Modal - Based Design Optimization of a Gearbox Housing

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Abstract: - The gearbox housing is the assembly which surrounds the mechanical parts of a gear transmission. As its weight typically represents about 50% of the gearbox's, optimizations of shape and weight are of particular importance, leading to material and cost savings. This paper presents an example of how the design of a gearbox housing can be improved by using Finite Element Analysis (FEA). For this objective, the work exposes the way the natural frequencies are influenced by the housing material and how these frequencies vary by changing the dimensions of some geometric elements, which define the rigidity of the housing.

Keywords: - gearbox housing, modal analysis, mode shapes, natural frequencies.

1. INTRODUCTION

The housing is an important part of a gearbox, which surrounds the mechanical parts of the transmission. It supports the shaft bearings, providing protection of internal components against the working ambiance and environment protection against contamination with lubricant. In gear systems, the vibration generated by the gear mesh is transmitted through shafts and bearings to the housing. The vibration of the housing is perceived as noise [1, 2].

Optimization of the housing design is necessary in order to decrease the noise emission, reduce weight, reduce complexity and subsequently the manufacturing costs. In previous researches [3, 4] were investigated, using Finite Element Method (FEM), the possibilities to improve the housing form and dimensions, focusing on the analysis of displacement and stress distribution. The obtained results show real opportunities regarding both weight reduction and optimization of material consumption and costs.

In other researches were studied the possibilities to reduce the gearbox radiated noise by increasing the housing stiffness [5-7]. This can be mainly done by arranging ribs, in different positions, on the gearbox surface. It has been shown that the stiffening ribs have beneficial effects by placing them along the lines which connect the bearing shells with the nearest fixed point of the housing [8, 9].

Modal analysis is also used as a powerful tool in the design optimization process of various applications in the field of mechanical engineering [10-12], being used more and more often, especially in the initial stages of the product development [13-15].

So, Kumar et al. [16] studied the effect of material mechanical properties on the mode shapes and the natural frequencies of the casing of a heavy vehicle gearbox. They investigated four types of material: structural steel, an aluminum alloy, a magnesium alloy and a grey cast iron. The simulation outcomes were compared to the experimental results available in literature. It was concluded that the mechanical properties of the casing material are directly linked with the vibration mode shapes and the natural frequencies.

Ognjanovic and Kostic [17] have analyzed the modal behavior of a gear housing, and the conditions for which a frequency of oscillation is excited (in real conditions). The same authors conclude [18] that the gear housing has a leading influence on the level and frequency content of the emitted noise of the gear unit.

Patil and Pise [19] have analyzed the casing of a differential gearbox, dealing with twelve combinations of stiffeners for the design optimization. The computed natural frequencies were compared to the gear mesh frequency and its harmonics, which were considered excitation frequencies. Furthermore, stress analyses in static condition were performed for the existing casing and for the proposed (optimized) design.

Saxena et al. [20] develop a finite element analysis model of the dynamic behavior of a gear - shaft - bearing system. It is shown that bearings characteristics may have a major influence on the dynamic behavior of the gear system.

Walunj et al. [21] have performed a modal analysis of a planetary gearbox housing using FEA. They examined the natural frequencies and the total deformations for the first six vibration modes of an existent housing. The fundamental frequency resulted from the analysis was considerably out of the range of the forcing frequency, thus avoiding resonance. Moreover, the same analyses were performed after adding stiffeners on the weak parts of the housing in order to reduce the housing deformation.

There are a lot of other investigations on the topic of modal analysis of gearbox housings [22-25], but considering the complexity of the aspect, the subject provides opportunities for alternative researches.

This work aims to accomplish investigations based on FEA, in order to reveal how the material and the geometrical elements of the housing are influencing its natural frequencies. The accurate evaluation of natural frequencies is required in order to avoid unwanted resonance in real operating conditions.

2. PROBLEM FORMULATION

The objective of the present research is to optimize the housing design of a single helical gearbox. The main technical data of the gearbox are presented in Table 1. A 3D-view of the housing with its main dimensions is shown in Figure 1.

Table 1. Main technical data of the gearbox

Data	Symbol [M.U.]	Value
Maximum power	P [kW]	2,5
Range of input speed	n1 [rpm]	1.100- 1.500
Center distance	A [mm]	125
Module	mn [mm]	4
Number of teeth	z1/ z2	17/ 43
Tooth width	B [mm]	40
Helix angle	ß [°]	11
Dimensions	Lx Bx H [mm]	439x 251x 280

In the first stage of the research, an Experimental Modal Analysis (EMA) of the existent housing was performed. The natural frequencies have been determined in order to identify the existence of any critical speed in the operating range of the gearbox.

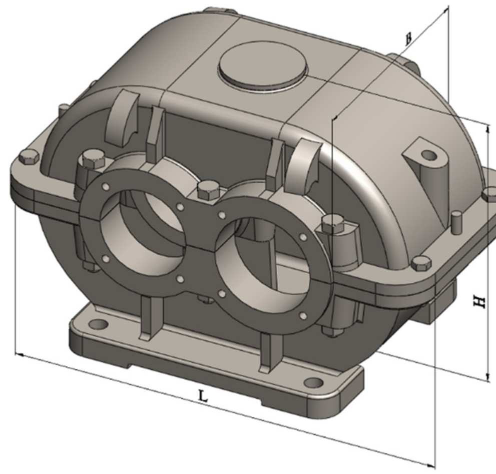


Figure 1. General view and main dimensions of the housing

Afterwards, the 3D model of the housing was build using the SolidWorks workbench. Next, using the facilities of the software, a FEA was performed in order to find the natural frequencies and the mode shapes. The experimentally obtained eigenfrequencies were compared with the FEA results.

Table 2. Mechanical properties of the housing materials

Case no.	Material designation (number)	Standard	Elastic modulus [GPa]	Poisson's ratio [-]	Mass density [kg/m^3]
1	EN-GJL-250 (0.6025)	EN 1561	120	0,26	7.250
2	GS 240 (1.0455)	EN 10293	210	0,28	7.800
3	EN AC-AlSi10Mg (3.2381)	EN 1706	72	0,33	2.670

In the next step of the research, besides the basic material of the housing (grey cast iron, according to EN 1561), other two types of materials (cast steel, according to EN 10293 and an aluminum alloy according to EN 1706) were investigated, finding their influence on the natural frequencies of the housing. The material names, their numbers and mechanical properties are shown in Table 2.

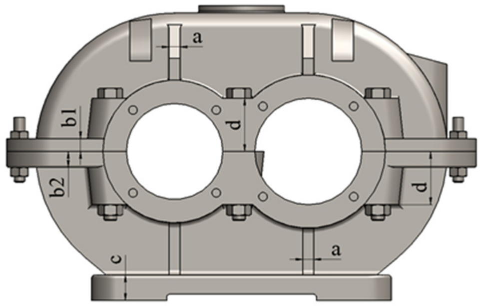


Figure 2. Housing with geometric elements proposed for adjustment

Table 3. Values of the geometric parameters for the considered simulation cases

Case no.	a [mm]	b_1/ b_2 [mm]	c [mm]	d [mm]
1	6			
2	8			
3	**10**	**12/ 15**		
4	12			
5	14		**25**	
6		8/ 11		
7		10/ 13		**50**
9		14/ 17		
10		16/ 19		
11			21	
12	**10**		23	
13			27	
14		**12/ 15**	29	
15				46
16			**25**	48
17				52
18				54

Finally, using FEA, it was investigated how the geometric elements, which determine the rigidity of the housing (thickness of stiffening ribs, thickness of assembling flanges, thickness of gearbox base and height of bearing bodies), have an influence on the natural frequencies. Figure 2 shows the parameters subjected to adjustment, in order to analyze their influence on the natural frequencies, while Table 3 presents the values which were assigned to these elements. The values of parameters from the original geometry (the existent housing) are marked in bold characters in the table (a=10 mm, b_1=12, b_2=15 mm, c=25 mm, d=50 mm).

3. EXPERIMENTAL MODAL ANALYSIS

Experimental modal analysis (EMA) is a physical test performed on an object in order to establish its natural frequencies. The results of the test may be used for the calibration of the FEA, in order to validate the underlying assumptions (the boundary conditions which were used or the correct material properties).

The purpose of this research stage was to determine the natural frequencies of the existent housing using EMA. For this objective, the test rig, shown in Figure 3, was organized. Besides the housing (1), which was rigidly fixed on the frame (2), the test facilities included an impact hammer (3) of type 086C01, produced by PCB Piezotronics and a Kistler 8772 accelerometer (4). The signal acquisition module with four channels, of type NI 9234 (5), has completed the hardware of the experimental test.

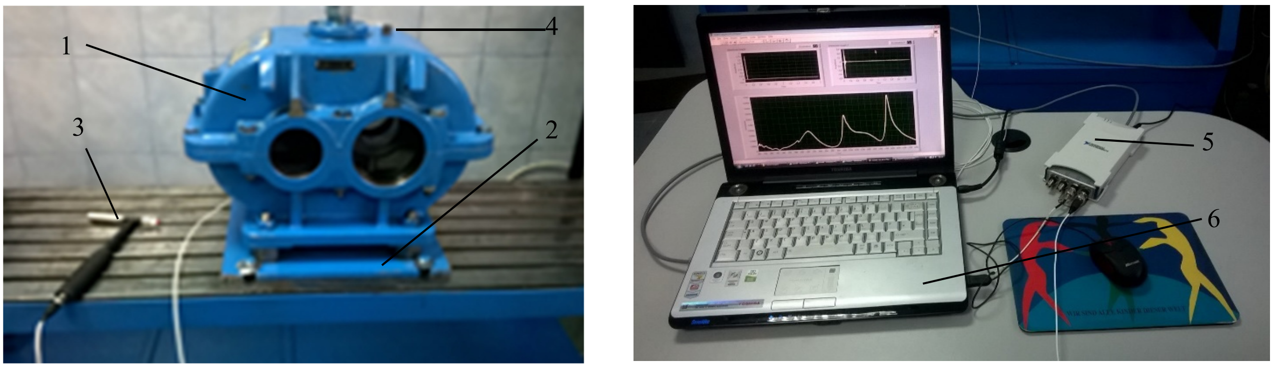


Figure 3. Views of the test rig

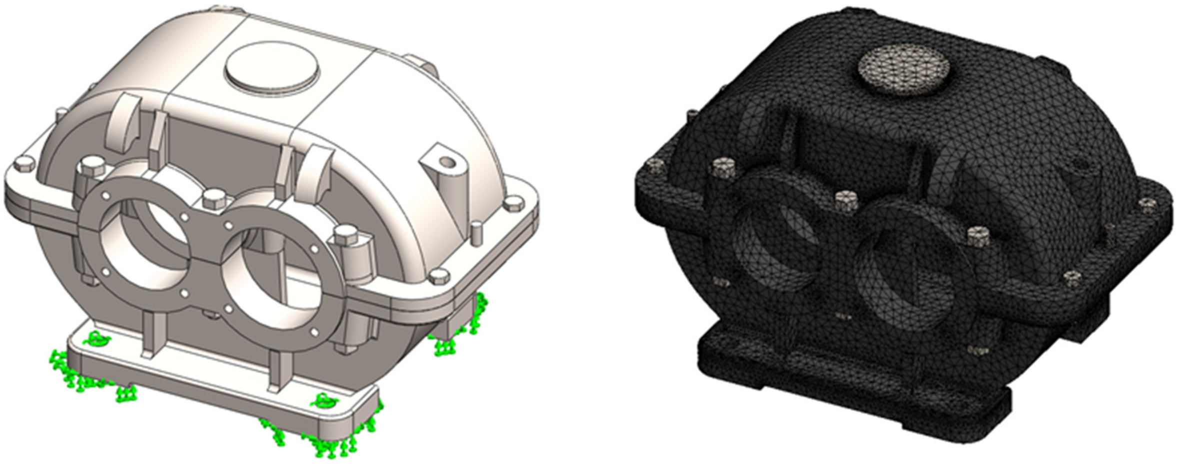
The processing of the measurement results and the computation of the natural frequencies was done by a PC (6) running a custom application developed in LabView software [26].

4. MODAL ANALYSIS USING FINITE ELEMENT METHOD

Experimental It is prevailing to use FEM to ascertain the natural frequencies and the mode shapes of a structure during free vibration, because, like other computation using the FEM, the object which is analyzed may have arbitrary configuration and the obtained results are close to the experimental results. Being used to solve numerous applications from the field of mechanical engineering, FEM has become a powerful tool in the field of Computer Aided Engineering (CAE).

For the purposes of this work, the frequency analysis module of SolidWorks was used. Figure 4a shows with green arrows the boundary conditions which were applied. In order to simulate the real operating conditions, the housing was fixed at its bottom part (the gearbox base) and on the foundation fastening holes. The upper and bottom housing where assembled by screws and nuts, the contact between the two parts being of bonded type.

In order to obtain reliable results, a high quality mesh of solid tetrahedral elements was applied, 89,4% of the elements having an aspect ratio smaller then 3. Figure 4b shows the mesh which was applied to the housing.



a. b.

Figure 4. Boundary conditions (a) and mesh (b) applied to the gearbox housing

5. RESULTS AND DISCUSSIONS

5.1 Comparison of the modal analysis results obtained by EMA versus FEA

Table 4 shows the values of the first six natural frequencies of the existent gearbox housing obtained by EMA, respective FEA. As it can be observed, the difference between the results does not exceed 6%, which confirms, on the one hand, that the experimental measurements were performed accurately and, on the other hand, that the digital (3D) model is correct as well as the assumed material properties and the boundary conditions.

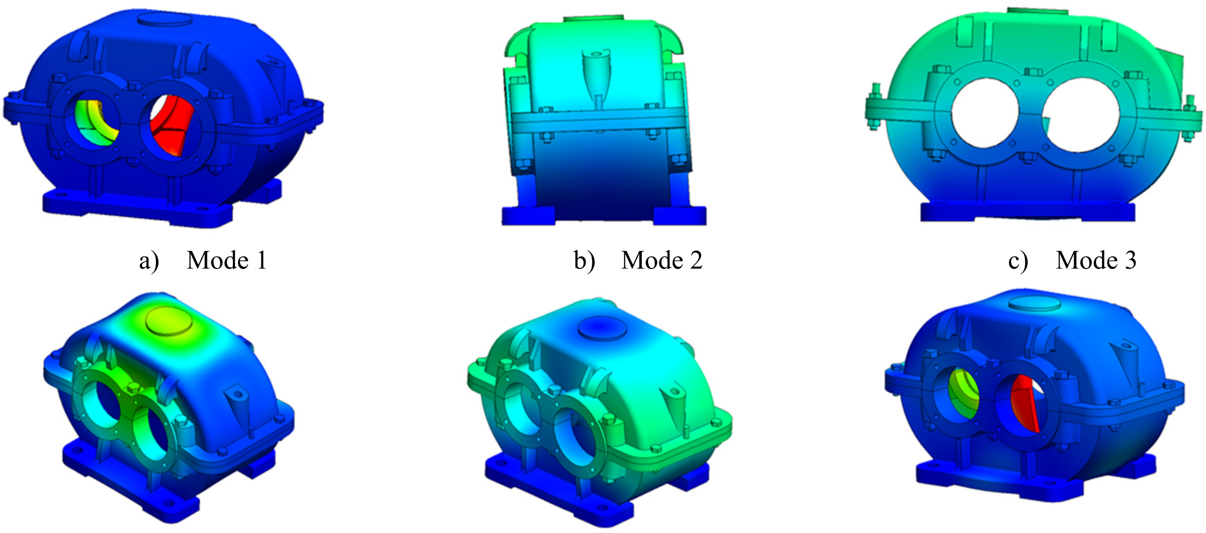
The differences between the results obtained by experimentation and FEA may be caused by some discrepancies between the material properties, mainly elastic modulus, Poison's ratio and mass density along with mass differences induced by the geometrical unevenness of the real housing.

Nevertheless, modal analysis using FEM gives the premise of obtaining reliable and accurate results in the attempt to optimize the housing design and to avoid any unwanted resonances in real operating conditions of the gearbox.

Table 4. Comparison of natural frequencies (EMA data with FEA results)

Mode no.	EMA- natural frequencies [Hz]	FEA- natural frequencies [Hz]	Deviation [%]
1	584	571,4	2,16
2	608	633,4	4,18
3	728	752,4	3,35
4	1115	1.136,9	1,96
5	1242	1.208,8	2,67
6	1410	1.447,6	2,30

To get a better image of the housing vibration, Figure 5 depicts its first six mode shapes, which were obtained by FEM simulation. In order to have a clear picture of the movements caused by the vibrations, the displacements were represented on the same scale for all six mode shapes.



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

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

Figure 5. First six mode shapes of the housing

5.2 Influence of the housing material on the natural frequencies

The paper aims to reveal how the natural frequencies are influenced by the mechanical properties of the housing material, without analyzing any manufacturing prospects conditions. For this purpose, in addition to the FEA performed for the original housing manufactured from EN-GJL-250 grey cast iron, two additional analyses, respectively for GS240 cast steel and EN AC-AlSi10Mg aluminum alloy, were carried out. The first ten natural frequencies computed by FEA, for the three materials, are shown in Table 5.

Table 5. Natural frequencies obtained by FEA for different housing materials

Mode no.	Natural frequencies [Hz]			Frequency shift [%]	
	EN-GJL-250	GS 240	EN AC-AlSi10Mg	GS 240	EN AC-AlSi10Mg
1	571,4	729,9	732,1	27,74	28,12
2	633,4	807,1	773,5	27,42	22,12
3	752,4	959,2	921,6	27,49	22,50
4	1.136,9	1.447,2	1.364,6	27,29	20,03
5	1.208,8	1.535,3	1.457,8	27,01	20,60
6	1.447,6	1.849,4	1.740,8	27,76	20,25
7	1.497,1	1.907,1	1.857,1	27,39	24,05
8	1.563,7	1.995,0	1.918,6	27,58	22,70
9	1.729,6	2.202,0	2.168,5	27,31	25,38
10	1.795,5	2.284,5	2.205,3	27,23	22,82
Average frequency shift [%]				27,42	22,86

Taking a closer look at the values of the first ten natural frequencies, one can observe that, for the original housing (grey cast iron), the frequency band is in the range 571,4- 1.795,5 Hz, while for cast steel and aluminum alloy the frequency bands are quite close: 729,89- 2.284,5 Hz and 732,06- 2.205,3 Hz respectively. The natural frequencies are shifted in average with 27,42% for the housing manufactured of cast steel and with 22,86%, for the housing manufactured of aluminum alloy.

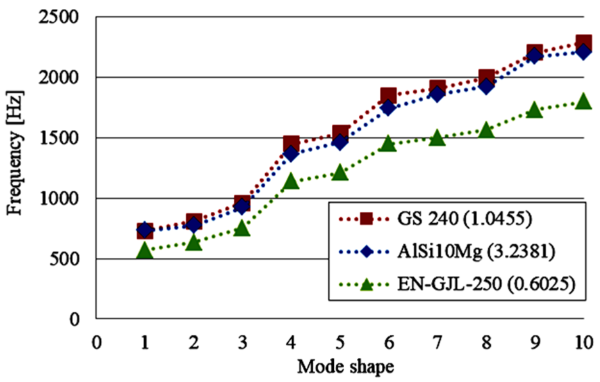


Figure 6. Natural frequencies for different housing materials

Even if by a simplistic approach one would be tempted to consider that in the case of the steel housing, because of the increase in mass, the natural frequencies should decrease, in practice the facts are contrary, because, in the process of calculating the natural frequencies, occurs not only the density, but also the Poisson's ratio and the elasticity modulus of the material. Figure 6 shows the natural frequencies variation for the three investigated materials.

5.3 Influence of the housing geometrical elements on the natural frequencies

This section presents an investigation which was carried out in order to survey the natural frequencies changes of the gear housing, generated by change of dimensions of some geometric elements which determine housing rigidity. The elements targeted in this analysis were: the thickness of stiffening ribs, the thickness of assembling flanges, the thickness of gearbox base and the height of bearing bodies. They are shown in Figure 2, while their values considered for the simulation cases, are presented in Table 3. This sensitivity analysis is a fundamental step in the design process of the housing. The results revealed by FEA are presented in Table 6.

a) Effect of varying stiffening ribs thickness

The first parametric study was performed for the thickness of the stiffening ribs. For this study, the nominal thickness of the ribs (a= 10 mm) was decreased with 2, respective 4 mm and increased with the same values (five cases of analysis). Figure 7 shows in graphical form the effect of the stiffening ribs thickness on the natural frequencies of the housing. One can see that by increasing the thickness of the stiffening ribs, all the natural frequencies increase, excepting the first one, where the values are fluctuating. The most visible increases correspond to the vibration modes 2 and 4, while the modes 3 and 5 have almost identical variations of the normalized frequencies.

Table 6. First six natural frequencies of the housing for all considered simulation cases

Case no.	a [mm]	b_1/ b_2 [mm]	c [mm]	d [mm]	Housing weight [kg]	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	f_4 [Hz]	f_5 [Hz]	f_6 [Hz]
1	6				38,182	571,1	619,3	746,1	1.096,3	1.198,0	1.443,9
2	8				38,278	571,7	628,8	748,8	1.118,4	1.202,2	1.445,3
3	**10**	**12/ 15**			38,375	571,4	633,4	752,4	1.136,9	1.208,8	1.447,6
4	12				38,472	572,0	638,6	755,5	1.151,0	1.214,2	1.448,1
5	14		**25**		38,569	571,8	643,9	759,4	1.162,8	1.220,2	1.448,8
6		8/ 11			37,465	570,9	636,6	765,9	1.128,0	1.236,9	1.424,3
7		10/ 13		**50**	37,919	571,7	634,8	759,3	1.133,1	1.220,6	1.436,5
9		14/ 17			38,834	571,9	631,4	745,9	1.137,3	1.197,3	1.455,6
10		16/ 19			39,295	572,5	630,1	739,1	1.141,5	1.182,2	1.464,4
11			21		37,640	570,7	615,8	721,5	1.122,8	1.175,1	1.434,5
12	**10**		23		38,009	570,5	624,8	736,6	1.129,9	1.191,9	1.441,3
13			27		38,738	571,6	642,1	767,9	1.141,2	1.225,4	1.451,7
14		**12/ 15**	29		39,098	572,0	651,9	784,1	1.146,9	1.243,2	1.454,9
15				46	38,122	571,4	633,8	752,4	1.127,7	1.211,5	1.445,7
16			**25**	48	38,254	570,8	633,3	751,6	1.132,4	1.209,2	1.445,6
17				52	38,513	571,3	632,9	752,4	1.138,9	1.207,3	1.449,1
18				54	38,668	571,1	632,7	752,8	1.142,3	1.205,5	1.448,4

Furthermore, it was observed that by doubling the ribs thickness from 6 to 12 mm, the weight is increasing with 0,76%, while the natural frequencies are increasing in average with 1,86%. The highest frequency increase (4,99%) was observed at mode 4, while the lowest increase (0,17%) at mode 1.

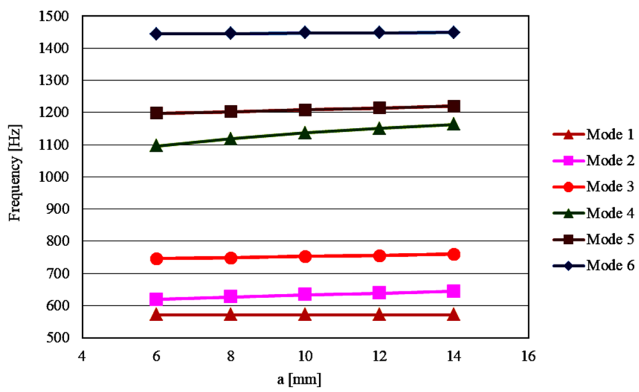


Figure 7. Influence of the rib thickness on the natural frequencies of the housing

b) Effect of varying assembling flanges thicknesses

In this case, the nominal thicknesses of the assembling flanges (b1= 12 mm, respectively b2= 15 mm) were simultaneously modified with -4 mm, -2 mm, +2 mm and +4 mm. Figure 8 illustrates the influence of these constructive parameters on the natural frequencies, respectively on the normalized frequencies.

Analyzing the natural frequency values in Table 6, respectively with the Figure 8, it can be observed that by increasing the thicknesses of the assembling flanges, the natural frequencies of the modes 1, 4 and 6 increase, while for the other three modes the frequencies decrease. The most notable changes in natural frequencies correspond to the vibration modes 3, 5 and 6.

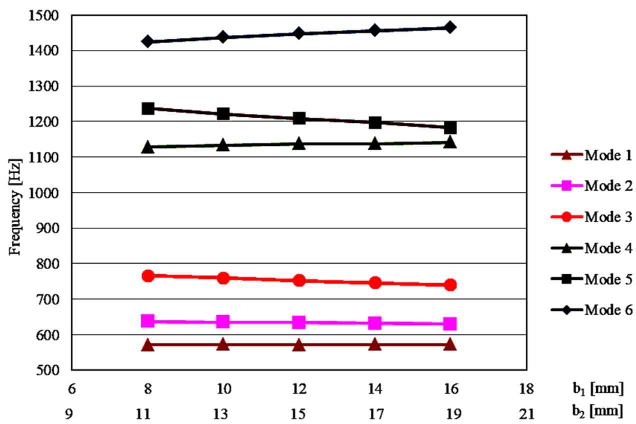


Figure 8. Influence of the assembling flanges thickness on the natural frequencies of the housing

Moreover, it was recorded that by doubling the assembling flange thickness of the upper part from 8 to 16 mm, simultaneously with growing from 11 to 19 mm the thickness of the assembling flange of the bottom part, the housing weight is increasing by 4,88%. This change determines an increase of the natural frequency corresponding to mode 6 by 2,82% and a decrease in the natural frequency corresponding to mode 5 by 4,42%.

c) Effect of varying gearbox base thicknesses

For this sensitivity analysis, the nominal thickness of the gearbox base (c= 25 mm) was modified with -4 mm, -2 mm, +2 mm and +4 mm. Figure 9 presents in graphical form the effect of the gearbox base thickness on the natural frequencies and on the normalized frequencies of the housing.

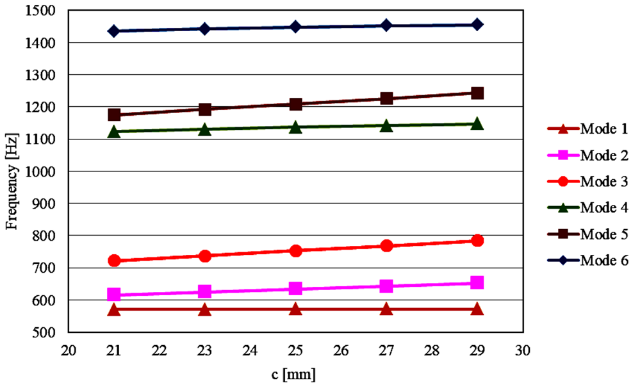


Figure 9. Influence of the gearbox base thickness on the natural frequencies of the housing

Evaluating the results of FEA, it can be noticed that the modification of the gearbox base thickness from 21 to 29 mm (a growth of 38,10%), generates the raise of the housing weight by 3,89% and the increase of the natural frequencies, in average, by 4,02%. The lowest frequency increase (0,23%) was noticed for mode 1, while the highest increase (8,68%) was obtained at the natural frequencies of mode 3.

d) Effect of varying bearing bodies height

In this last state of sensitivity analysis, the influence of the bearing body's height (ranged from 46 to 54 mm) on the natural frequencies of the housing was investigated. The results of FEA are depicted in graphical form in Figure 10.

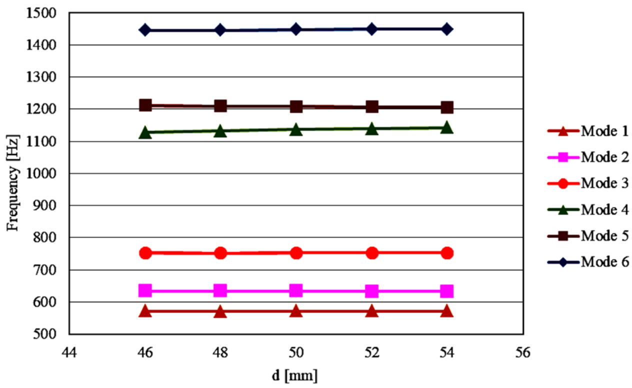


Figure 10. Influence of the bearing bodies height on the natural frequencies of the housing

As it can be observed, the variation of this design parameter, between the above mentioned limits, has a negligible influence both on the housing weight (an increase of 1,43%) and on the natural frequency values, were an average rise of 0,14% was noticed. The changes made to this constructive element do not have a significant contribution to the first six natural frequencies of the housing.

6. CONCLUSIONS

The optimization of the gearbox housing through numerical analysis should led to decrease of housing weight and material consumption. To achieve this goal it is necessary to analyze by FEM the stress and displacement states and the modal behavior of housing for various housing geometries. The modal analysis is primarily used to obtain the natural frequencies of the system and to build the Campbell diagram.

Experimental modal analysis was performed in order to validate the FEM model developed for a housing of a single stage gear. The results obtained by numerical simulation are close to the results obtained experimentally, with a maximum deviation of 4,18%. The deviations may be generated by the non-homogeneity of the material (cast iron) of the analyzed housing.

The analysis of the influence of the material to modal behavior of the gear housing showed that natural frequencies increase by 27% for a GS 240 steel housing versus the original EN-GJL-250 iron housing. For the EN AC-AlSi10Mg aluminum housing, the natural frequencies increase by 22%, versus the values obtained on the original housing. These variations are generated by the mass variations but also by the variation of the elastic properties of the materials.

The influence of the geometry of the gear housing on the natural frequencies has been studied by the variation of the next dimensional parameters: rib thickness, flange thickness, housing base thickness and height of bearing bodies. For all parameters analyzed, it is noticed that the natural frequency variations are not similar for the six modes.

Changing the thickness of the ribs has a greater influence on modes 4 and 2 of natural frequencies. This is due to the fact that in modes 4 and 2, the largest displacements occur on the direction of the bearing axes and the stiffening ribs are arranged along these axes.

Changing the thickness of the housing flanges leads to largest variations of the natural frequencies for modes 5 and 3 (displacements in the longitudinal plane of the housing, perpendicular to the plane of the flange and to the bearing axes) and 6 (displacement of the inner wall of the lower housing).

The largest variations in natural frequencies are generated by the change of the housing base thickness. The highest variation corresponds to mode 3 (8,68% increase, corresponding to a base thickness variation from 21 mm to 29 mm.). The smallest variations of natural frequencies are obtained at the change of height of bearing bodies.

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