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Preliminary communication

Modal Properties of Bolted Housing depending on the Methodology of a Solution of Bolted Joints

Peter WEIS*, Ján ŠTEININGER, Milan SAPIETA, Branislav PATIN

Abstract: This paper presents the research of modal characteristics of the bolted housing. The aim of the research was to find out the impact of the methodology of the solution of bolted joints on modal characteristics of the bolted housing of the gearbox unit. Results of research can be applied to bolted housings of any machineries. An impact of bolted joints and their modal properties was also the subject of research. The first three analyses focused on an application of various approximations of bolted joints. The analysis of their substitution by a simplified 3D geometry was solved. The second analysis focused on an application of Beam elements and the third one focused on substitution by bonded contact types. The fourth analysis regarded housing as one body without bolted joints. The impact on modal properties of pre-stress load in joints was researched. The housing was also loaded by the torque moment of an electric motor by means of bearing reactions and also the weight of the motor and brakes mounted to the housing. The article also deals with the efficiency of individual methods regarding the calculation time.

Keywords: bolted connections; bolted housing; bolt preload; modal analysis

1 INTRODUCTION

Noise and vibrations in the environment are caused by various processes by which specific structures activate dynamic effects. Then noise and vibration effects affect environmental quality, fatigue, safety and it also may result in health damages. In machinery, the vehicles or buildings' vibrations contribute to decreased durability, an increased failure rate or other damages. Most problems connected with noise and vibrations are caused by the phenomenon termed as resonance. Resonance takes place when exciting frequencies are the same as own frequencies of a given system.

This is one of the main reasons for a solution of the modal analysis. Many types of machinery contain bolted joints. They cannot be neglected in finite element analyses due to their impact on modal properties of the system. That is why there exist efforts to find a suitable approximation of the bolted joint model in the configuration to obtain an optimal solution time and accuracy of results. Authors of most studies deal with the issue of analyses of machinery with bolted joints intending to understand modal properties and to identify their own critical frequencies.

Marinković et al. [1] modelled and simulated dynamic behaviour of electric motor driven mechanisms with the aim to demonstrate that a combination of a simplified model with an accurate description of drive and load torques produces satisfactory results. Kulkarni et al. [2] solved the pre-stress load effect in bolted joints on natural frequencies under impact loading. Pengxing et al. [3] solved the modal analysis of the gearbox of the wind turbine in which finite-element calculations were also compared with experiments. He described a substitution of bearings and contacts in the rack in the calculation model employing "spring elements" with defined rigidity. Chavan et al. [4] solved a modal analysis of a power take off gearbox. The goal of the present project study was to understand the generation of the vibration in PTO gearbox and provide recommendations to reduce vibrations by 15-20 per cent of current levels. Ashawni et al. [5] studied the effect of mechanical properties of materials on the natural frequency and mode shapes of heavy vehicle gearbox transmission casing. Effects of bolt preload on the dynamic response of a bolted interface were also examined by Butner et al. [6]. Vladic et al. [7] show a process of forming adequate mechanical models for elevators grouped according to their features. Obtained results were graphically shown through diagrams with varying dynamic parameters with conclusions on their influence on elevator behaviour. Tomovic et al. [8] tested a vibration response of a rigid rotor in an unloaded rolling element bearing. They experimentally verified a defined vibration model and a parametric analysis. Barač et al. [9] researched generated noise in the cabin of agricultural tractors. Caresta et al. [10] study a relationship between natural frequencies and a pull out force for plates with two clamped edges. A modal analysis was performed to relate the natural frequencies to torque used to fasten bolts. Sofian et al. [11] performed a vibration analysis of a gearbox casing via Finite Element Method. They also modelled bolted connections between the upper and lower casing. Anđelić et al. [12] study the influence of a circular saw blade rotation, slot shapes and a number of slots on its natural frequencies and critical speeds. The results were compared with the ones obtained using FEM method and the FEM method was then applied to the real circular saw blade model. Kim et al. [13] investigated a modelling technique of the structure with bolted joints. They took into account a pretension effect and contact behaviour between flanges to be joined. They came to the conclusion that the solid bolt model could most accurately predict the physical behaviour of the structure. Ericson et al. [14] performed an experimental modal analysis to characterize the planar dynamic behaviour of two spur planetary gears. They found out that accuracy of natural frequency prediction is improved when the planet bearings have different stiffness in tangential and radial directions, consistent with the bearing load direction. Shrenik et al. [15, 16] compared a theoretical modal analysis of a gearbox with experimental results from Fourier frequency transformer analysis. Belorit et al. [17] dealt with the description of countershaft gearboxes and their basic division. Łukasiewicz et al. [18] present a diagnostics technique of a beach buggy gearbox technical state based on the measurement of modal vibrations. Nigade et al. [19] performed a modal analysis to examine vibration characteristics of the top cover of an integrally geared centrifugal compressor in detail.

The article deals with an examination of differences in natural frequencies of the bolted housing in various methods of approximation of bolted joints. It also compares them in relation to a consideration or an omission of bolted joints. Moreover, it evaluates the efficiency of individual methods regarding the computational time.

2 FINITE ELEMENT METHOD

Four analyses are solved. In the first analysis, bolted joints are substituted by 3D geometry. It is the most accurate approximation of bolted joints. The second analysis focuses on the application of Beam elements. In these two methods, we can examine also load in critical points near bolted joints simultaneously with an examination of modal properties. The third analysis considers a substitution of bolted joints by bonded contact types. It is a rather simplified approach regarding the impossibility of an application of pre-stress load in bolted joints. The fourth analysis considers a gearbox as one body without bolted joints. It is the simplest approach to the solution of the issue. As in the computational model contacts are not present either among individual components or bolted joints and the task is linear.

2.1 Production of Computational Models

The analyzed housing is a part of the gearbox unit that serves as a drive for the bevel strand conveyer. The power flow from the input to the output shaft is transmitted through the bevel gearing and two planetary rows. The weight of the electric motor and a brake is represented by mass points attached to the gearbox housing consisting of several components. Within one analysis, the static and modal analyses are solved. In the static analysis, there is defined the operation load and the resulting contact status changes the matrix of stiffness entering the modal analysis. Before the finite element analyses, complex modifications of geometry in CAD software were performed; for example, the removal of small holes, fillets or chamfers. Depending on the solved analysis, the computational model is moderately modified.

Preload in bolted joints was defined in the first load step. In the second load step there was defined torque of the value $M_k = 274.72$ Nm by means of reaction forces in bearings calculated by the software KISSsoft. During the second load step pre-stress load in the bolted joints was locked. Moreover, the load from weight and inertia effects of the electric motor and the brake was applied on the gearbox via mass points. On the cylindrical surface of the output shaft, all degrees of freedom were removed. A reaction force was measured on the surface in the bottom part of the reaction arm by means of the removed translation degree of freedom on the axis y and rotary degrees of freedom around axis x and axis z. The load and supports were identical in all computational models with the exception of the third and fourth analyses in which pre-stress load in bolted joints was not considered. Fig. 1 shows the geometry of the computational model of the first analysis with 3D geometry of bolted joints.

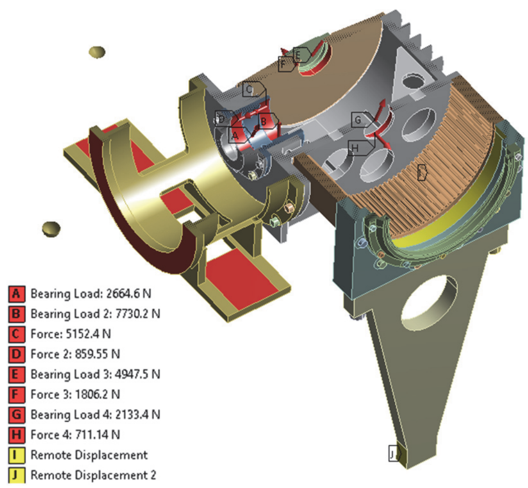

Figure 1 Boundary conditions

In the first case, the bolted joints were represented via 3D geometry. This is the most authentic model of computation of the bolted joint. The time of calculation strikingly prolongs due to a large number of contacts. Thread connections were simulated via Bonded contact type. Among bolt heads and the housing surfaces the contact of the Frictional type was simulated. In case of the contact Frictional, the formulation Augmented Lagrange with detection in gauss points was set up. The method of Augmented Lagrange is convenient due to an automatic reduction of the penetration level, which is favourable in most non-linear issues.

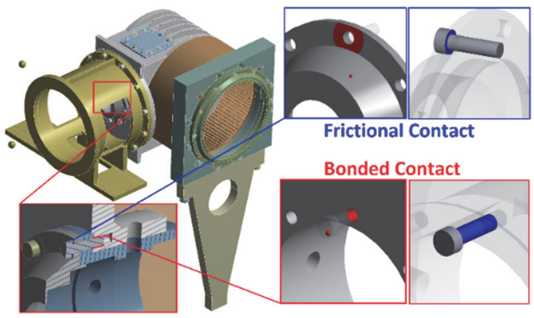

Figure 2 FEM model with 3D Bolts

In the second case, the bolted joints were substituted by beam elements. Therefore, the 3D geometry of bolted joints is not needed. One Beam element is formed between connected components. To design and form connections, it was necessary to define edges of the bolt hole in one component and the cylindrical surface simulating the thread connection in the second component. Pre-stress load and a cross-section were both defined for beam elements following the bolt type. A disadvantage of the method, in comparison with the previous one, is an impossibility to find out a distribution of equivalent stress in the bolted joint.

In the third case, bolted joints were substituted by contacts of bonded type. Bolted joints were completely removed from the model. The fixed connections are defined around bolt holes. Sizes of contact areas are defined by diameters of bolt heads. This type of connection is suitable to be applied in complex structures. However, preload in bolt connections is not possible to apply. The frictional contact with a coefficient $f = 0.3$ is defined for the contact surfaces of particular components of the housing.

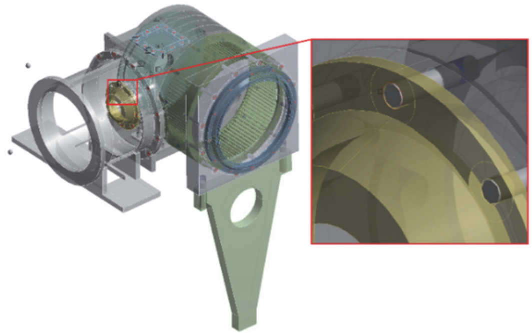

Figure 3 FEM model with Beam Bolts

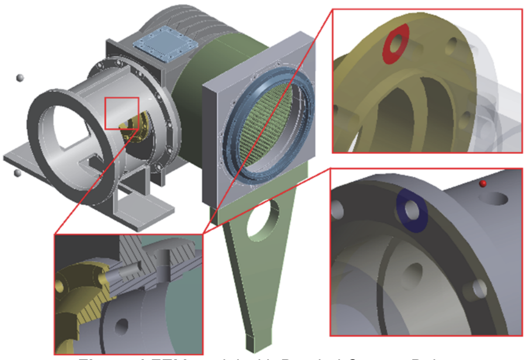

Figure 4 FEM model with Bonded Contact Bolts

In the fourth case, the analysis without consideration of bolted joints was solved. All bodies including individual components of the housing and bolted joints were merged into one body. No contacts were present in the model. In comparison with other computational models, this model represents the simplest approach towards the analysis solution. However, it describes real bonds among bolted components of the housing rather inaccurately. This is not very suitable for purposes of the modal analysis, as contact rigidity is one of key factors affecting solution accuracy.

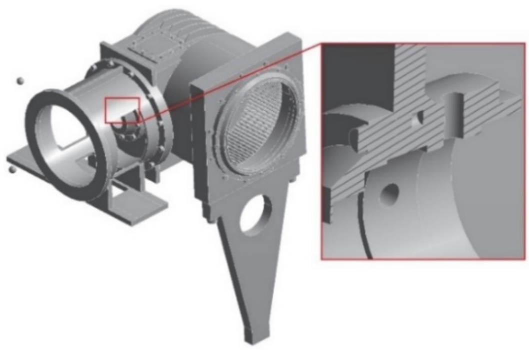

Figure 5 FEM model without bolts

We used the finite element mesh with linear elements. However, the application of linear elements, regarding their characteristics in rigidity, may lead to final natural frequencies that are higher than real ones. On the global level, the size of the element with the value of 10 mm was defined. On the contact surfaces between components of the housing the size of the element was defined in the value of 3 mm. The size of elements of bolted connection surfaces was set to 1.5 mm. The method of meshing of bolted joints was designed in Multizone, which enabled us to create a mapped hexahedron mesh.

It results from Tab. 2 that by the substitution of bolted joints by beam elements approximately 9.92 percent lower number of nodes was applied compared with the analysis with 3D geometry of bolts.

2.2 Results

The substitution of bolted joints by beam elements markedly decreased computational times. In the sum of times of the static and modal analyses, we speak of approximately 46.6 percent of the saving of the computational time when considering preload in bolted joints. In Tab. 1 reductions of a computational time are stated in percentages regarding the first analysis in which bolted joints are substituted by the simplified 3D geometry.

Table 1 Computational time

Type of bolted connections	Structural analysis / hour	Modal analysis / hour	Total / hour	Time reduction / %
3D	12.46	1.21	13.67	-
Beam	6.43	0.87	7.30	46.60
Bonded	3.86	0.67	4.53	66.86
Without	3.20	0.87	4.07	70.23

Fig. 6 shows dependence between the number of nodes and the computational time. The graph also shows that the computational time of analyses is affected by the number of nodes as the density of the finite-element network on a large scale. Even the advantage of the substitution of the geometry of bolted joints by beam elements is manifested here, as we can rather accurately model a real condition of the analysed system including preload in bolted joints by a considerable reduction of nodal points.

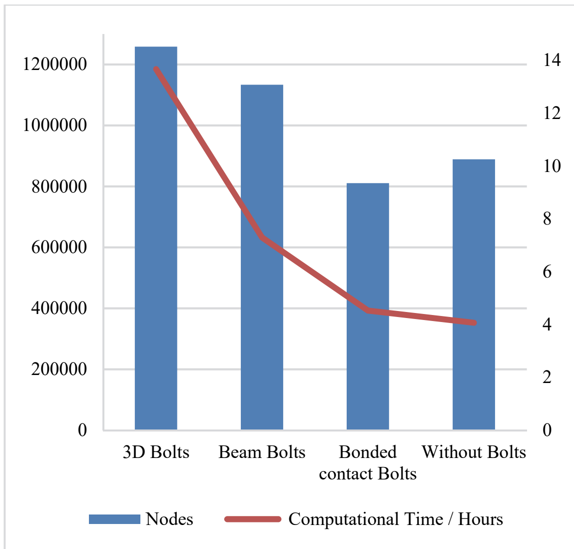

Figure 6 Computational time reduction

Fig. 7 shows equivalent stress on the housing evaluated in all methods. For a comparison of all the methods, the second highest value of equivalent stress is defined by the limit of 20 MPa. When considering preload in bolted joints, negligible differences can be recorded in points of bolted joints. However, the size and distribution of stress are similar in both analyses.

In the third and fourth analysis, an increase of equivalent stress from preload in bolted joints disappears. The maximum values are recorded in the area of the bolted joints connecting the reaction arm with the gearbox housing.

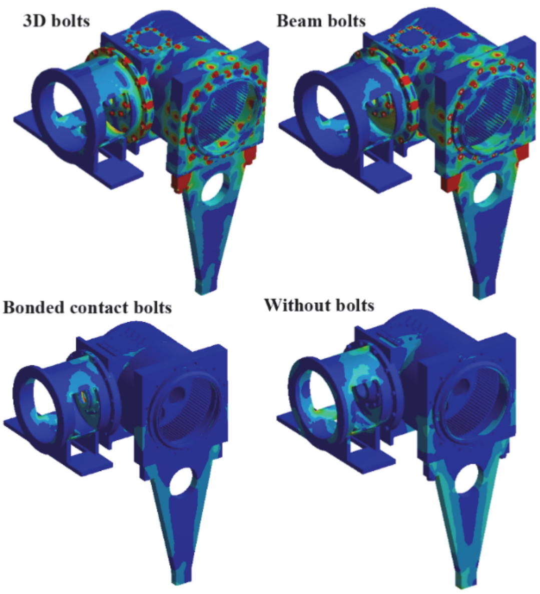

Figure 7 Equivalent stress distribution

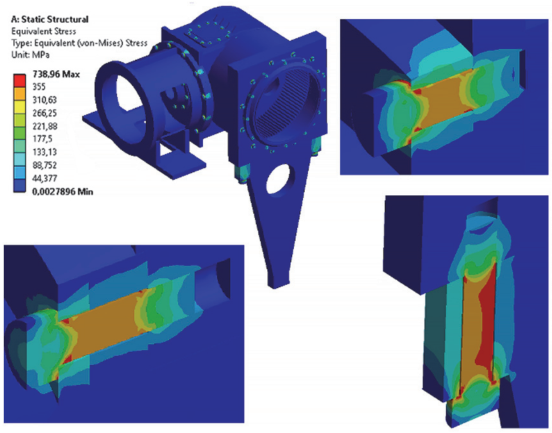

Figure 8 Local equivalent stress - 3D bolted joints

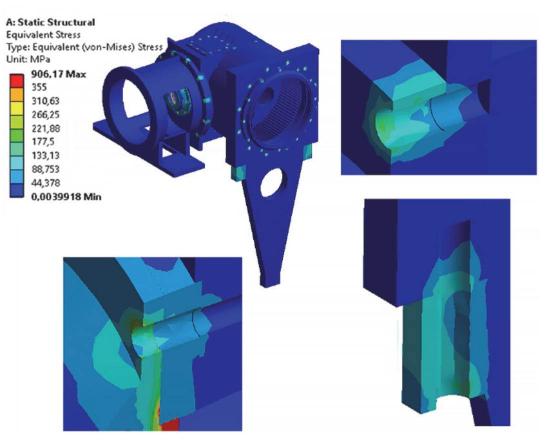

Figure 9 Local equivalent stress - Beam bolted joints

Fig. 8 and Fig. 9 show local equivalent stress in the bolted joints of the housing. Moderate differences in maximum values are caused by absent geometry. For comparison and better clarity, the second highest value of equivalent stress is defined by the limit of 355 MPa. One may see that final stress with the application of beam elements relatively accurately responds to the results of the analysis with 3D bolt geometry.

Moreover, the first 20 lowest natural frequencies were calculated and their corresponding mode shapes. Tab. 2 and Fig. 10 show that, regarding the methodology of the solution of bolted joints, there are obvious small deviations in natural frequencies.

Table 2 Finite element mesh

Mode shape No.	Natural frequency / Hz			
	3D	Beam	Bonded contact	Without
1	33.21	36.09	36.11	37.53
2	45.42	44.87	46.93	51.85
3	51.86	53.75	53.35	59.05
4	58.15	61.16	61.55	69.14
5	84.99	88.35	78.07	101.71
6	94.41	95.95	97.15	101.82
7	212.70	207.11	194.44	278.46
8	231.27	224.24	221.39	287.21
9	268.04	275.75	280.89	306.68
10	311.25	311.65	307.15	360.21
11	371.95	380.06	385.35	416.49
12	401.61	404.38	408.46	440.71
13	437.94	438.84	429.61	518.77
14	460.15	468.09	472.62	536.56
15	519.73	527.36	505.11	728.79
16	704.01	707.29	700.78	823.09
17	736.12	755.52	764.79	879.15
18	750.44	768.32	780.99	916.01
19	815.27	833.34	793.60	942.82
20	835.93	836.48	838.61	983.89

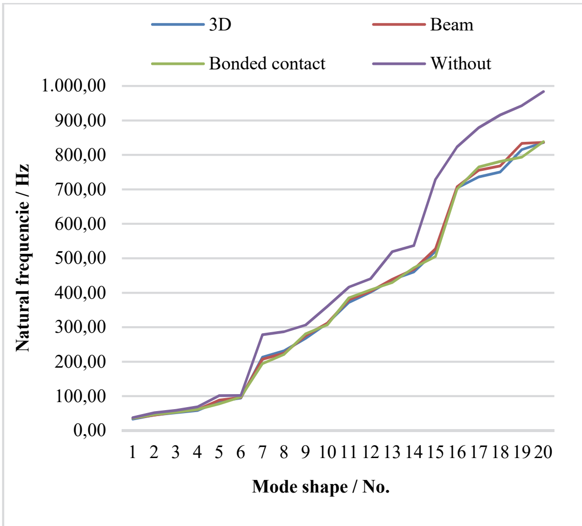

Figure 10 Natural frequencies comparison

The deviations are caused mainly by the absence of 3D geometry of bolted joints thus affecting the whole contact stiffness. Natural frequencies are rather close to each other due to a large number of components in the analysed structure. Generally, the final natural frequencies may be similar in analyses in which bolted joints are considered, and therefore the housing is not a single body. An impact of preload in bolted joints does not considerably affect the final natural frequencies. Results confirm the fact that in the modal analysis of bolted housings, it is critical to record relations among particular components. Differences start to deepen in higher natural frequencies, namely depending on consideration or an omission of bolted joints solved by any method.

The following figures show mode shapes corresponding to the first four natural frequencies have a tendency of vibration, especially in the area of the input gear shaft. We may assume that maximum values of mode shapes depending on a method of the solution of bolted joints have their positions in the same points. However, in case of higher frequencies differences in mode shapes start to deepen in a similar way as in the case of natural frequencies. Mode shapes belonging to higher natural frequencies differ mostly in an analysis without consideration of bolted joints. It is especially caused by an incorrect definition of contact rigidity on contact surfaces of components of the housing. An impact of preload in bolted joints can be also regarded as negligible.

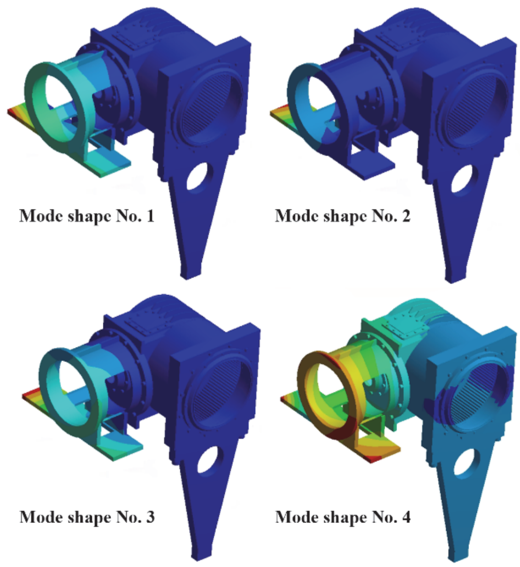

Figure 10 Mode shapes - 3D bolted joints

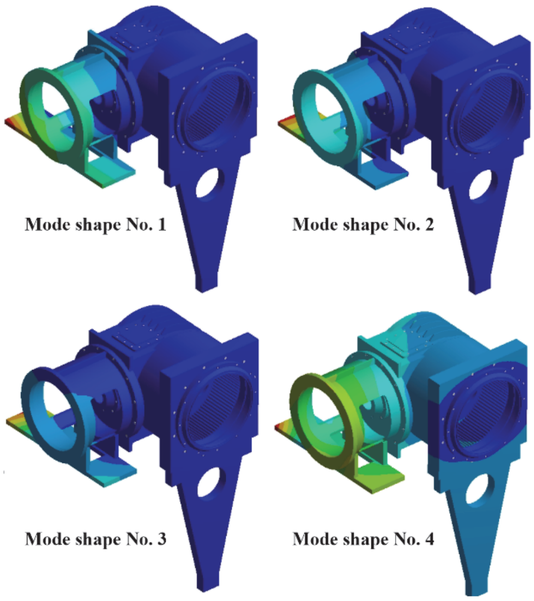

Figure 11 Mode shape - Beam bolted joints

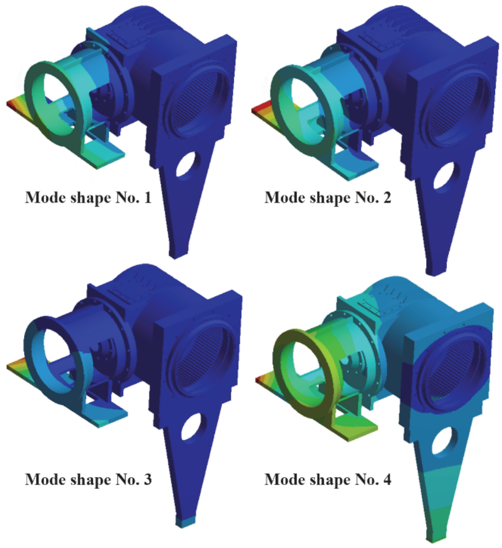

Figure 12 Mode shapes - bonded contact bolted joints

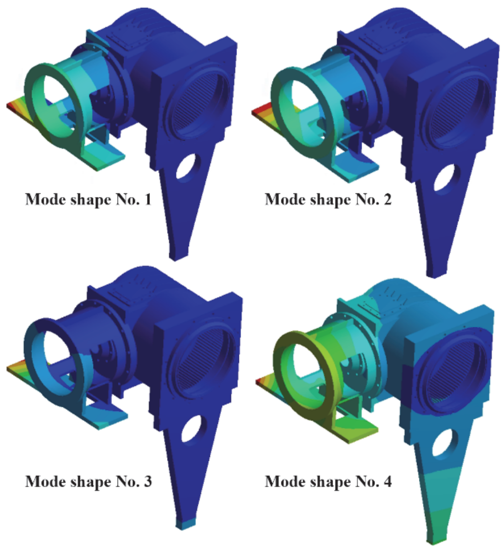

Figure 13 Mode shapes - without bolted joints

3 CONCLUSION

In the article, we dealt with the issue of the modal analysis of the gearbox housing loaded by operational forces. We investigated the impact of the methodology of the solution of bolted joints on modal properties. Bolted joints were solved via three methods. In the first method, they were defined by means of 3D geometry, in the second method by means of beam elements. In the third analysis, bolted joints were removed and a connection of housing components was simulated by means of bonded contacts. In the fourth analysis, all the components of the analysed system, including bolted joints, formed one body. From the standpoint of an examination of modal properties of bolted housings, the third method with bonded contacts was the most efficient, as an impact of preload in bolted joints does not affect them. It accurately defines relations among contact surfaces of the housing. Even a need for meshing of 3D geometry of bolted joints is not necessary. That considerably decreases the number of finite elements in case of a great number of bolted joints. Moreover, it is necessary to define the amount of beam elements simulating bolted joints as opposed to the second method. However, we need to mention one fact and, thus, the missing geometry of bolted joints manifests itself to some extent in final natural frequencies. From the comparison of individual methods results the fact that the differences are not considerable. Maximum values of mode shapes across individual methods appear on the same points. Differences in natural frequencies and to them belonging mode shapes deepen in higher frequencies, especially in the fourth method, in which we consider the housing as one body. The results indicated that by request for the most accurate calculation of modal properties of similar bolted housings, we cannot neglect the connections of individual components. In the case of secondary requests for solutions of local stress of critical points near bolted joints, the second method appears as the most efficient. A substitution of 3D bolted joints by beam elements manifested itself by the saving of the time of calculation by 46.6 percent. Even differences in natural frequencies are the lowest according to Tab. 2 regarding the most accurate method with 3D geometry of bolted joints.

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4 REFERENCES

[1] Marinković, Z. et al. (2012). Modelling and simulation of dynamic behaviour of electric motor driven mechanisms. *Tehnicki vjesnik, 19*(4), 717-725.

[2] Kulkarni, P. & Kulkarni, V. V. (2017). Effect of Preload on Natural Frequency of Bolted Joint under Impact Loading. *International Journal of Innovatice Science and Reasearch Technology, 2*(6), 185-188.

[3] Pengxing, Y., Peng, H., & Tielin, S. (2016). Numerical analysis and experimental investigation of modal properties for the gearbox in wind turbine. *Frontiers of Mechanical Engineering, 11*(4), 388-402. https://doi.org/10.1007/s11465-016-0404-z

[4] Chavan, D. S., Mahale, A. K., Thakur, A. G. (2013). Modal Analysis of Power Take off Gearbox. *International Journal of Emerging Technology and Advanced Engineering, 3*(1), 70-76.

[5] Ashawni, K., Himanshu, J., Rajat, J., & Pravin, P. (2014). Free Vibration and Material Mechanical Properties Influence Based Frequency and Mode Shape Analysis of Transmission Gearbox Casing. *Procedia Engineering, 97*, 1097-1106. https://doi.org/10.1016/j.proeng.2014.12.388

[6] Butner, Ch. M., Adams, D. E., & Foley, J. R. (2013) Experimental Investigation of the Effects of Bolt Preload on the Dynamic Response of a Bolted Interface. *Journal of Applied Mechanics, 80*(1). https://doi.org/10.1115/1.4006807

[7] Vladić, J., Đokić, R., Kljajin, M., & Karakašić, M. (2011). Modelling and simulation of elevator dynamic behavior. *Tehnicki Vjesnik - Technical Gazette, 18*(3), 423-434.

[8] Tomović, R., Miltenović, V., Banić, M., & Miltenović, A. (2010). Vibration response of rigid rotor in unloaded rolling element bearing. *International Journal of Mechanical Sciences, 52*, 1176-1185. https://doi.org/10.1016/j.ijmecsci.2010.05.003

[9] Barač, Ž., Plaščak, I., Jurišić, M., Tadić, V., Zimmer, D., & Duvnjak, V. (2018). Noise in the Cabin of Agricultural Tractors. *Tehnicki Vjesnik - Technical Gazette, 25*(6), 1611-1615. https://doi.org/10.17559/TV-20170223093448

[10] Caresta, M. & Wassink, D. (2011). Relationship between natural frequencies and pull out force for plates with two clamped edges. *Acoustics Australia, 39*(1), 15-18.

[11] Sofian, M., Hazry, D., Saifullah, K., Tasyrif, M., Salleh, K., & Ishak. I., (2009). A study of Vibration Analysis for Gearbox Casing Using Finite Element Analysis. *Proceedings of International Conference on Applications and Design in Mechanical Engineering, 39*(1), 10E-1-10E-7.

[12] Anđelić, N., Braut, S., & Pavlović, A. (2018). Variation of Natural Frequencies by Circular Saw Blade Rotation. *Tehnicki Vjesnik, 25*(1), 10-17. https://doi.org/10.17559/TV-20160210110559

[13] Kim, J., Yoon, J. Ch., & Kang, B. S. (2007). Finite element analysis and modeling of structure with bolted joints. *Applied Mathematical Modelling, 31*, 895-911. https://doi.org/10.1016/j.apm.2006.03.020

[14] Ericson, T. M. & Parker, R. G. (2013). Planetary gear modal vibration experiments and correlation against lumped-parameter and finite element models. *Journal of Sound and Vibration, 332*, 2350-2375. https://doi.org/10.1016/j.jsv.2012.11.004

[15] Shrenik, M. P. & Pise, S. M. (2013). Modal and Stress Analysis of Differential Gearbox Casing with Optimization. *Journal of Engineering Research and Applications, 3*(6), 188-193. https://doi.org/10.1016/j.jsv.2012.11.004

[16] Shrenik, M. P. & Pise, S. M. (2013). Modal Analysis and an Experimental Study into a Marine Gearbox Featuring Confluence Transmission. *Transactions of FAMENA, 42*(4), 43-52. https://doi.org/10.21278/TOF.42404

[17] Belorit, M., Hrček, S., Gajdošík, T., & Šteininger, A. (2017). Description of the bearing check program for countershaft gearboxes. *Proceedings of 58th international conference of machine design departments*, 32-35.

[18] Łukasiewicz, M., Kałaczyński, T., Musiał, J., & Shalapko, J. (2014). Diagnostics of buggy vehicle transmission gearbox technical state based on modal vibrations. *Journal of Vibroengineering, 16(*6), 3137-3145.

[19] Nigade, R. V., Jadhav, T. A., & Bhide, A. M. (2012). Vibration Analysis of Gearbox Top Cover. *International Journal of Innovations in Engineering and Technology,* 1(4), 26-33.

Contact information:

Peter WEIS, Ing. PhD
(Corresponding author)
University of Žilina, Faculty of Mechanical Engineering,
Univerzitná 8215/1, 01026 Žilina
E-mail: peter.weis@fstroj.uniza.sk

Ján ŠTEININGER, Ing. PhD
University of Žilina, Institute of Competitiveness and Innovations,
Univerzitná 8215/1, 01026 Žilina
E-mail: jan.steininger@fstroj.uniza.sk

Milan SAPIETA, Ing. PhD
University of Žilina, Faculty of Mechanical Engineering,
Univerzitná 8215/1, 01026 Žilina
E-mail: milan.sapieta@fstroj.uniza.sk

Branislav PATIN, Ing.
University of Žilina, Faculty of Mechanical Engineering,
Univerzitná 8215/1, 01026 Žilina
E-mail: branislav.patin@fstroj.uniza.sk