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Modal analysis in relation to the casing of an electric power steering system

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Abstract. The article presents the results of modal analysis (experimental and numerical using Finite Element Method - FEM) with reference to the power steering worm drive gear housing. The experimental analysis was performed by the Least Squares Complex Exponential (LSCE) method using a modal hammer equipped with a force sensor which allowed the measurement and recording of the excitation. Numerical analysis was based on the Finite Element Method in PLM Siemens NX 10. Based on results from the experimental modal analysis the FEM numerical model was tuned. The resulting consistency of results led to the conclusion the correctness of the model FEM. The adapted numerical model was used for further analysis with respect to modified power steering worm drive gear housing designs. The obtained results allowed to estimate how the change of the material and adjusting the geometrical form to the strength conditions will affect the frequency and form of the vibration of the modified worm drive gear housing.

1. Introduction
Dynamically changing market trends force manufacturers to launch new products quickly. This makes the engineers who create new solutions have to use powerful computer tools that are able to significantly accelerate their operations while maintaining cost-effectiveness, quality, and durability for new products [1,2,3,4,5,6,7,8]. Contemporary CAD / CAE programs have the power to carry out advanced endurance, fatigue, kinematic, dynamic or modal analysis of considered product [9,10,11,12]. They allow to simulate and then analyse many of the phenomena that occur during operation of technical devices. Thanks to such tools it is able to shape the properties of objects in the early stages of the design process. One can quickly conduct preliminary research on the device in question, which in turn reduces the scope, time and cost of research on real objects (prototypes). An important factor affecting the durability and comfort of use of machines and equipment is generated by them vibrations and noise. Therefore, an important issue in construction work is modal analysis with respect to the constructed object. The result of the modal analysis is the so-called "Modal model", which is an ordered set of resonance frequencies, corresponding attenuation coefficients and the form of their own vibrations. Based on the knowledge of the modal model, it is possible to predict the reaction of the object to any of the excitation, both in time and frequency domain [13,14]. Knowing the frequency of own vibration is very important from the point of view of the strength of the whole device, because the introduction of the object resonance most often adversely affects its operation. The analysis of the form of the system's own vibrations shows "weak" areas of construction showing a high

dynamic susceptibility, which can be reduced by changing the structural features (geometric form, material). In Institute of Engineering Processes Automation and Integrated Manufacturing Systems a lot of works concerned with modelling, simulate and analysis of statically and dynamical behaviour of mechanical and mechatronic systems are conducted [15,16,17,18,19,20,21,22,23,24,25,26,27,28].

2. Description of the purpose and object of the study

Current trends in the automotive industry determine changes in approach to design, construction and manufacturing of components. It is aimed at minimizing production costs, reducing their weight, maximizing the exploitation of material used and reducing the vibration generated for example by the drive system, which significantly affects the durability and ergonomic of the equipment. Engineering activities related to the modification of the power steering worm drive gear housing require these aspects to be taken into account. Due to the costs associated with conducting real-world research, very often, active experiments are being replaced with simulation tests conducted using specialized software based on the appropriate model. The presented approach enables a comprehensive analysis of accepted research assumptions and economically justified limitation of experimental research to the necessary minimum. The article presents the results of modal analysis for the modified power steering worm drive gear housing manufactured by Nexteer Automotive Poland company. These studies are one of the stages in the project number PBS3/B6/37/2015 in 2015-2017.

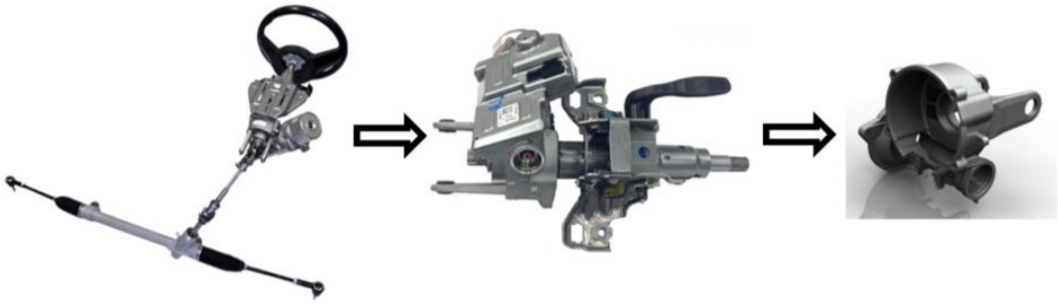

Figure 1. The power steering system with a separated geometrical form of the worm drive gear housing.

The modification of the power steering gear housing consisted in changing the material from which it is made. So far, the gear bodies were made of aluminium alloy by hot-injection. The work currently undertaken is aimed at using the pDCPD (dicyclopentadiene) plastics material and cold injection technology to produce a new generation of power steering worm drive gear housing. Of course, change of the material (due to strength properties) causes a significant modification of the geometrical form of the gear housing, which will greatly affect the form and frequency of the gear housing's own vibrations.

3. The conducted study

In the first stage of the study, a classical experimental modal analysis (EMA) was conducted with respect to the standard power steering worm drive gear housing made of aluminium alloy. In experimental modal analysis, modal parameters are determined by analysing the frequency characteristics measured on a real object by means of an active experiment involving controlled oscillation of the system and the identification of the vibration acceleration response. In this study, impulse excitation with a modal hammer was used. LSCE (Least Squares Complex Exponential) method was used to identify the modular characteristics of the power steering worm drive gear housing based on the designated frequency response function. This method makes possible to estimate

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model parameters in terms of their own frequencies and modal attenuation coefficients. During the measurements, the body was suspended on rubber ropes as shown in Figure 2. At measuring points, denoted P1 - P6 impulse excitations were applied with a modal hammer. The triaxial accelerometer ICP (M356A02) was placed in the location marked with X (Figure 2*b*).

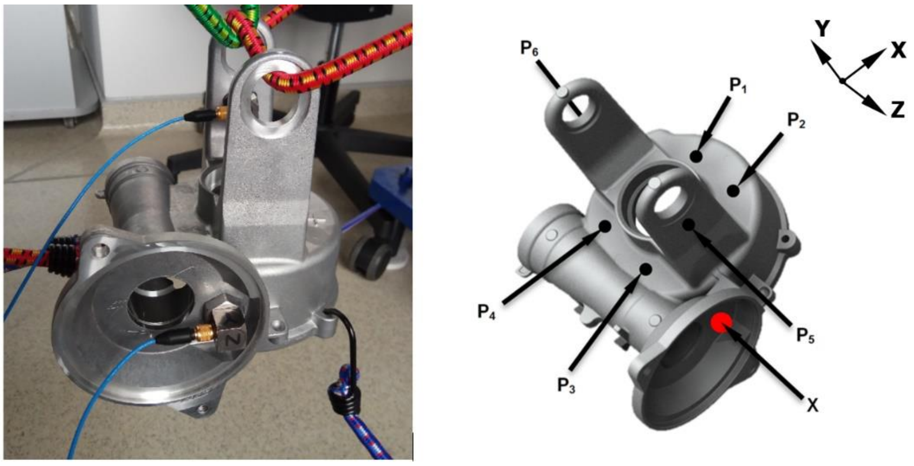

Figure 2. Conditions for carrying out experimental modal analysis: ***a*)** the way of clamping the corpus during measurements. ***b*)** Location of the points of the system excitation with the modal hammer and the location of the sensor.

The following set of measuring instruments was used for the measurements:

- Signal analyzer SigLab 20-42 DSPT Technology,
- Triaxial Accelerometer ICP (M356A02), sensitivity 10 mV / g, 0.5 Hz to 6 kHz range,
- Modal hammer with force sensor, 1 kHz range, force range 22000 N, sensitivity 0.23 mV/N.

Figures 3-5 show the sample graphs autospectrum of signals recorded by triaxial accelerometer placed on the power steering worm drive gear housing during the experimental analysis. It can be clearly noticed at what frequencies the system enters the resonant states. Figure 6 shows the stabilization diagram obtained after analysis of all measured dynamical responses of the system.

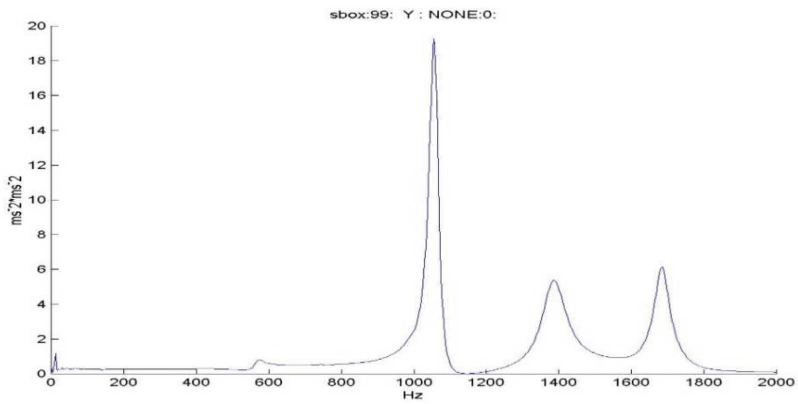

Figure 3. Autospectrum of the signal measured in direction of the axis Y during excitation by modal hammer at point P6 in direction of the axis Z.

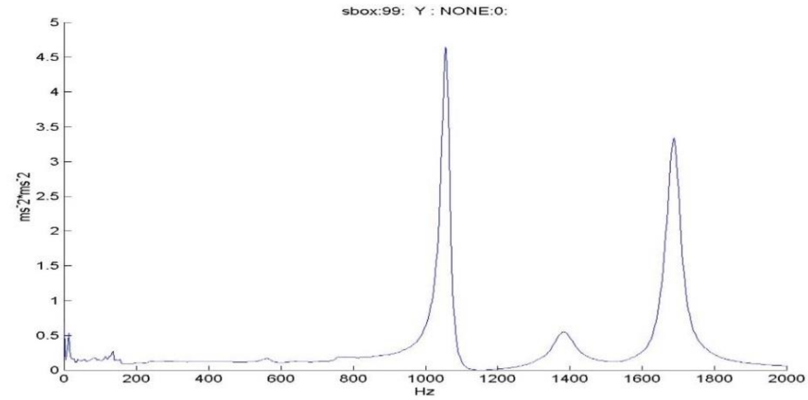

Figure 4. Autospectrum of the signal measured in direction of the axis Y during excitation by modal hammer at point P3 in direction of the axis Y.

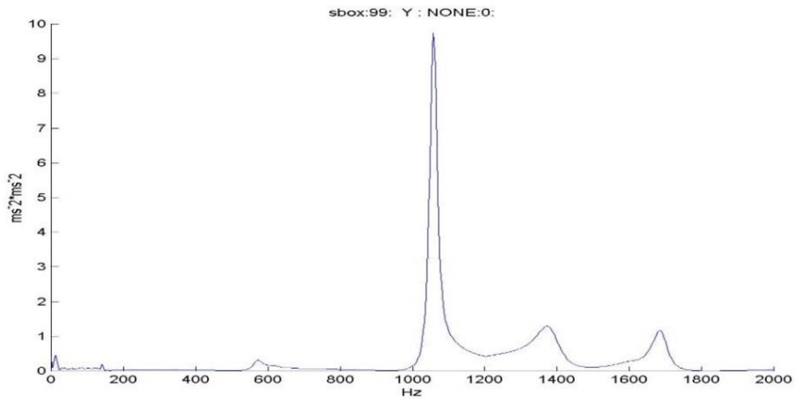

Figure 5. Autospectrum of the signal measured in direction of the axis Y during excitation by modal hammer at point P2 in direction of the axis Y.

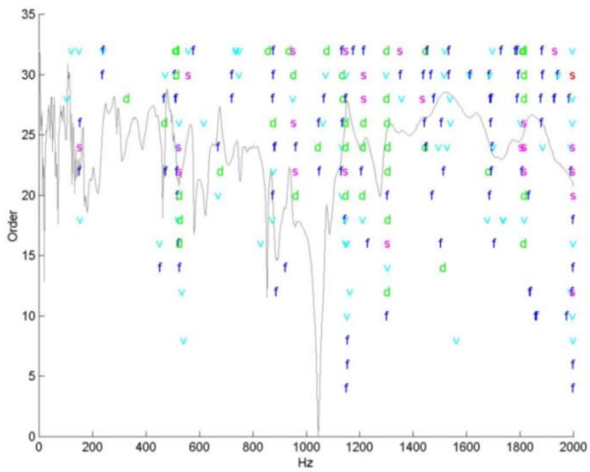

Figure 6. Stabilization diagram.

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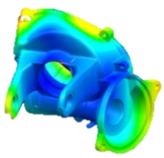
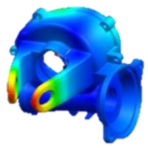
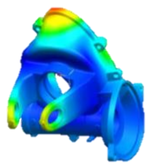
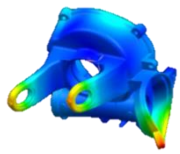
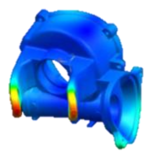
Curried out classical modal analysis allowed to determine the modal parameters with respect to the examined power steering worm drive gear housing. Table 1 shows the results of the experimental analysis. Because of the limited measuring range of frequencies during measurements (up to 2000 Hz) the first three vibration frequencies were identified.

Table 1. Values of resonance frequencies of analysed corpus vibration identified on the basis of experimental analysis.

Number of mode	1	2	3
Frequency [Hz]	1029	1390	1698

At the next stage of the study the numerical modal FEM analysis was performed in case of the standard power steering worm drive gear housing made of aluminium alloy. The "Advanced Simulation" module of PLM Siemens NX 10 was used for this analysis. SOL 103 Real Eigenvalues solver was used. Significant influence on the results obtained in the FEM numerical analysis has the type and size of finite elements used. The difference in results depending on the type and size of items can reach up to 50%. That is why it is very important to fine-tune the numerical model. For this purpose, based on the results of the previous experimental analysis, the FEM model was tuned so that the results were convergent. In the given task satisfactory results were obtained using tetragonal nodes finite element with size of 3.5 mm. Table 2 shows obtained values of the power steering worm drive gear housing's own vibration frequencies and corresponding vibration modes.

Table 2. Frequencies and forms of power steering worm drive gear housing vibration identified by numerical analysis.

Number of mode	1	2	3	4	5
Mode shapes					
Frequency [Hz]	1033	1430	1691	2110	2379

After numerical analysis, a relative error was determined to assess the convergence of the results obtained from the numerical model with respect to experimental modal analysis:

$$\delta = \frac{|f_e - f_n|}{f_e} \cdot 100\% \qquad (1)$$

where: f_e – the frequency determined by experimental modal analysis,
f_n – the frequency determined by numerical modal analysis.

The results of the calculations for the first three power steering worm drive gear housing vibration frequencies are shown in Table 3. Calculated values of the relative error values demonstrate the high compatibility of the developed and tuned FEM model with the real object.

Table 3. Relative error values.

Number of mode	Measured values [Hz]	FEM values [Hz]	The relative error [%]
1	1029	1033	0.38
2	1390	1430	2.8
3	1698	1691	0.41

At the next stage of the study the numerical modal analysis was carried out on modified variants of the power steering worm drive gear housing based on the previously-designed FEM model. Figure 7 shows variants of modified power steering worm drive gear housing that were created for the purposes of the study. Changes and modifications of the housing concerned the material and the geometric form. The aluminium alloy used so far has been replaced with pDCPD. Necessary modifications with respect to the geometric form were caused by the inferior strength properties of the new material. It was necessary to increase the volume and change the geometrical form of the housing in the places where the greatest stresses and displacements occur. Although the housing volume was increased by approx. 40%, due to the lower specific weight of the pDCPD material, the weight of the individual variants of the modified bodies was less than the weight of the housing made of aluminium alloy. Figure 7 and table 4 show effects of introduced modifications of the power steering worm drive gear housing on the volume and mass of individual housing variants.

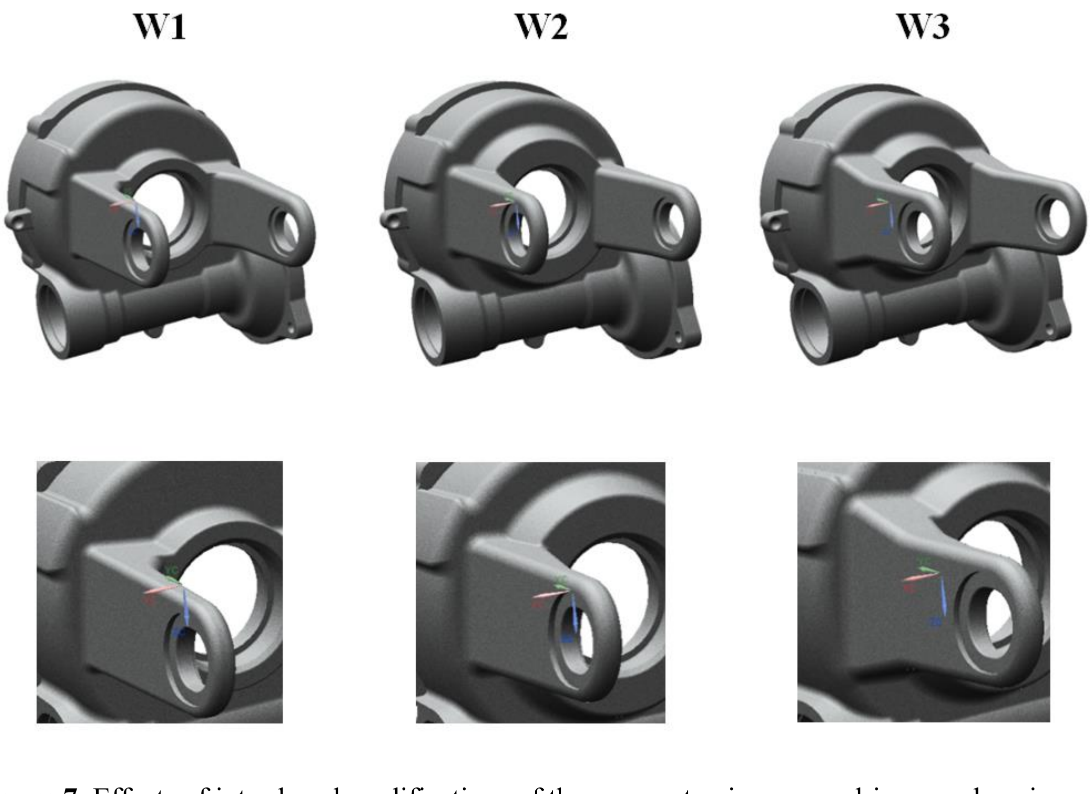


Figure 7. Effects of introduced modifications of the power steering worm drive gear housing on the geometric form of individual housing variants.

Table 4. Effects of introduced modifications of the power steering worm drive gear housing on the volume and mass of individual housing variants.

Variant of the housing	Volume [cm^3]	Mass [kg]
Standard housing made of aluminium alloy	240.454	0.652
W1	436.276	0.449
W2	464.960	0.479
W3	463.792	0.477

The performed modal analyses allowed to determine how introduced modifications of the housing influenced the forms and values of the frequencies of the own vibrations. Table 5 shows the results of modal analysis for each three variants of the power steering worm drive gear housing.

Table 5. Resonance frequencies for individual variants of the housing.

Number of mode	Natural frequencies [Hz]			
	Standard housing	W1	W2	W3
1	1033	396	408	413
2	1430	479	531	533
3	1691	582	658	657
4	2110	628	752	765
5	2379	805	842	846

The results obtained in the numerical experiment indicate that the change of material and geometric form significantly affects the body's own vibration frequencies. When analysing the developed variants of the bodies, the W3 variant, which is characterized by the highest mass and rigidity is best (it has the highest value of the first resonance frequency of vibration).

4. Conclusions

Conducting experimental modal analysis allowed correct tuning of FEM numerical models. The results obtained confirm the correctness of the developed FEM models. The largest relative error for the value of the second resonance was only 2.8%. For remaining frequencies, the error was less than 1%. The modal analysis of the different versions of the considered power steering worm drive gear housing made it possible to assess the impact of the made modifications on the forms and frequencies of the housing vibrations with respect to the modified bodies. The use of numerical analysis allows you to pre-estimate modular parameters of the system without the need to build a prototype, which significantly speeds up the research and reduces the cost. Numerical analysis is the basis for further research into the dynamical behaviour of the modified the power steering worm drive gear housing and whole power steering system. In the final version of the product it will be necessary to perform an experimental modal analysis of the entire power steering system.

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