Numerical Study of Noise and Vibration Behaviour of Lightweight Gearbox Housing

Khadijeh Farshi[1], Manuel Bopp[2], Manuel Petersen[3], Tobias Gohlke[4], Albert Albers[5]

[1] *IPEK – Institute for Product Development at KIT, 76133 Karlsruhe, E-Mail: khadijeh.farshi@kit.edu*

[2] *IPEK – Institute for Product Development at KIT, 76133 Karlsruhe, E-Mail: manuel.bopp@kit.edu*

[3] *IPEK – Institute for Product Development at KIT, 76133 Karlsruhe, E-Mail: manuel.petersen@kit.edu*

[4] *IPEK – Institute for Product Development at KIT, 76133 Karlsruhe, E-Mail: tobias.gohlke@kit.edu*

[5] *IPEK – Institute for Product Development at KIT, 76133 Karlsruhe, E-Mail: albert.albersn@kit.edu*

Abstract

The gearbox housing is one of the main components of an electric vehicle which has an influence on the NVH behaviour of the gearbox and overall vehicle, especially in the context of e-mobility. Vibrations inside the gearbox are mainly excited at the gear mesh and then transmitted to the housing through shafts and bearings, where it is radiated as air-borne noise. Because of the importance of reducing the weight of electric vehicles, housing structures are often target of lightweight design measures, which, in turn, often lead to inferior NVH behaviour.

In this paper, the effects of different lightweight design measures on the vibrational behaviour of a gearbox housing are evaluated by numerical simulations. Firstly, the basic model (without lightweight design) has been simulated numerically in a commercial finite element software to extract the natural frequencies, mode shapes and frequency response functions for specific points of interest. These results have been verified by the measurement using 3D laser scanning vibrometer. Then, multiple variants of the electric vehicle gearbox housing are created in CAD and numerically simulated with different lightweight design. The results of the modal analysis provide valuable insights on the vibrational behaviour due to lightweight design measures.

Introduction

The vibrations in a gearbox are mainly generated at the gear mesh and transmitted to the housing via shafts and bearings. The sound pressure determined from simulations and experiments shows that the housing vibration is the main noise source of the gearbox, and the internal noise can be neglected compared to the housing noise [1]. Therefore, the design of the gearbox housing is important to reduce the emission of unwanted structure-borne noise and vibration. To reduce noise and vibration levels, some modifications are frequently used on gearbox housings. For electric vehicles to have a higher efficiency, it is important to utilizing lightweight structures. Because of the importance of reducing the weight in electric vehicles, housing structures are often target of lightweight design measures. When applying lightweight design on the housing, it is important to consider the vibrational behaviour of the housing at a same time, because reducing the weight of system mostly have a negative effect on NVH behaviour [2]. The purpose of this paper is to describe the effect of some variants of lightweight design modifications on the vibrational behaviour of an electric vehicle gearbox housing.

Problem Containment

It is necessary to reduce the weight of the system to decrease the energy consumption at electric vehicle; on the other hand, by reducing the weight of the system, generation and transmission of noise and vibration of powertrain's components are increased [3]. So, a method needs to be developed to achieve an optimized design of transmission system to consider the effect of both lightweight specs and NVH behavior at a same time on the vehicle. Several studies have shown, the main source of noise from the gearbox is the housing [4,5]. Most relevant modifications on the gearbox housing are divided into two categories: material and geometry. For the material the aim is to use a low-density material for example composite material. In terms of geometry, the goal is to use structures with less mass in return with sufficient strength. To this end, adding ribs and reducing wall thickness are common methods to reduce weight in some parts on the housing surface [6].

In this paper, we are focusing to the type of modifications that relates to the geometry. Based on the previous studies [4,7], ribs were designed to improve the stiffness of the housing. Modifying the housing by introducing ribs helped to reduce its vibration. Another proposed solution to minimize the vibration of the gearbox housing is to modify its wall thickness. Decreasing the wall thickness helps to reduce the body weight but it causes to increase the vibration activity of the gearbox [4]. Besides these modifications, the arrangement of ribs also has an influence on the vibration of gearbox housing. In this paper the focus is on the two more common options that are used for reducing the weight of the gearbox housing. It depicts the effects of minor changes in rib counts and wall thickness on an existing electric vehicle gearbox housing, on its vibrational behaviour.

Procedure and Method

The procedure of this paper is divided into four main steps as shown in Figure 1: numerical simulation of original housing, experimental analysis of the original housing, numerical simulation of modified housings with considering the lightweight structures, and comparison. The numerical simulation for both the original and modified housings are with the same mesh size, measurement points and excitation points.

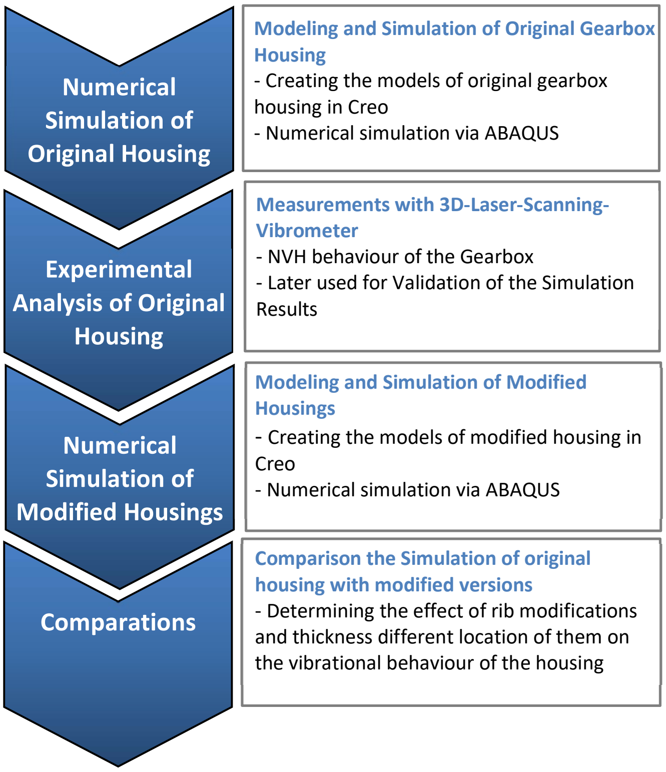


Figure 1: Process diagram showing the main steps

Numerical Analysis of the Original Housing

The noise of the gearbox is mainly generated by vibration of gearbox components and to analysis of noise distribution, the first step is modal analysis of the gearbox housing. The gearbox housing that is used in this simulation is from an electric vehicle. This gearbox reduces the input speed in a two-step reduction with 7.13 gear ratio and the maximum rational speed of input shaft is 8000 rpm. The model of the housing gearbox used for simulation is shown in Figure 2. It is an aluminium cast housing the housing with a Young's modulus of 7700 N/mm^2, Poisson's ration 0.33, damping ratio 0.3% and a density of 2700 kg/mm^3. The total mass of the modelled housing was 2.243 kg.

Finite element analysis (FEA) was performed in Abaqus FEA software to obtain the dynamic characteristics of the actual gearbox housing. For creating the model of the housing, the geometry of the housing is firstly simplified to remove small features such as little bore holes, small chamfers, and small rounds as they do not have a significant contribution to the dynamics. Then, the mesh convergence process was performed to reach the accurate eigen-frequencies by resizing the element size.

The structural mesh was created with Tetrahedral element type and in the free-free boundary condition. The element size selected for simulation, started with 10 mm, and refined it to 4 mm. Results show that by refining the element size to 4 mm, the obtained first fourth natural frequencies are in good convergency. For the eigenfrequency analysis first fourth natural frequencies until 4000 Hz are extracted.

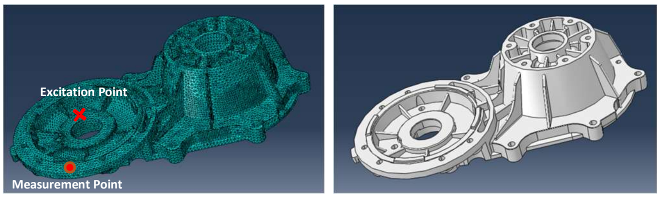


Figure 1: Gearbox housing that is used for the simulation and measurement.

Eigenfrequencies and mode shapes are necessary for the frequency response function. The structure is excited and measured at the point that is mentioned in figure 2. The first four natural frequency and corresponding mode shapes derived from finite element analysis are shown in figure 3. Based on the points on the surface with maximum deflection, that could be derived from the mode shapes, the point of measurement was determined. Besides, it is concluded that the rigidity of these parts is weaker compared to the other parts due to their greater deflection. At the figure 4, the frequency response function has mentioned.

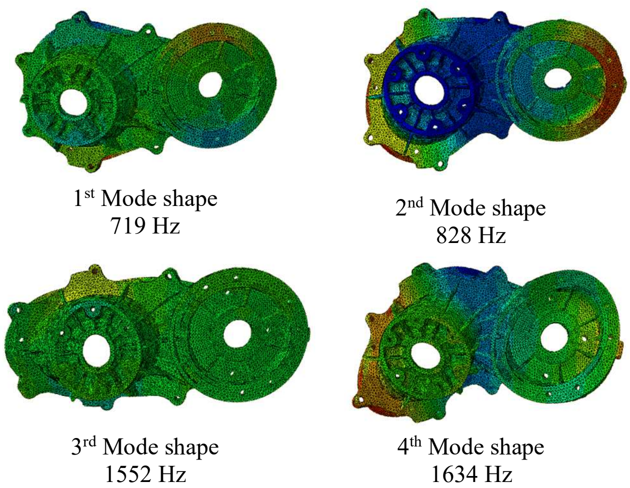


Figure 3: First four natural frequencies and corresponding mode shapes derived from FEA

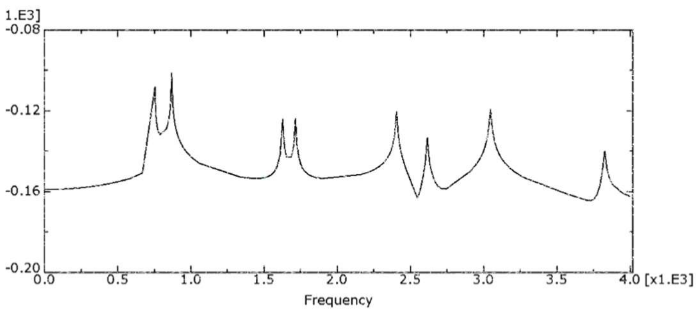


Figure 4: Simulated frequency response function of the original housing

Validation of Simulation Results

To verify the accuracy of the simulation results, a measurement was conducted. The test setup is shown in figure 5, the housing is excited via a shaker and the excitation is done with a pseudo-random signal. The surface displacement of the structure is measured using a PSV 3D laser scanning vibrometer. The excitation and measurement points are the same as the previous part for all the simulation and measurements during this paper.

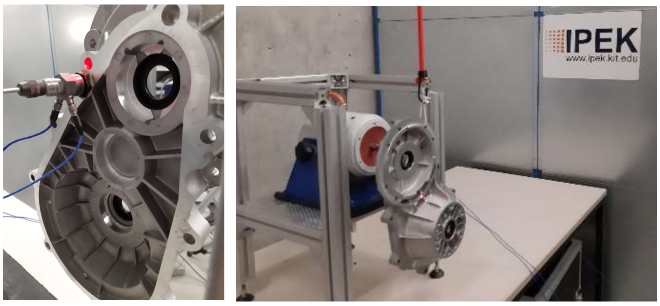


Figure 5: Test setup with shaker, the housing is measured by laser scanning vibrometer

The measurement points were derived based on the numerically simulation and mode shapes in the previous part. Based on the working rotational speed of the gearbox, the target frequencies were defined, and the frequency range of interest was between 500-2000 Hz. The housing has four natural frequencies in the frequency response function in this frequency range, shown in figure 6.

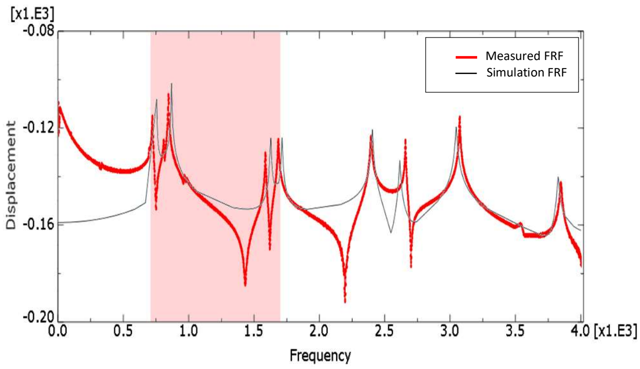


Figure 6: Measured and simulated frequency response function (FRF) of the housing

Table 1 shows that there is a good agreement between the natural frequencies obtained in the experiment and the numerical FEM. For achieving a better fit for simulation and measurement we have updated the material properties for aluminium as mentioned in the previous section. In the following steps, models of the housing without ribs and reduced thickness in the region near the input side bearing were created to determine their impact on the vibrational behaviour. Additional models with different rib configurations were created for investigating the effect of the location of existing ribs on the vibrational behaviour.

Table 1: Comparison of natural frequencies obtained by experimental and numerical for original housing

	1st natural frequency (Hz)	2nd natural frequency (Hz)	3rd natural frequency (Hz)	4th natural Frequency (Hz)
Calculated by FEM	755	868	1628	1713
Measured values	757	870	1611	1707

Modifications and Numerical Results

The area near the input and output side bearings is the focus of attention when making the changes since the transmission of vibrations from other components to the gearbox housing is mainly through the bearings [6]. The first step is to create both models of the housing with the same mass by removing the ribs on the surface of the housing near the input side bearing and reducing the wall thickness in the respective area. The mass of both the created models is the same as 2.230 kg, decreasing the weight as 5% in comparison to the original model. Figure 7 shows the modified versions of the housing.

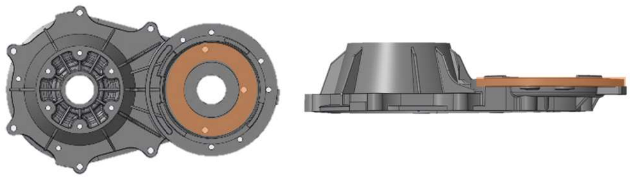


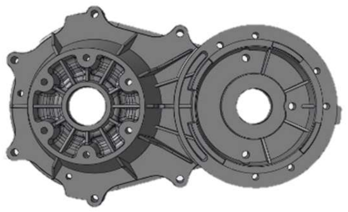
Figure 7: Left: case1 for the modified version without ribs on the surface near to the input bearing. Right: case2 for the modified version by reducing thickness on the surface with the equivalent mass with case1, the modified surfaces are highlighted at the figure.

The results of numerical simulation according to each modification were compared in table 2 and it depicts that each modification, has a specific effect on the natural frequencies, even though the mass of each one after modification was equivalent. For example, for case 1 which focuses on the influence of removal of the ribs, the natural frequencies are decreased in frequency. On the other hand, for the case 2, which focusses on the influence of the thickness, the natural frequencies are increased in frequency after the modifications. In other words, modification showed that it was more effective to remove the ribs than to reduce the thickness with the same mass in terms of decreasing the natural frequencies. The mass for the original case is 2.243 kg, and the mass of the housing after modification is 2.230 kg for both cases. Even by minor changes in mass, we can see the effect of modifications on the 2nd and 4th natural frequencies.

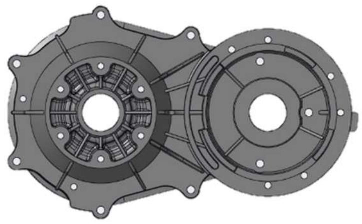
Table 2: first four natural frequency for the original and modified housing

Model	1st natural frequency (Hz)	2nd natural frequency (Hz)	3rd natural frequency (Hz)	4th natural Frequency (Hz)
Original housing	755	868	1628	1713
Modified housing case1	754	**859**	1625	**1689**
Modified housing case2	758	**873**	1629	**1720**

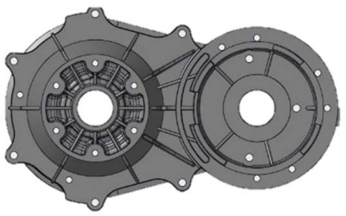
For the next step, the focus lies on the effects of the location based rib configurations, on the vibrational behavior. The three modified versions are shown in figure 8. In each of the three cases, the focus is on the effect of the kept ribs on the housing surface and thus the vibrational behaviour separately. The mass of each case is the same, and only the place of the ribs is changed.



(a)



(b)



(c)

Figure 8: modified versions with differently removed ribs from the different locations on the housing surface (a), (b) and (c).

As it is shown in the table 3, different natural frequencies are influenced regarding each case. Of these four natural frequencies, the fourth natural frequency is most affected by the change in the position of the ribs in cases (a) and (b), and the first and third natural frequencies are being the least affected by said changes.

Table 3: first four natural frequency for the original and 3 modified housing

Model	1st natural frequency (Hz)	2ndnatural frequency (Hz)	3rd natural frequency (Hz)	4th natural frequency (Hz)
Original housing	755	868	1628	1713
Modified housing case (a)	754	861	1627	1700
Modified housing case (b)	754	867	1626	1701
Modified housing case (c)	756	873	1628	1707

Conclusion

In this paper, effect of some variant design modifications such as ribs and wall thickness in the surface area close to the bearing on the vibrational behaviour of an electric vehicle gearbox housing was presented. Firstly, some simplification was done on the real model of the housing to reduce the time of simulation process, and then the model is simulated numerically by ABAQUS. The result from the simulation approach was measured by PSV 3D laser scanning vibrometer. The results mentioned a good agreement with the simulation results.

For the modification approach, among the possible modifications, we were focusing on the options that could be changed at the existing electric vehicle housing. In the first two cases, the effects of rib and wall thickness were evaluated separately. The results shows that the type of modifications, removing the ribs or reducing the wall thickness with the equivalent mass did not have the same effect on the natural frequencies of the housing. With the reduction of the mass by 0.5% mass for both cases, removing the ribs had the max effect on the fourth natural frequency by reducing the frequency of the eigen frequencies as 1%. The other modified cases were developed to mention the effect of ribs in different locations on the eigen-frequencies of the housing. The results of the finite element analysis verified that not only the type of the modifications are important, but also the location is important.

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