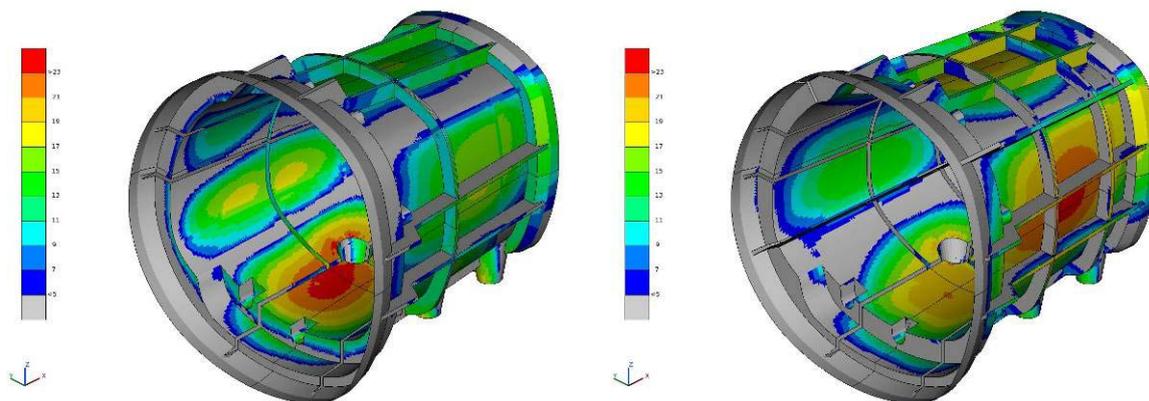


Figure 16: ERP in dB of original and improved design at 1700Hz

#### 4. CONCLUSIONS

The scripting functionality and the Toolbar Designer in  $\mu$ ETA have been used to implement a new User Toolbar for the evaluation of equivalent radiated power. The formulation and implementation have been verified by comparison of the derived results of simple test

problems with those from solver results. The use of the ERP toolbar has proved to be valuable in solving practical engineering problems like optimization of gearboxes.

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