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Connecting bolt constraint based design parameter optimisation of vibrating transmission gearbox housing using RSM *

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Abstract. Transmission gearbox housing is subjected to meshing excitation, harmonic excitation and transmission errors. In resultant vibration is produced. To reduce the damage from this vibration, transmission assembly is mounted on truck frame using connecting bolts. The number of connecting bolts may vary as depends on design and size of gearbox assembly. In condition of connecting bolts looseness, gearbox housing vibrates and caused damage to gears. Therefore it is required to tightly mount the housing on vehicle chassis frame. The main objective of this research study is to find the optimised number of connecting bolts required for tight mounting of gearbox system on vehicle chassis frame. Parametric optimisation was done using Response Surface Method (RSM). Detuning principle was used to find the safe condition for gearbox housing. In design of present gearbox system, there were 37 connecting bolts holes in housing for tight mounting. FEA simulation is used for simulation of optimised connecting bolts. Ansys 14.5 was used for FEA analysis and solid edge, Pro-E for solid 3D modeling.

Keywords: Central Composite Design (CCD), Optimisation, RSM, FEA and ANOVA

1 Introduction

Response surface method (RSM) is well suited where input variables influenced the response of a system. In this research article RSM is used for analysis of heavy vehicle medium duty truck transmission gearbox housing. For RSM study two design parameters and one response parameter was selected. Response parameter shows the quality characteristics of process. The design parameters are connecting bolts, Young's modulus and output parameter is frequency (Hz). RSM and FEA numerical methods have been used since long time for complex problem solution. The literature study shows that authors have used RSM in vehicle parts analysis, vibro-acoustic analysis, damping structure analysis, welding parameters optimization, Rapid prototyping parameters optimization etc. Vibro-acoustic design was optimized using RSM[9, 11–13, 19]. The sound level inside passenger cabin has been studied using FEM-BEM combination. For structural analysis FEM was used. Boundary Element method (BEM) was coupled with FEM for acoustic analysis. Design of Experiment (DOE) has been used for finding the relation between input and output parameters. For shape optimization, first eigen frequency was optimized. RSM has been adopted for damping structure optimization. RSM analysis reduces the cost of system. Transmission gearbox looseness analysis was performed by kumar[8, 10], and Dogan[5]. Vehicle modelling and optimization were studied[6, 14, 17].

Patil et al.[16] have used the RSM technique in electromechanical Coriolis mass flow sensor (CMFS). They have measure the performance of CMFS by varying sensor location and excitation frequency parameter. Central composite design (CCD) was used for RSM. Lü and Yu[7], Kinkaid et al.[15] have studied the brake squeal

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reduction of vehicle. Kinkaid has conducted the review study and Lu has used complex eigenvalue analysis (CEA) and Finite element model to study the brake squeal reduction of vehicle using uncertain optimization method. The parameters are material properties, frictional coefficient and the thicknesses of wearing components. In this research study gearbox housing material property (young's modulus) is also selected as one of design parameter.

2 Model establishment of transmission gearbox housing

Fig. 1 shows solid model (isometric view) of transmission gearbox housing. Complete transmission system was designed by assembling more than 600 components. The part modeling was done by obtaining details from manufacturer of medium duty trucks in India. The main part of assembly is shafts, bearing and gears. Housing material has damping property to absorb shock and impact loading. Housing is required to provide sealing against gear oils and prevent direct damage to gears. Gearbox housing is subjected to internal excitation and harmonic excitation. It is mounted on vehicle frame using connecting bolts. The number of connecting bolts varies up to 37 depending on size of housing. With tetrahedron element (Tet 4) the Ansys 14.5 [18] meshed model have 2, 14,644 nodes and 1, 24,531 elements. For 3D modeling Solid Edge[1] and Pro-E [3] were used. First twenty natural frequency and mode shapes were evaluated for accurate analysis of results.

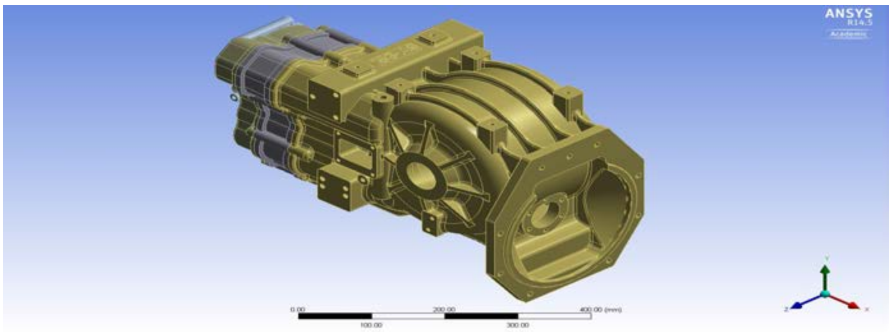


Fig. 1: Heavy vehicle medium duty truck transmission gearbox housing

3 Response SURFACE METHOD (RSM) optimisation results

In present research work RSM has been used to find optimized number of connecting bolts for transmission housing. The design parameters are number of connecting bolts (5-12) and material properties of housing material (young's modulus, 110-120 GPa). The response was measured in form of frequency (Hz). Central composite design (CCD) with quadratic function was used in RSM optimization. The result of RSM can be expressed graphically in form of 3D surface graph and contour plots. These graphs are used in visualization of the frequency response. A regression model is developed using design parameters. It is a second order non-linear polynomial equation relating design parameters with output response. RSM uses Taylor series expansion. Table 1 shows RSM design layout. Based on design requirements and literature review the range of parameters was selected. The range of connecting bolts studied is (5-37) and young's modulus range was (110-120) GPa. Output response variable studied is frequency (Hz).

The design layout of RSM for heavy vehicle medium duty truck transmission housing was generated using software Design Expert version 9.0[2]. From ANOVA (Analysis of Variance) result, significant model terms are A, B, AB, A2, and B2 (A-Connecting bolts number and B- Young's Modulus). Quadratic model has provided best fit and shows insignificant lack of fit that is desirable. Coefficient of correlation (R2) terms are close to 1. The predicted R2 of 0.9640 is in agreement with the adjusted R2 of 0.9799. Adequate precision is 49.574. It

Table 1: RSM design layout

Run Order	Design Parameters		Response: Frequency (Hz)
	Connecting Bolts	Material Property: Youngs Modulus	
1	5	110	667.57
2	11	110	1176.9
3	5	120	697.25
4	11	120	1234.4
5	8	115	1038.6
6	8	115	1038.6
7	8	115	1038.6
8	4	115	323.33
9	12	115	1219.6
10	8	107.9	1006.5
11	8	122	1069.8
12	8	115	1038.6
13	8	115	1038.6
14	8	115	1038.6
15	5	110	667.57
16	11	110	1176.9
17	5	120	697.25
18	11	120	1234.4
19	8	115	1038.6
20	8	115	1038.6
21	8	115	1038.6
22	4	115	323.33
23	12	115	1219.6
24	8	107.9	1006.5
25	8	122	1069.8
26	8	115	1038.6
27	8	115	1038.6
28	8	115	1038.6

measures signal to noise ratio. A ratio more than 4 is required, which was satisfied here. ANOVA concludes that present model can be used for design study. Regression equation is given in form of design parameters. Regression model equation is given as

$$\text{Frequency Variation} = 1038.11 + 296.67 \times A + 22.28 \times B + 6.96 \times AB - 134.24 \times A^2 + 13.54 \times B^2.$$

A, B is known as coded factors. The regression model equation in form of coded factors is useful for predictions about the response for given levels of each factor. High level factor is shown as $+1$ and the low level factor as -1.

Fig. 2 (3D surface graph), Fig. 3 (contour graph) evaluates the design parameters (connecting bolts, young's modulus) and frequency response. Surface graph has linear profile fitting according to quadratic model. The natural frequency varies (323.33-1234.4) Hz. From contour graphs as connecting bolts number increases frequency increases linearly in higher order range. As per detuning principle optimized frequency range is higher than fundamental frequency range (10-100) Hz. Corresponding to 8 number connecting bolts frequency is greater than 1000 Hz that is 10 time higher than fundamental frequency. So optimized frequency at 8 connecting bolt is safe. Using RSM results it can be concluded that 8 number of connecting bolts are suitable for tight mounting of gearbox housing on vehicle chassis frame.

After selecting the optimized number of connecting bolt FEA numerical simulation was performed for 06 and 08 connecting bolts condition. 6 connecting bolt was selected from lower frequency range and 08 connecting bolt was selected from higher frequency range. Fundamental frequency for 06 bolts condition is 804.73 Hz and 08 bolts condition is 1106.8 Hz. These two frequencies are in higher range and eliminate the chances of resonance. FEA simulation results shows that using 8 connecting bolts for constraining housing on vehicle frame frequency lies in higher order, it verifies the safety of housing using detuning conditions.

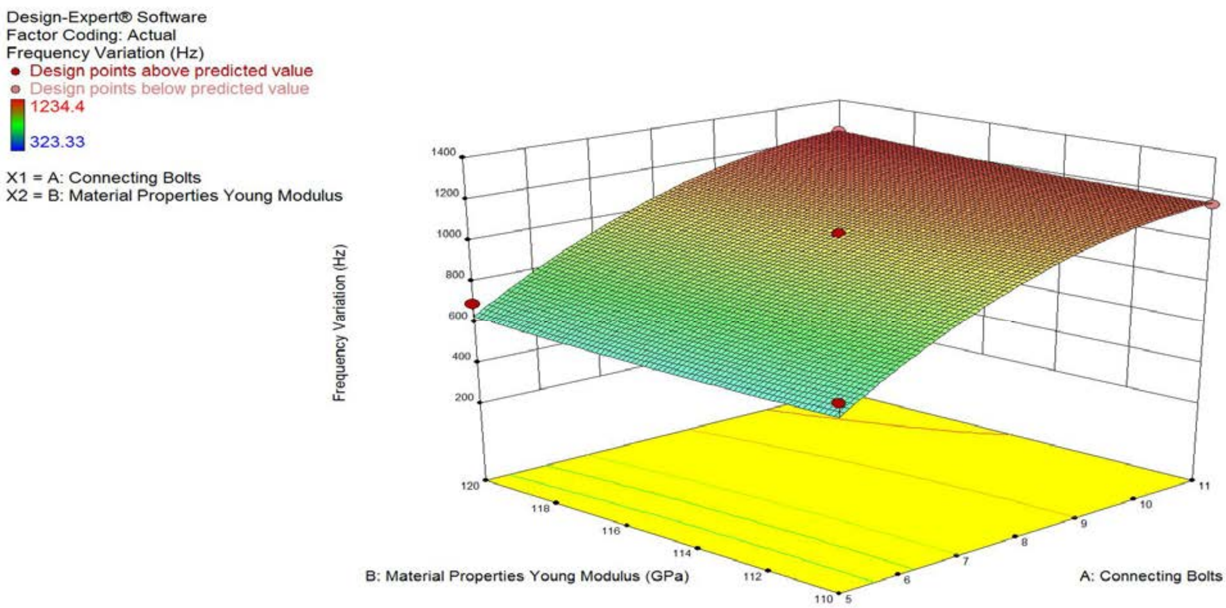


Fig. 2: 3D surface graph for frequency response

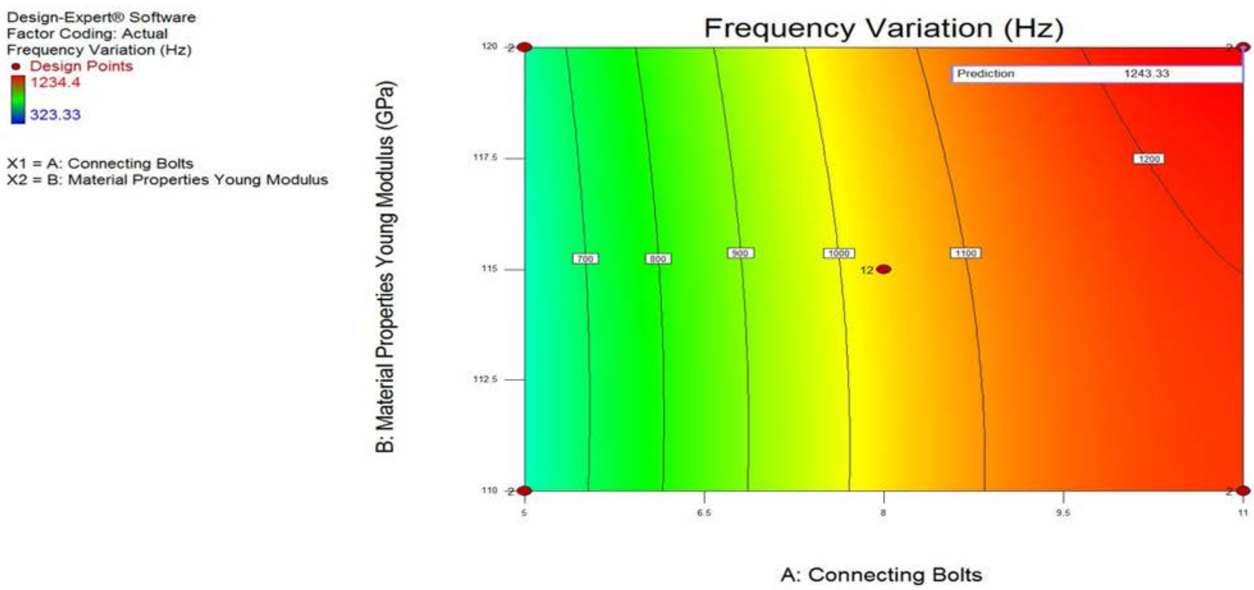


Fig. 3: Contour graph for frequency optimization

4 Finite element analysis (FEA) simulation results

FEA numerical simulation was performed for natural frequencies and mode shapes corresponding to optimize connecting bolts number (08). In FEA environment heavy vehicle medium duty transmission gearbox was constraint at 08 positions using connecting bolts uniformly adjusted in all directions. Ansys 14.5 was used for FEA analysis. In workbench module, modal analysis was selected and load is applied by program. From the governing equation of free vibration natural frequency depends on stiffness and mass structure of housing. For FEA meshing tetrahedron element (Tet 4) was applied. FEA analysis results shows that the natural frequency vary (804.73-2359.7) Hz.

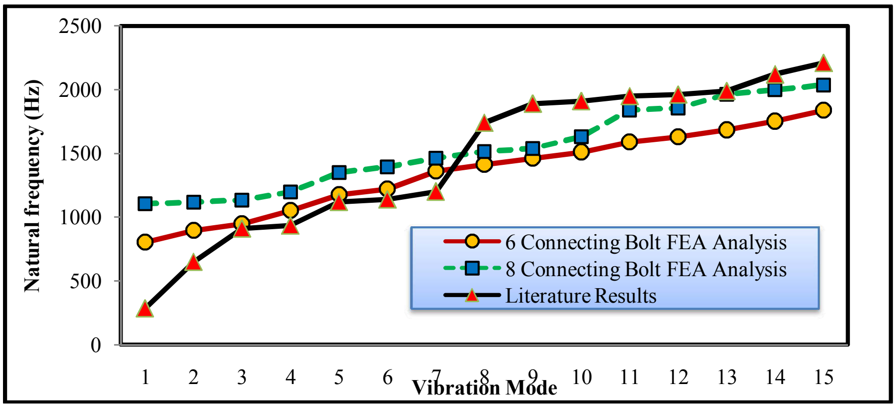


Fig. 4: Natural frequency variations for 6 and 8 connecting bolt conditions.

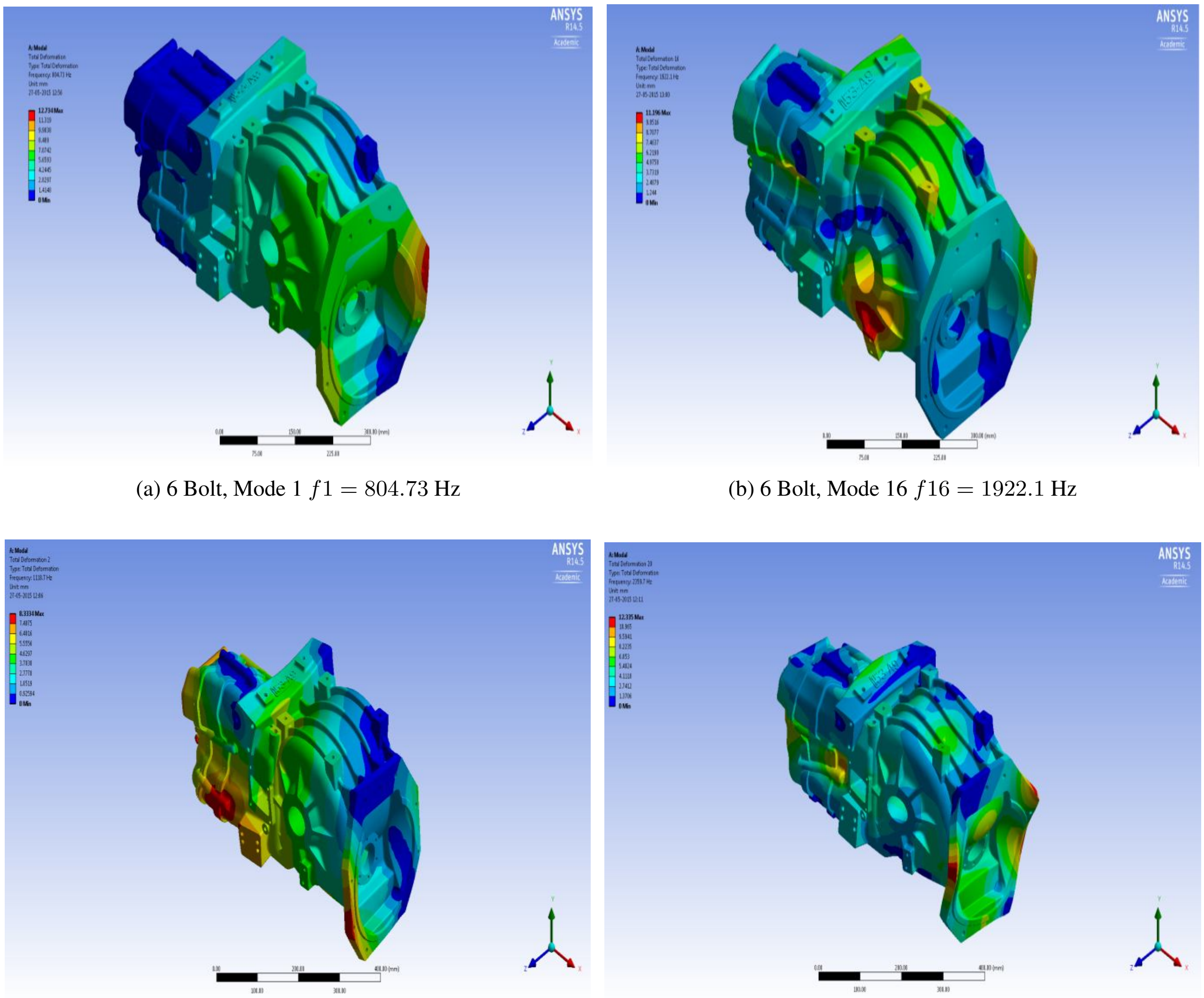
Fig. 4 shows shifting of frequency from lower range to higher range as number of connecting bolts increases from 6 to 8 (first fifteen natural frequencies). Higher order frequencies eliminate the chances of resonance. RSM results predict the same condition. Fig. 2 & Fig. 3, 3D surface graph and contour graph shows the increment in frequency as number of connecting bolts increases. Fig. 4 shows graph of first twenty natural frequency and vibration mode. The lowest frequency is 804.73 Hz and highest frequency is 2359.7 Hz. The FEA simulation result was validated through literature results. Abbes et al.[4] have performed the dynamic analysis of transmission gearbox housing for reducing vibration level. They have used FEM and DSM method. The natural frequency of housing varied (285.65-2210.15) Hz. In presented research article the fundamental frequency obtained from RSM, varied (323.33-1234.4) Hz. RSM & FEA frequency range are within literature frequency range. For optimized connecting bolt (08) condition, difference between FEA simulation result and literature result is less than 8% (mode 15).

Vibration mode shapes shows deformation regions due to vibration effect. Blue hues shows minimum deformation level and red hues shows large deformation. Torsional, bending, axial bending and torsional with axial bending vibration mode were identified in housing. Axial bending and torsional vibration are harmful but 08 bolts constraint condition shows less deformation within acceptable range at constraint point (Fig. 5). To have more control on torsional and axial vibration, identify the region and constraint it tightly using connecting bolts.

5 Effect of optimised connecting bolts on torsional vibration

In maximum cases during FEA analysis it was observed from transmission housing mode shapes that torsional vibration causes large deformation and heavy vibration. Under torsional vibration objects shows twisting action with large deformation. Twisting action of housing can be controlled using optimized connecting bolts at selected location. This condition was studied in FEA by applying moment to generate twisting action.

To prevent twisting action optimized 08 connecting bolts number were used for constraining transmission housing on vehicle frame. To generate twisting action in FEA environment moment was applied using 5000N force in two opposite direction at centre of housing. This condition causes twisting action in transmission housing. Under twisting action total deformation of housing was measured using FEA analysis. Fig. 6 shows transmission housing deformation under twisting action resulting in torsional condition. Using 08 optimized connecting bolts at selected location in transmission housing it was found that total deformation is less than 0.1 mm. This condition explained the strength of transmission housing, structural rigidity and proved that optimized connecting bolts have importance in reduction of vibration. Blue hues shows minimum deformation level (0 mm) and red hues explains maximum deformation level (0.037 mm). Front portion of housing shows zero deformation in blue hues. Centre portion have blue, green, yellow and red hues. Red hues are observed at top back portion and extreme left corner. From Fig. 6 it is concluded that using optimized connecting bolts condition torsional vibration was reduced and deformation in housing is less than 0.1 mm.



(a) 6 Bolt, Mode 1 $f1 = 804.73$ Hz

(b) 6 Bolt, Mode 16 $f16 = 1922.1$ Hz

(c) 8 Bolt, Mode 2 $f2 = 1118.7$ Hz

(d) 8 Bolt, Mode 20 $f20 = 2359.7$ Hz

Fig. 5: Natural frequency and vibration mode shape of transmission gearbox housing

6 Conclusions

RSM and FEA based optimization shows effect of design parameters on frequency response. Numbers of connecting bolts directly effect the frequency response. Using detuning principle the main aim was to obtain a range of natural frequency that is outside range of fundamental frequency using optimization of connecting bolts number. The critical frequency range for heavy vehicle medium duty trucks varies (0-100) Hz. RSM results shows safe condition as natural frequency varies (323.33-1234.4) Hz. FEA results shows (804.73-1106.8) Hz fundamental frequency range. RSM and FEA frequency range is outside critical frequency range. This condition signifies excellent structural rigidity and safe design of transmission gearbox housing. In rigidity simulation it was found that using optimized 8 connecting bolts condition deformation is less than 0.1mm in twisting mode under torsional vibration condition. In future this research work can be extended to find deformation in housing under the influence of different optimized connecting bolts. Transmission gearbox assembly is an expensive part of vehicle. Therefore design and analysis is required. The present research study has significance in designing and analysis of transmission housing and provides reference for advanced simulations.

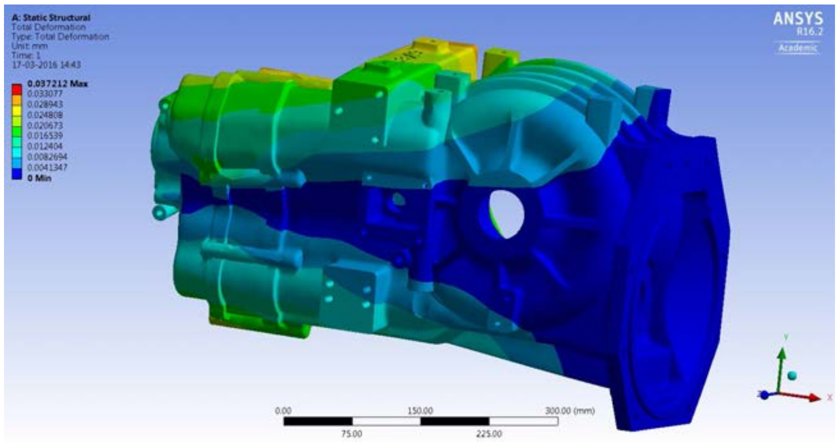


Fig. 6: Total deformations in transmission housing under optimized bolt condition in twisting mode

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