Shape Improvement of a Gearbox Housing Using Modal Analysis

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Abstract: - In the process of geometric optimization of the gear reducers, an important role is played by the decrease of the housing weight. The optimization of housing should include stress state analysis, as well as modal analysis. This paper focuses on the modal analysis of the housing from a two-stage cylindrical reducer transformed into a one-stage reducer. The frequencies are obtained using finite element analysis and experimental modal analysis, highlighting the good correlation between the results. Also, the differences between the first six vibration modes of the original housing in relation to the first six vibration modes of a modified housing (without the intermediate frame designed for the two-stage reducer) are analyzed. In the last part of the paper were discussed, based on the mass participation factors, the displacement trends for each mode of vibration.

Keywords: - gearbox housing, mass participation factor, modal analysis, mode shapes, natural frequencies

1. INTRODUCTION

The housing is an essential part of a gear transmission, because it surrounds the mechanical parts, supports the bearings and provides protection both of the inner parts against the working ambiance and the environment against pollution with lubricant.

Also, the housings are transmitting the vibrations generated by the meshing of gears, which are perceived as noise [1-2]. Therefore, any optimization of the housing shape, which is able to reduce the noise emitted by gear transmissions, is essential in the fight against the environmental pollution.

Several researches [3-5] were focused on reducing the gearbox noise radiation by increasing the stiffness of the housings. It was concluded that, by placing the ribs along the lines connecting the bearing shells with the nearest surface for fixing the housing, beneficial effects in relation to the radiated noise are obtained [6-7].

Patil and Pise [8] have investigated the possibility of optimizing the housing design by placing twelve combinations of stiffening ribs on the casing of a differential gearbox. They compared the natural frequencies obtained by finite element method (FEM) with the gear mesh frequency and its harmonics, which were treated as excitation frequencies. In addition, they performed stress analysis on the existent housing and for the optimized versions.

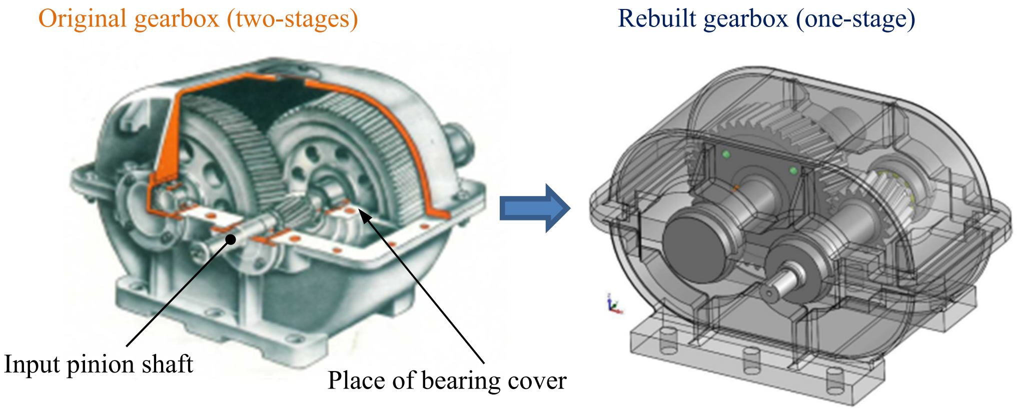
Kumar et al. [9] analyzed the impact of the mechanical properties of the casing material on the natural frequencies of the housing of a gearbox equipping a heavy vehicle. Four types of materials were studied in their research: grey cast iron, structural steel, a magnesium alloy and an aluminum alloy, the FEM simulation outcomes being correlated with experimental results available in literature. They established that the natural frequencies and the mode shapes of the casing are directly associated with the mechanical properties of the housing material.

In another research, Saxena et al. [10] examined the dynamic behavior of a gear-shaft-bearing system using finite element analysis (FEA). It was concluded that the characteristics of the bearings are influencing in a major way the dynamic behavior of the gear transmission.

A lot of other researches were also focused on the subject of modal analysis of gearbox housings [11-14], but considering the multilateral aspects of the subject, this topic offers many other exploration opportunities.

2. PROBLEM FORMULATION

The main objective of the present research was to improve the shape of gearbox housing by using the modal analysis tool. It has to be mentioned that initially this housing has equipped a two-stages coaxial gear transmission (with two gear pairs), the gearbox being rebuilt for various research purposes [15-18] into one with a single reduction stage (one gear pair). This has been done by keeping the housing and removing only the bearing cover used in the two-stage gearbox for supporting the inner bearing of the input pinion shaft. Figure 1 shows the initial gear transmission and the gearbox after rebuilding.


Original gearbox (two-stages)

Rebuilt gearbox (one-stage)

Figure 1. Original and rebuilt gearbox

This research aimed to investigate how the frame supporting the intermediate bearing body, which became useless for the rebuilt gearbox, is influencing the vibration behavior of the housing and the benefit of removing this constructive element by means of machining (milling). Table 1 shows the main constructive data of the housing.

Table 1. Main constructive data of the housing

Data	Symbol	M.U.	Value
Housing main dimensions	LxBxH	mm	439x251x280
Housing weight	m	kg	38.375
Housing material	EN-GJL-250 (0.6025/EN1561)		
Elastic modulus	E	GPa	120
Poisson’s ratio	ν	-	0.26
Mass density	ρ	kg/m^3	7250

In order to accomplish the objectives set for this research, the explorations have been organized in several steps. In the first stage of the investigations, the 3D model of the housing was built by involving the SolidWorks workbench. Using the software facilities, a FEA was accomplished in order to obtain the first six natural frequencies and the corresponding mode shapes of the housing.

In the second stage of the research, an Experimental Modal Analysis (EMA) was performed on the existent housing, with the purpose of validating the 3D model, the boundary conditions used in the FEA and the accuracy of the assumed material properties.

Finally, the intermediate bearing body and its supporting frame were removed from the 3D model of the housing, the influence of this constructive modification on the vibration behavior of the housing related to the operating speed range of the gearbox being investigated.

3. FINITE ELEMENT ANALYSIS

FEA is a powerful tool used for various mechanical engineering applications [19- 24], which is employed for the modeling of products or complex systems in a virtual background, with the intention of discovering and solving existing or potential performance and structural matters.

In order to fulfill the objectives of this research, the frequency analysis module, available in the SolidWorks software, was used. For simulating the operating conditions, as close as possible to the real ones, the housing was fixed on the foundation through the fastening holes from gearbox base plate. Figure 2 shows with green arrows the boundary conditions which were set for the modal analysis. The two parts of the housing (upper and bottom part) were assembled using screws, nuts and centering pins. The contact type between the housing parts was set as “bonded”.

In the interest of obtaining accurate results, on the housing was applied a high quality mesh, consisting of solid tetrahedral elements, 89.4% of these elements having an aspect ratio of maximum 3. Figure 2 illustrates the applied mesh on the housing, with a detail view on the ribs area (figure 2 b).

4. EXPERIMENTAL MODAL ANALYSIS

Experimental Modal Analysis (EMA) is a physical procedure performed on mechanical systems or structures in order to establish their natural frequencies and to characterize their vibration mode shapes. These information are indispensable to the processes in which it is desired to avoid or/ and diagnose resonance. In this research, EMA was employed for the calibration of FEA, the results obtained, being used for validation of the boundary conditions which were set and to confirm that the assumed material properties are correct.

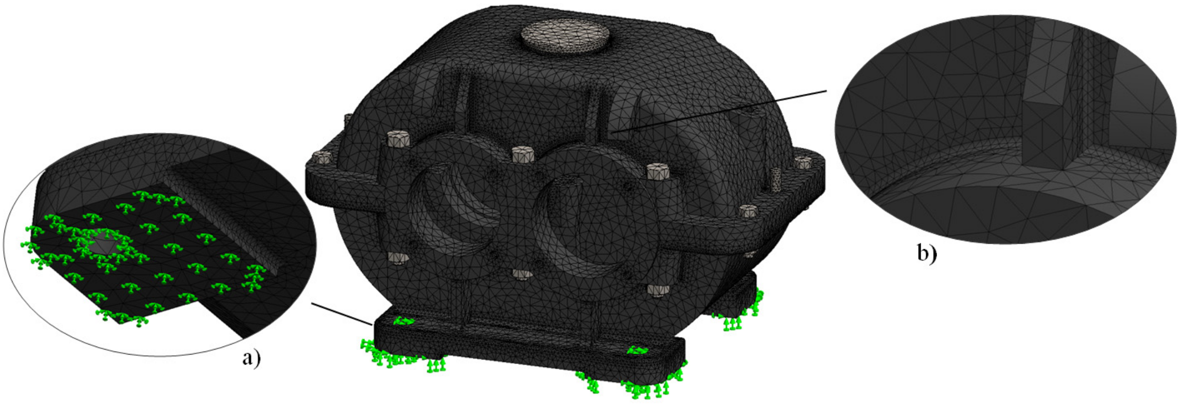
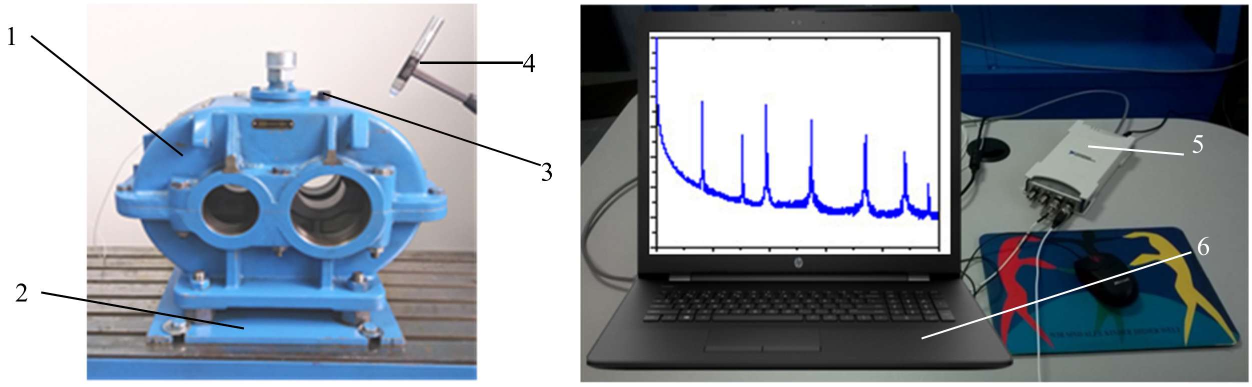


Figure 2. Boundary conditions (a) and mesh (b) applied to the gearbox housing

As EMA involves most commonly a mechanical excitation achieved with an impact instrument and then measuring the obtained vibratory response, the test rig shown in Figure 3 includes, besides the housing 1, rigidly fixed on the base frame 2, an impact hammer 4 (type 086C01- producer PCB Piezotronics) and an accelerometer (type 8772- producer Kistler) fixed with wax on the upper part of the housing. The electrical signals from the impact hammer and the accelerometer were collected by a four-channel signal acquisition module 5 (type 9234 - producer National Instruments), being transmitted to the PC 6, which was used for processing the measurement results and computing the natural frequencies by means of a customized software tool developed in LabView [25].



a. b.

Figure 3. Views of the testing facilities

5. RESULTS AND DISCUSSIONS

5.1 Natural frequencies of the original housing obtained by FEA

In most cases, FEA is a computerized process, appropriate for the analysis of complex structures, providing their static and dynamic properties (including the natural frequencies and the corresponding mode shapes).

In conjunction with the actual high-speed computing facilities, FEA has been proved as an extremely efficient tool for the prediction of complex structures subjected to various dynamic excitations and variable environmental conditions, which may include the impact of temperature or entrained fluid effects.

Table 2 presents the values of the first six natural frequencies of the original gearbox housing obtained by FEA, as described in section 3.

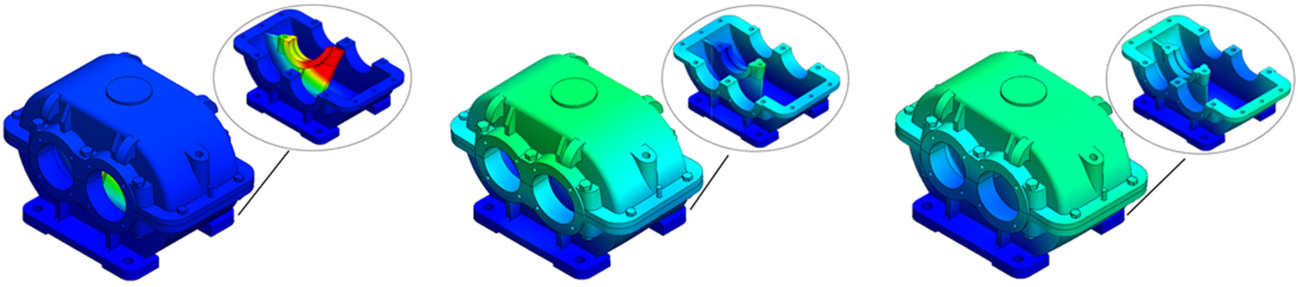
Table 2. Natural frequencies of the original housing, obtained by FEA

Mode no.	1	2	3	4	5	6
Nat. freq. [Hz]	571.4	633.4	752.4	1136.9	1208.8	1447.6

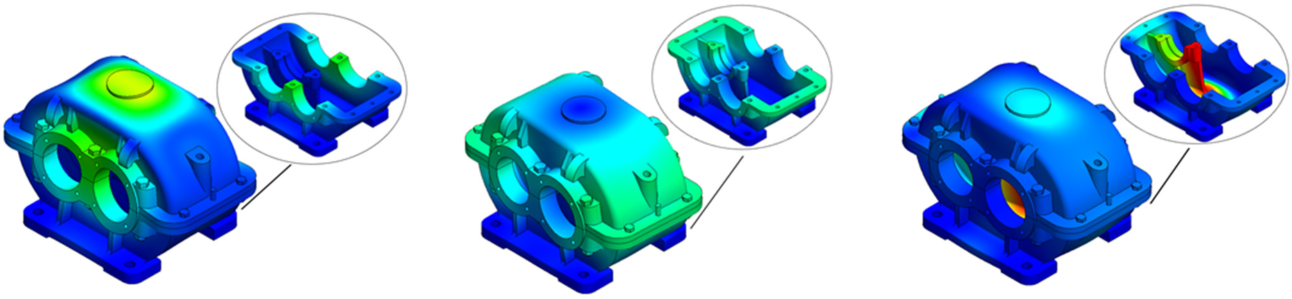
In order to have a clearer description of the housing vibration, Figure 4 presents the shapes of the first six vibration modes obtained by FEM simulation. To get a better picture of the housing movement, the displacements caused by the vibration were represented on the same scale for all six computed mode shapes.

As it can be noticed from the pictures corresponding to the vibration modes 1 and 6, on the intermediate bearing frame (which became useless after the rebuilding process of the gearbox), the highest displacements in the vibration process occur.

In this context, it is justified to investigate the benefit of removing this constructive element (by milling), on the vibration behavior of the housing.



a) Mode 1 b) Mode 2 c) Mode 3



d) Mode 4 e) Mode 5 f) Mode 6

Figure 4. First six vibration modes of the original housing

5.2 Natural frequencies of the original housing obtained by EMA

Table 3 displays the first six natural frequency values of the original housing acquired by EMA, as described in section 4 and the percentage deviation to the values obtained by FEA. As it may be observed, the differences between the frequencies achieved by the two methods (FEA versus EMA) does not surpass 5%, which certifies the accuracy of the experimental measurements and validates the 3D model of the housing, together with the boundary conditions and the material properties used in FEA.

Table 3. Natural frequencies of the original housing, obtained by EMA and percentage deviation to FEA

Mode no.	1	2	3	4	5	6
Nat. freq. [Hz]	584	608	728	1115	1242	1410
Deviation to FEA [%]	2.16	4.18	3.35	1.96	2.67	2.30

The deviations between the FEA and EMA outcomes may be explained by the occurrence of some divergences among the current material properties, such as mass density, elastic modulus or Poison's ratio, together with small mass differences caused by the geometrical irregularities of the real housing. Finally, the fact that the differences are so small is a guarantee that the results obtained on the virtual model, with regard to the constructive modification under investigation, may be reliable.

5.3 Natural frequencies of the modified housing obtained by FEA

Table 4 summarizes the values of the natural frequencies obtained by FEA, for original housing and for modified housing (the frame of the intermediate bearing body removed by milling). For the modified housing, the frequencies of all vibration modes increase, mainly because the mass decreases. To get a better understanding of how the frequencies change, the frequency shift was defined, calculated with the relation:

$$FS = \frac{f_{m_i} - f_{o_i}}{f_{o_i}} \cdot 100 \ [\%] \qquad (1)$$

where:

f_{m_i} [Hz]- frequency of the i vibration mode for the modified housing;

f_{o_i} [Hz]- frequency of the i vibration mode for the original housing.

Table 5 lists the mass participation factors for the original housing and the modified geometry housing. This factor, resulting from the FEA, defines the displacement trends for each mode of vibration. The Z axis of the reference system is parallel to the axis of the gear shafts, the X axis is perpendicular to Z in the horizontal plane, and the Y axis is vertical.

Table 4. Natural frequencies of the original versus modified housing and the resulted frequency shifts

Mode number	Natural frequencies [Hz]		Frequency shift [%]
	original	modified	
1	571.4	630.9	10.41
2	633.4	751.9	18.70
3	725.4	1123.5	49.33
4	1136.9	1215.2	6.89
5	1208.8	1470.2	21.62
6	1447.6	1574.0	8.73

Table 5. Mass participation factor

Mode number	Mass participation factor [%]					
	Original geometry			Modified geometry		
	X axis	Y axis	Z axis	X axis	Y axis	Z axis
1	0.0	0.0	7.8	0.0	0.0	60.4
2	0.0	0.0	53.1	51.6	0.0	0.0
3	51.9	0.1	0.0	0.0	5.5	0.0
4	0.0	5.8	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	21.2	0.0
6	0.2	2.1	0.0	0.0	0.0	0.8

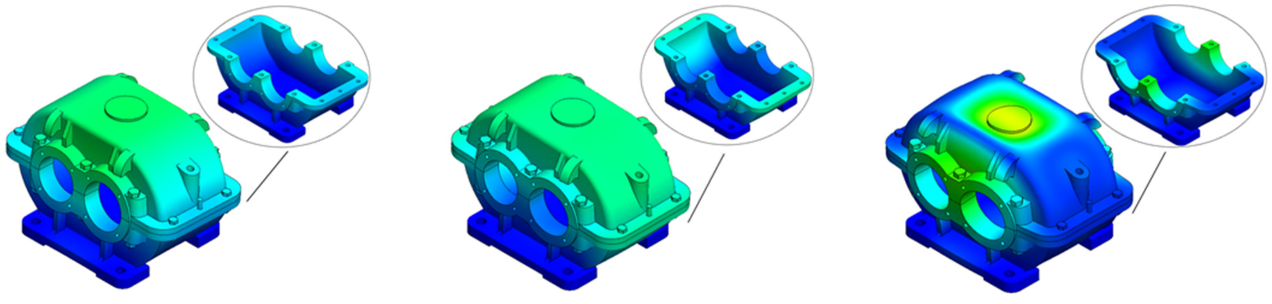
In order to have a better picture of how the dynamic behavior of the housing changes by eliminating the intermediate frame, figure 5 illustrates the first six vibration modes of the modified geometry. The displacements caused by the vibration were pictured on the same scale (used also for figure 4) for all the six mode shapes.

Analyzing the values from Table 5, it can be seen that mode 2 from the original housing and mode 1 from the modified geometry show large mass participation factor on the Z axis. From figures 4 b) and 5 a) it can be seen that the shift trend from mode 2 of the original housing is similar to the shift trend from mode 1 of modified geometry (displacement on Z axis). Also, one can notice the similarity between:

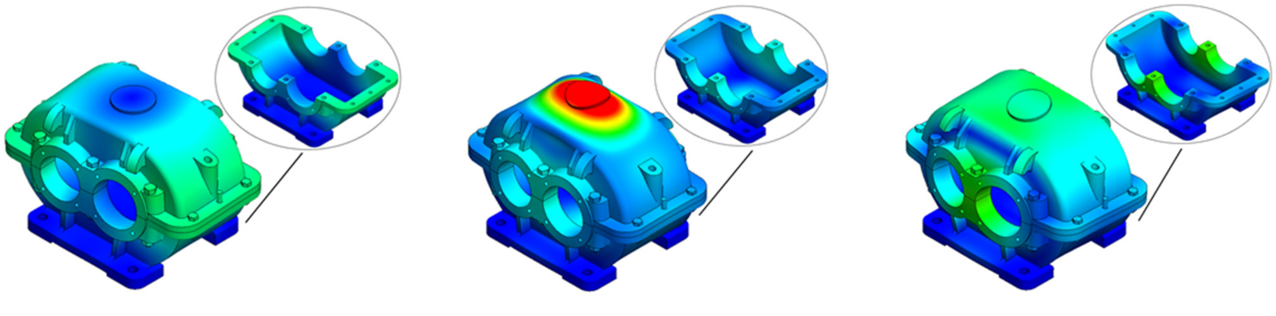
- Mode 3 from the original housing and mode 2 from the modified geometry (displacement on X);
- Mode 4 from the original housing and mode 3 from the modified geometry (displacement on Y);
- Mode 5 from the original housing and mode 4 from the modified geometry (mass participation factors that tends to zero);

There are no similarities between modes 1 and 6 from the original geometry (large displacements on the intermediate frame) and mode 5 (displacement on Y) and mode 6 (mass participation factors that tends to zero) from the modified geometry.

On the original housing, for one of the first six modes, all mass participation factors tend to zero. On the modified housing, for two of the first six modes, all mass participation factors tend to zero.



a) Mode 1 b) Mode 2 c) Mode 3



d) Mode 4 e) Mode 5 f) Mode 6

Figure 5. First six vibration modes of the modified housing

6. CONCLUSIONS

The paper presents the modal analysis of a reducer housing, with basic original geometry and a modified geometry. The geometric change consists in removing the intermediate frame (the casing was designed for a two-stage reducer and transformed later for a one-stage reducer). The main conclusions that come out of the paper are as follows:

- The results obtained by the finite element analysis are very close to those obtained by the experimental tests, thus validating the FEA model;
- On four of the first six modes of vibration, similarities between the behavior of the original housing and the behavior of the modified housing are highlighted. Vibration modes 1 and 6 of the original housing particularly involve the intermediate frame and are not found on the modified housing;
- At the modified housing, on two of the first six modes of vibration, the mass participation factors tend to zero for all three axes. At the original housing, the mass participation factors tend to zero for all three axes only in one vibration mode.

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