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Parametric Optimization of Vibrating Heavy Vehicle Medium Duty Transmission Gearbox Housing Using Response Surface Method

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ABSTRACT:

This research study highlights two main objectives, first is selection of best suited material for gearbox housing and second objective is selection of number of connecting bolts to eliminate the excitation and heavy vibration. Heavy vehicle medium duty truck transmission gearbox housing is subjected to harmonic and internal excitations which are the main source of noise and vibration. Noise and vibration harness is required to increase the performance of transmission gearbox. Gearbox housing materials should have damping nature to sustain the vibration and minimised the gear damage by reducing the amplitude of vibration. To select best suited material Young's modulus was selected as design parameter. To prevent the excitation and heavy vibration gearbox housing is tightly mounted on vehicle frame using connecting bolts. To find the optimized number of connecting bolts Response Surface Method (RSM) was used. Design parameters are number of connecting bolts and housing material property (Young's modulus). The output response is frequency (Hz) and detuning principle was used to find the safe condition for gearbox housing. Results of this research study have been validated with available literature results. Ansys version 14.5 was used for FEA analysis and solid edge, Pro-E for solid 3D modelling.

KEYWORDS:

Response surface modelling; Analysis of variance; Young's modulus; Gearbox housing; Finite element analysis

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1. Introduction

Response surface method is an optimization technique used for development, improvement and optimization of design processes. It is well suited when input variables and output of system are well connected and they affect each other. Using RSM technique parameters can be easily optimized in all field of engineering. In general response parameter shows the quality characteristics of process. In earlier research of heavy vehicle transmission system RSM was used. As vibro-acoustic design was optimized using RSM [1-5]. Connecting bolt looseness study was performed earlier by Kumar [6-7] and Dogan [8]. Kumar et al. [6] have studied the heavy vehicle transmission gearbox housing using FEA. 37 connecting bolts were used to mount the housing tightly on truck frame. Positional bolt looseness condition was studied for front and bottom loose condition and fundamental frequency was evaluated as 750.4Hz and 2103.4Hz. Kumar et al. [7] have studied the loose transmission casing/housing for back and right positional loosening condition.

The FEA results show the effect of looseness and natural frequency reduces 3-30%. Four resonance conditions were identified. Dogan [8] has studied the torsion vibration rattle noise problem using FEA. Transmission housing looseness investigation is important as it causes heavy vibration and noise problem leads to failure of gearbox system. Authors have studied vehicle concept modelling using optimization approach to improve the noise and vibration, stiffness, crash performance etc. Morphing was used to study the vehicle structure modelling and optimization [9-11,19]. Kumar et al. [12] have used the RSM optimization for fused deposition modelling. For optimized process parameters experiments were performed. Abbes et al. [13] have conducted the dynamic analysis of gearbox housing. Transmission error was studied with the help of FEA. The natural frequency of gearbox housing varies 285-2210Hz. A stretcher was introduced in gearbox housing to control the vibration. The lower frequency causes resonance condition leads to failure of system. RSM has been used in advance field like coriolis mass flow sensor [14] and brake squeal noise reduction of vehicle [16].

2. Solid modelling of gearbox housing

CAD model of transmission gearbox housing is shown in Fig. 1 that was designed by assembling more than 600 components. Modelling dimensions were obtained from manufacturer of heavy vehicle medium duty trucks in India. Gearbox housing is manufactured using grey cast iron, damping materials that absorb shock (generated from sudden load on gears) and vibration due to excitation. 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. Fig. 2 shows FEA Ansys 14.5 mesh generation of gearbox housing. Tetrahedron element (Tet 4) is used for mesh generation having 2, 14,644 nodes and 1, 24, 531 elements. Solid edge and Pro-E were used for gearbox housing modelling.

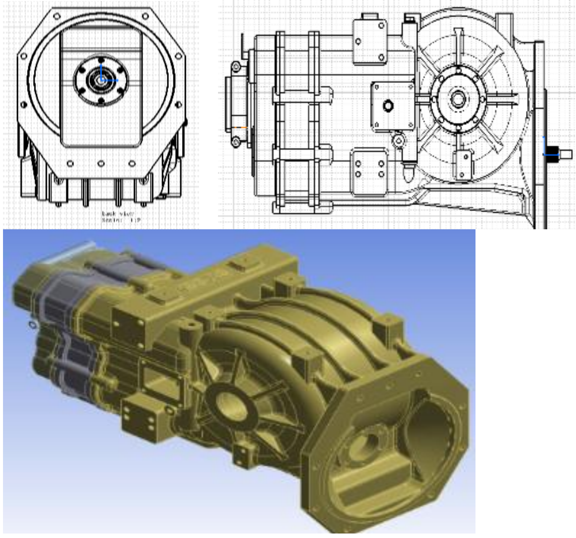


Fig. 1: CAD model of heavy vehicle medium duty truck transmission gearbox housing

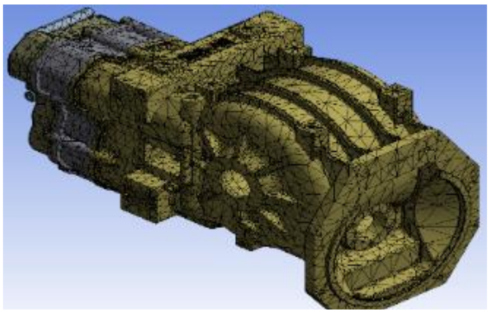


Fig. 2: Finite element model mesh of housing

3. RSM optimization result

RSM is used for finding relation between design parameters. It is a statistical and mathematical technique uses explicit functions for solution. In this research work, RSM was used to find optimized number of connecting bolts for housing. RSM uses Taylor series expansion. Table 1 shows RSM design layout. Based on design requirements and literature review the range of parameters was selected. Input design parameter connecting bolts varies (5-12) and Young's modulus 110-120GPa. Output response was measured in natural frequency Hz. Using the optimized value of design parameters and output response of frequency best suited material and connecting bolts number is selected. When analyzing natural frequencies detuning principle was used for finding safe frequency range. Central Composite Design (CCD) with quadratic function was used in RSM optimization. RSM output is expressed in 3D surface graph and contour plots. These graphs are used in visualization of the output frequency response. A regression model (second order non-linear polynomial equation) was developed using design parameters.

Table 1: RSM design layout

Run order	Design parameters Connecting bolts	 Material property: Young's Modulus	Response: frequency (Hz)
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

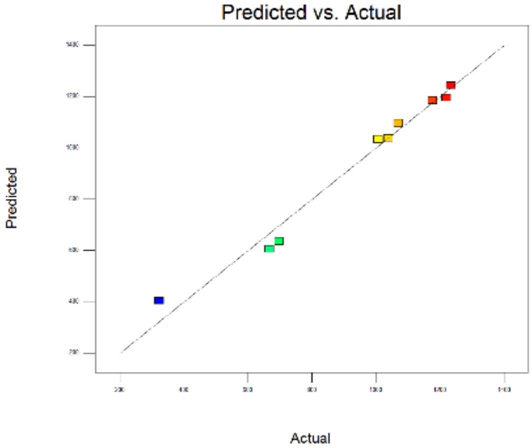


Fig. 3: Predicated frequency vs. actual frequency plot

Design layout of RSM for heavy vehicle medium duty truck transmission housing was generated using software design expert version 9.0. From Analysis of variance (ANOVA) result, significant model terms are

A, B, AB, A^2, and B^2 (A-Connecting bolts number and B-Young's Modulus). Regression equation is given in terms of design parameters. Design parameters are A-connecting bolts number and B-material properties (Young's Modulus). Regression model equation is:

$$\begin{aligned}\text{Freq. variation} &= 1038.11 + 296.67\text{A} + 22.28\text{B} \\ &\quad + 6.96\text{AB} - 134.34\text{A}^2 + 13.54\text{B}^2\end{aligned}$$

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. The F-value 254.32 of ANOVA result signifies that model is significant. The probability (p) > F less than 0.05 Table 2 shows model terms are valid. Quadratic model has provided best fit and shows insignificant lack of fit which is desirable. Coefficient of correlation (R^2) terms are close to 1. The predicted R^2 of 0.9640 is in agreement with the adjusted R^2 of 0.9799. Adequate precision is 49.574. It 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.

Table 2: ANOVA for frequency response

Source	SS	DF	MS	F	P
Block	3516.35	1	3516.35		
Model	1.567×10^6	5	3.135×10^5	254.32	< 0.0001
A	1.33×10^6	1	1.330×10^6	1078.97	< 0.0001
B	7919.56	1	7919.56	6.42	0.0193
AB	386.98	1	386.98	0.31	0.5812
A^2	2.24×10^5	1	2.24×10^5	181.75	< 0.0001
B^2	2694.68	1	2694.68	2.19	0.1541
Residual	25885.42	21	1232.64	-	-
Lack of fit	25885.42	3	8628.47	-	-
Pure error	0.000	18	0.000	-	-
Cor total	1.597×10^6	27	-	-	-
			Adequate R^2		98.38%
SD	35.11		Adjusted R^2		97.99%
Mean	973.35		Predicted R^2		96.40%
C.V.%	3.61		Adequate precision		49.574

The surface graph in Fig. 4 and contour graph in Fig. 5 evaluate 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 from 323.33 Hz to 1234.4 Hz. From contour graphs, it was concluded that 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 10-100Hz. At 8 number connecting bolts frequency is greater than 1000 that is 10 time higher that fundamental frequency. From RSM results 8 number of connecting bolts is selected as optimized connecting bolts for tightly mounting of gearbox housing. Using detuning principle the main aim was fulfilled to obtain a range of natural frequency 323.33-1234.4Hz that is outside range of medium duty fundamental frequency 0-100Hz using optimization of connecting bolts number. Hence, the optimized frequency at 8 connecting bolt is safe. Using RSM results it can be concluded that 8 numbers of connecting bolts are suitable for tight mounting of gearbox housing on vehicle chassis frame. At same design point corresponding to 8 number of connecting bolts, the Young's modulus is 115GPa. At this value of Young's modulus grey cast iron HT 200 is used for transmission gearbox housing manufacturing. Grey cast iron HT200 material mechanical properties are density 7200 kg/m^3 Young's modulus 110 GPa and Poisson's ratio 0.28. These material properties are useful in FEA numerical simulation. Contour graph shows that, for tightly mounting of housing on truck frame use 08 or more connecting bolts. Because at this point frequency is in higher range and transmission gearbox assembly will be safe.

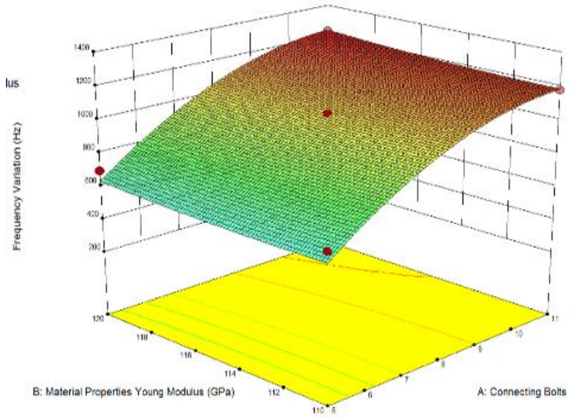


Fig. 4: 3D surface graph for frequency response

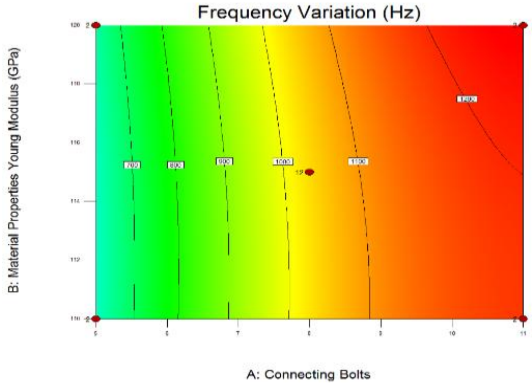
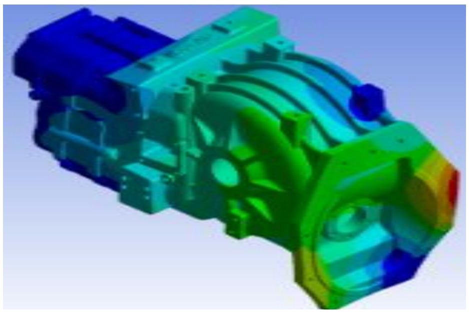


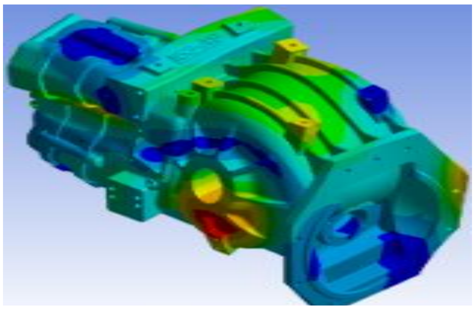
Fig. 5: Contour graph for frequency response

4. Finite element analysis (FEA) results

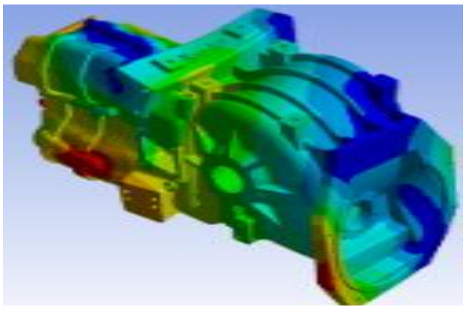
FEA numerical simulation was performed for natural frequencies and mode shapes corresponding to optimise connecting bolts number 8. In FEA environment heavy vehicle medium duty transmission gearbox was constraint at 8 positions using connecting bolts uniformly adjusted in all directions. Ansys 14.5 was 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 results show that the natural frequency vary 804.73-2359.7Hz. Fundamental frequencies are 804.73Hz (06 connecting bolts) and 1106.8Hz (08 connecting bolts). Vibration mode shapes shows deformation regions due to vibration effect. Blue fringe shows minimum deformation level and red fringe shows large deformation. Torsion, bending, axial bending and torsion with axial bending vibration mode were identified in housing. Axial bending and torsion vibration are harmful but 08 bolts constraint condition shows less deformation within acceptable range at constraint point Fig. 6.



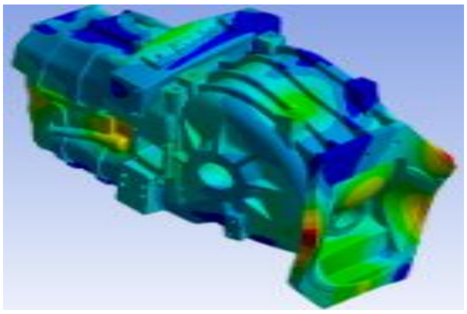
6 Bolt, Mode 1 f1= 804.73Hz



6 Bolt, Mode 16 f16 = 1922.1Hz



8 Bolt, Mode 2 f2= 1118.7Hz



8 Bolt, Mode 20 f20= 2359.7 Hz

Fig. 6: Natural frequency and vibration mode shape of transmission gearbox housing

To have more control on torsion and axial vibration, identify the region and constraint it tightly using connecting bolts. Fig. 7 shows FEA simulation result graph and comparison with literature results. From graph it is concluded that natural frequency and numbers of connecting bolts are bound to each other. As connecting bolts increases natural frequency shift in higher order range. Fundamental frequencies are 804.73Hz (06 connecting bolts condition) and 1106.8Hz (08 connecting bolts condition). Over all frequency range is 804.73-2036.3Hz. This frequency range is similar to RSM frequency range 323.33-1234.4Hz. FEA simulation results and RSM optimization results are in full agreement. Mohamed Slim Abbes et al. [15] 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 285.65-2210.15Hz [15]. In this work, the fundamental frequency varied 323.33-1234.4Hz for (5-12) number of connecting bolts. The optimal frequency varied is 1243.33 Hz. For optimized connecting bolt (08) condition, difference between FEA simulation result and literature result is less than 8% (mode 15). FEA simulation frequencies are within experimental literature frequency range [15]. These conditions justify the validation of this research work.

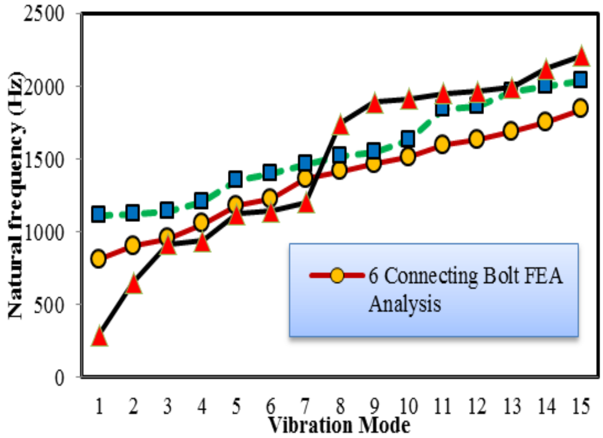


Fig. 7: FEA simulation frequency variation and comparison with literature results

Table 3: First twenty natural frequency variation for transmission gearbox housing

S. No.	Connecting bolt frequency (Hz)	Connecting bolt frequency (Hz)
1	804.73	1106.8
2	896.29	1118.7
3	948.27	1134.1
4	1052.5	1199.8
5	1176.4	1349.3
6	1222.7	1396.
7	1362.9	1464.1
8	1413.8	1514.9
9	1461.3	1540.4
10	1511.8	1630.6
11	1590.2	1840.7
12	1631.1	1854.9
13	1684.6	1962.3
14	1752.3	1998.5
15	1838.4	2036.3
16	1922.1	2061.1
17	1978.5	2164.4
18	2028.6	2209.5
19	2099.	2309.1
20	2247.9	2359.7

5. Conclusion

RSM and FEA investigation has shown the effect of two design parameters (connecting bolt and Young's modulus) on natural frequency of medium duty transmission gearbox housing. Grey cast iron HT200 has been selected as best suited material for heavy vehicle medium duty transmission gearbox housing. Using detuning principle other frequencies was eliminated and safe frequency range was obtained at optimized connecting bolts condition (08 bolts). The critical frequency range varies 0-100Hz; RSM results vary 323.33-1234.)Hz and FEA results vary 804.73-2036.3Hz. RSM and FEA frequency range is outside critical frequency range. This condition signifies excellent structural rigidity and safe design which prevents resonance. The 3D surface graph has established a linear relation between constraint connecting bolt and frequency response. Ansys 14.5 was used for FEA analysis. The results of this research work have theoretical significance in the design stage of truck transmission housing.

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