Geometry-Based Updating of 3D Solid Finite Element Models

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Abstract
Structural responses obtained with finite element (FE) simulations normally differ from those measured on physical prototypes. In the case of monolithic structures, the differences between the simulated and measured responses are mainly caused by inaccuracies in the geometry and material modeling. Such inaccuracies may result from the manufacturing process. The presented work illustrates how the geometry of CAD-based FE-models can be updated using a high-fidelity representation of the actual manufactured geometry, to improve the correlation between measured and computed resonant frequencies and mode shapes.
The study presented in this paper was performed on a cast iron lantern housing of a gear box. In a first step, the resonant frequencies and modes shapes of the test structure were measured using impact testing. Next, a set of digital pictures were taken from a number of different angles. By means of photogrammetry, these pictures were converted into a surface model that represented the actual geometry of the lantern housing. This surface model was then compared with an FE-model derived from a CAD-model of the lantern housing. In this way, the regions where there was a substantial difference between the actual geometry and CAD-model could be identified. Finally, the geometry of the FE-model was corrected based on the measured geometry using a mesh morphing technique. For the considered test case, the correction of the geometry provided a significant improvement of the quality of FEM-test correlation of the modal parameters.

1. Introduction

Structural responses obtained with finite element simulations normally differ from those measured on physical prototypes. The observed differences are mainly caused by inaccuracies in the geometry, material behavior and joint properties of the simulation model. Finite element model updating [1] is a commonly accepted technique to improve the validity of simulation models. By tuning physical element properties, model updating aims at reducing the differences between the measured and simulated responses as much as possible. However, in the case of 3D solid elements, the geometry of the model is not controlled by element properties, like a shell thickness in the case of 2D elements, but by the positions of the nodes of the elements. Direct updating of the individual nodal positions would lead to an excessive amount of independent updating variables and is therefore practically unfeasible. With 3D elements, the geometrical uncertainties are usually compensated in an indirect way. For example, an overestimation of a thickness has to be compensated by a reduction of the stiffness and mass density of the material in the considered area. Although such compensations can eventually provide models that correlate well with the test data set, the improvement in reliability of the model is limited as the modifications are physically not correct, which restricts the application range of the updated finite element model.

The goal of the present work was to investigate the impact of the geometrical inaccuracies on the correlation between numerical and experimental resonant frequencies and mode shapes, and to verify if the correlation can be improved by updating the geometry of the FE-model using mesh morphing techniques [2-3]. To simplify matters, a monolithic cast-iron lantern housing was used. In this way the impact of any joint uncertainties was eliminated. A high-fidelity representation of the geometry was obtained by a combination of optical scanning and photogammetry. The point cloud that resulted from these optical measurements served as a starting point to generate a 3D solid finite element model representing the as-built geometry of the housing. To evaluate the impact of using the actual geometry on the correlation and model updating results, two FE-models were used: an FE-model derived from the measured geometry and an FE-model derived from the CAD model of the lantern housing. Both models had a similar mesh density and mesh quality. These two models were first correlated with the measured modal data and then updated by tuning the material properties. Finally, the potential benefits of geometry-based updating were evaluated by correcting the geometry of the CAD-based FE-model using the measured geometry in combination with mesh morphing techniques.

2. Measuring the Geometry

To obtain an accurate geometrical description of the lantern housing, optical scanning and photogrammetric techniques were used to acquire a point cloud of the part as-built. Optical scanning was performed using a GOM ATOS I scanner, shown in Fig. 1.

Fig. 1 GOM ATOS I scanner which was used to digitize the lantern housing.

The digitizing principle is based on a white light fringe pattern from a projector (center part on Fig. 1) onto the scanned object. Two cameras (left and right on Fig. 1) capture images of the object and reference geometries. Since the lantern housing is too large to fit the scanning volume of the scanner, photogrammetric techniques were applied to combine the partial scans. Photogrammetry uses photographical images of multiple marker systems to merge optical scans of different regions of the lantern housing. Fig. 2 shows pictures of the lantern housing during the scanning process. A white spray is applied to reduce reflections. Small marker stickers are used for local optical scanning. Large stickers and two reference bars on the ground are used for the merging software.

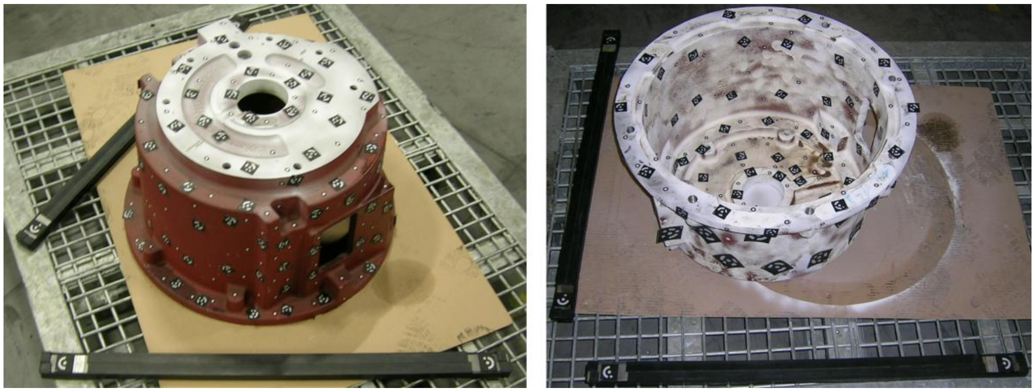


Fig. 2 Images showing the lantern housing during the digitizing process.

Triangulation techniques are applied to reconstruct a point cloud from these images based on the distance and angle between the cameras, the projected grid information and the photogrammetry pictures. Using the GOM ATOS Professional software [4] the point cloud data is converted into the Standard Triangulation Language (STL) model shown in Fig. **3**. An STL model is a triangle facet surface mesh representation based on the scanned point cloud. In case of the lantern housing, the minimal geometrical accuracy of this STL model, taking into account scanning and point cloud post-processing, is approximately 0.2 mm. However, the STL model resulting from the digitization process is not suitable to generate an FE mesh because it is not watertight. Therefore, the model was corrected with the STL fixing, design & meshing software package 3-matic [5].

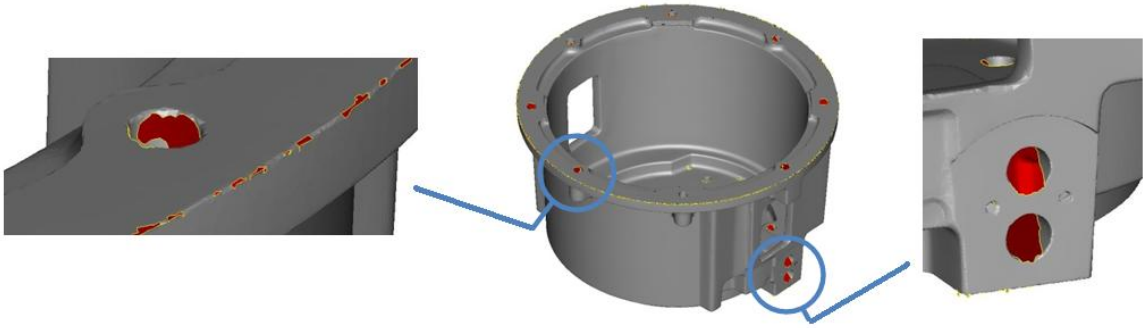


Fig. 3 Detail views of typical scan surface mesh imperfections: non-watertight edges (left) and incomplete hole or slot information (left and right).

The defects along the edges were fixed using automated hole filling and stitching algorithms. For the virtual fixing of slots and holes CAD information was locally copied into the scan to complete the missing geometry. Once the STL model was watertight, the enclosed volume was meshed using 54040 10-noded tetrahedron elements. A section of the final volume mesh is shown in Fig. 4.

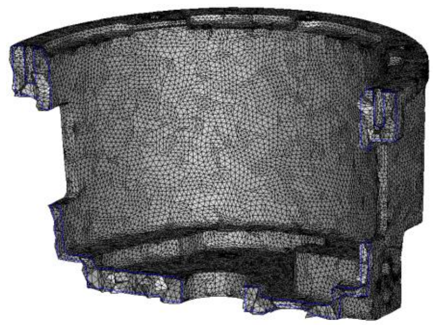


Fig. 4 Resulting 10-noded tetrahedron mesh

3. Evaluation of the Impact of the Measured Geometry

The impact of using high-fidelity geometries was evaluated by comparing the reliability of the responses of the CAD-based model with those of the geometry-based model. Both FE-models had a similar number of elements (± 55000) to exclude the influence of the mesh density.

3.1. Modal Testing

A standard experimental modal analysis was performed to measure the resonant frequencies and mode shapes up to 1.5 kHz. The test structure was suspended with a number of elastic bands to simulate free-free boundary conditions. The frequency response functions were measured using a roving hammer test and using 6 tri-axial accelerometers. The input and response signal were measured up to 2 kHz using 2048 spectral lines. The average of 5 individual FRFs measurements was used as measured FRF. The first 18 modes of the lantern housing could be extracted from the measured FRFs. Fig. 5 shows the AutoMAC of the measured mode shapes.

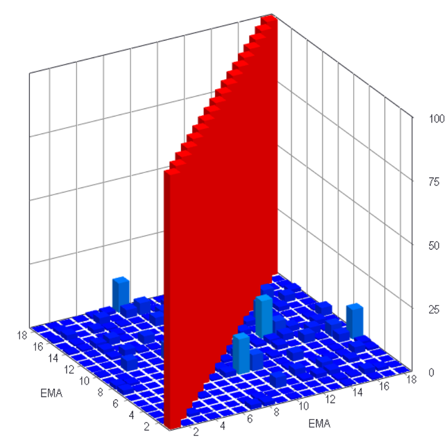


Fig. 5 The AutoMAC of the measured mode shapes

3.2 Initial Correlation

3.2.1 The CAD-Based FE-Model

The correlation analysis between the results of the CAD-based FE-model and the test provided 18 mode shape pairs. The mode shape order in the two data sets was identical. The correlation results showed that the FE-model underestimated all the frequency about 6.9 %. The MAC values ranged between 40.1 and 97.7, with an average value of 82.0.

4.2.2 The Geometry-Based FE-Model

The correlation analysis between the results of the geometry-based FE-model and the test also provided 18 mode shape pairs. As for the CAD-based model, the order of the FE-modes corresponded with the order of the test modes. The correlation results showed that the geometry based FE-model underestimated all the resonance frequency about 8.6 %. The MAC values ranged between 88.8 and 97.8, with an average value of 83.8.

3.3 Updating of the Material Properties

Both FE-models were updated using the FEMtools **Error! Reference source not found.** model updating module. The updating procedure that was used consisted of two separate steps. In the first step the overall mass of the FE-model was set to the mass value of the test structure by modifying the mass density of the material in the model. In the second step the stiffness of the model was updated by modifying the Young's modulus of material. The Young's modulus was defined as a global parameter, i.e. the Young's modulus remained uniform over the whole FE-model during updating. The 18 measured resonant frequencies were used as targets for the updating procedure. The mode shape data was only used for mode tracking purposes, not as target values for the updating.

3.3.1 The CAD-Based FE-Model

The CAD-based FE-model underestimated the mass by 3 kg, i.e. 108.0 kg instead of 111.0 kg. To increase the mass by 3 kg, the mass density of the material had to be raised from 7100 to 7295 kg/m^3. The mass correction resulted in a drop of the overall frequency correlation with 1.2 %, i.e. -8.1 % instead of -6.9%.

The stiffness updating of the FE-model increased the Young's modulus from 110.5 GPa to 130.7 GPa. This resulted in frequency residuals ranging between -1.72 % and 3.64. Note that a global updating of the mass and stiffness does not have a significant effect on the mode shapes. Hence, the updating did not provide any improvement in the mode shape correlation.

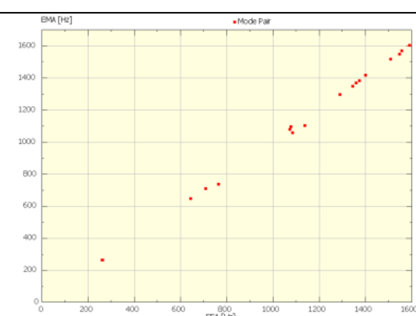
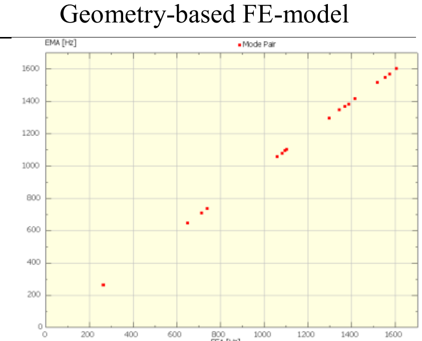
4.3.2 The Geometry-Based FE-Model

The geometry-based FE-model had an overall mass of 105.0 kg instead of the 111.0 kg of the test model. This required an increase of the mass density of the material from 7100 kg/m^3 to 7503 kg/m^3. This increase resulted in an overall frequency drop of 2.5 %; increasing the underestimation of the resonant frequencies by the FE-model.

The second step of the updating procedure increased the Young's modulus from 110.5 GPa to 139.9 GPa resulting in frequency residuals ranging between -0.29 % and 0.24 %.

4.3.3 Comparison

Table 1 provides an overview between the correlation results of the updated CAD-based FE-model and the updated geometry-based FE-model with the measured shapes and frequencies. The frequency match of the updated geometry-based FE-model is significantly better than the frequency match of the CAD-based FE-model. However, the most remarkable difference between the two models is their correlation with the test modes. While the CAD-based FE-model is missing a few mode shape pairs, the geometry based FE-model has an excellent correlation for all 18 considered modes. More details and background information on this correlation analysis can be found in [7].

	CAD-based FE-model	Geometry-based FE-model
Frequency residuals		
Average |freq. residual|	1.04%	0.14%
Min. |freq. residual|	0.01%	0.00%
Max. |freq. residual|	3.64%	0.29%

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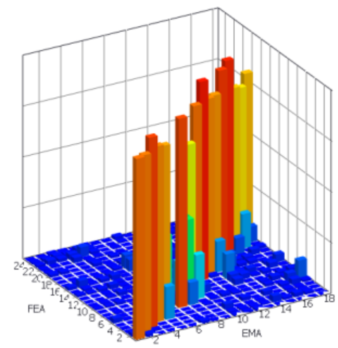
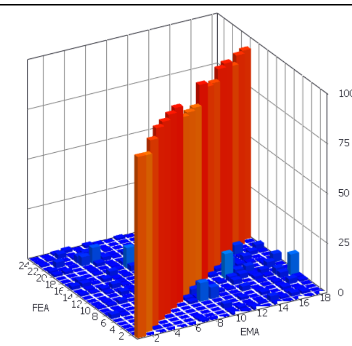
MAC FEM-EMA		
Average MAC	82.0	94.3
Minimum MAC	40.1	88.9
Maximum MAC	97.7	98.2
Updated mass density	7295 kg/m^3	7503 kg/m^3
Updating Young's modulus	130.7 GPa	139.9 GPa

Table 1 Comparison of the CAD-based and geometry-based FE-model

4. Geometry-Based Updating

The correlation analysis revealed that the errors in the CAD geometry have a significant impact on the accuracy of the FE-model. A reliable FE-model thus requires a better approximation of the geometry. However, instead of using the scan data to generate a geometry-based FE-model, one could also use the measured geometry to update the geometry of the CAD-based FE-model. In the case of 1D of 2D elements, this could be done by simply correcting the geometrical properties of the elements. However, in the case of 3D elements this will require the repositioning the nodes of the FE-model.

4.1 Comparison of the CAD and Measured Geometry

Fig. 6 presents the differences between the measured and CAD geometry; red indicates that the surface geometry-based model is below the CAD model, blue indicates that the geometry-based model is above the CAD model and green indicates there is no difference. The color maps reveal that the difference between the two models is of a systematic nature; the major difference between the two models seems to be a tilt of the top and bottom surfaces and an incorrect diameter for the cylindrical bulging in the center of the bottom surface. The tilt of the planes is most likely a result of warping and/or shrinkage during the casting process.

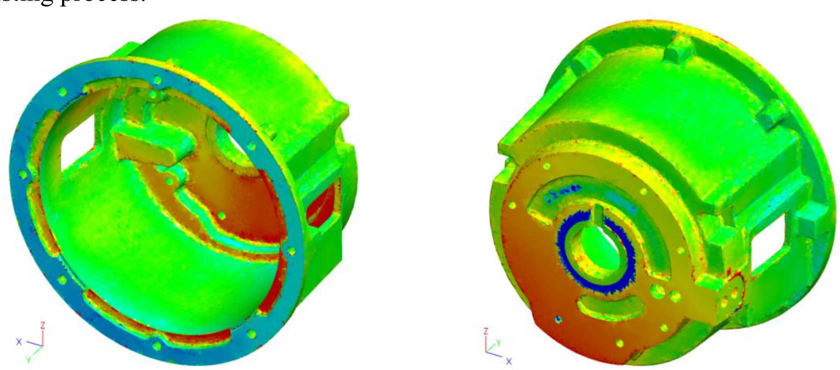


Fig. 6 The difference between the measured and CAD geometry.

4.1 Lattice-Based Mesh Morphing

The observed inaccuracies in the CAD geometry could, for example, be eliminated by tilting the surfaces of the FE-model using mesh morphing techniques. The latticed-based mesh morphing technique [2-3] starts by defining a number of hexahedral lattice cells that envelop a part of the FE-mesh, i.e. the mesh associated to the lattice cell. When one of the vertices of the lattice cell is moved, all the nodes of the associated mesh will move as well. The new position of the nodes is determined using a Bezier interpolation between the lattice vertices. In this way an FE-mesh can be deformed using a limited number of control points.

4.2.2 Application to the Lantern Housing

Six mesh deformations are considered to morph the CAD-based model and bring it closer to the actual geometry of the structure. Fig. 7 gives on overview of the considered mesh deformations: the first three tilt the surfaces at the bottom, the next two tilt the surfaces at the top, and the last one changes the diameter of the bulging at the bottom.

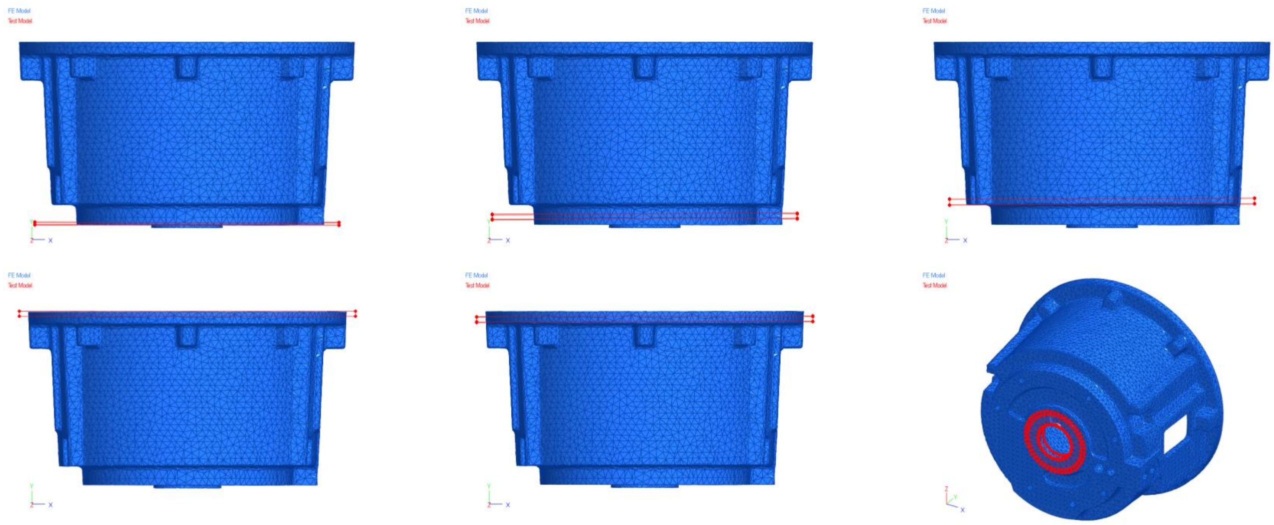


Fig. 7 The six considered mesh deformations

The mesh morphing was executed in FEMtools [6] as follows. In a first step three points were selected on the bottom surface in order to simulate the case were the geometry is only measured in a discrete number of points, instead of a full scan. The geometry measurements in those three points were used to compute the required tilt to align the CAD surface with the measured surface. Next the mesh was morphed by tilting the lattice box using the estimated tilt. Fig. 8 shows the result of the first mesh deformation. It confirms that the difference between the CAD and measured geometry on the bottom surface has been removed. The other mesh deformations were applied in a similar way.

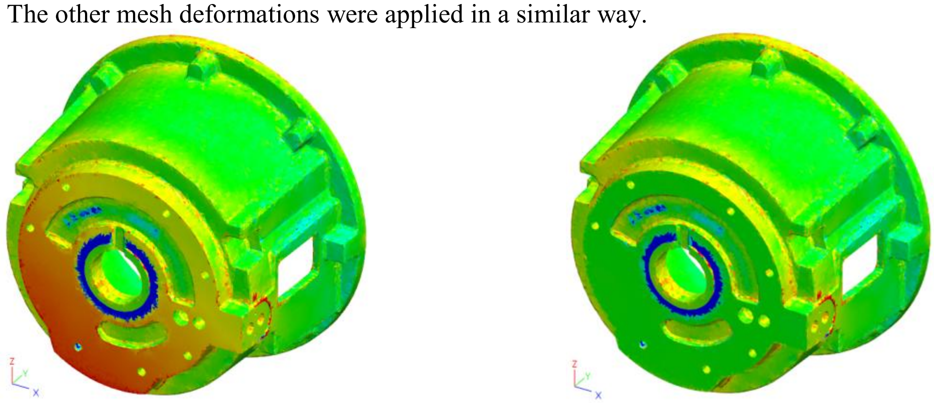


Fig. 8 The differences before (left) and after (right) the first mesh deformation

4.3.2 Effect on the Modal Correlation

The effect of the various mesh deformations on the modal correlation is presented in Fig. 9. On this plot, the frequency and mode shape differences between the original CAD and geometry-based model are taken as a reference, i.e. 100%. Both models use the material properties of the updated geometry-based FE-model, i.e. E = 139.9 GPa, ρ = 7503 kg/m^3.

The first mesh deformation removed about 20% of the frequency differences and about 35% of the mode shape difference. The impact of the first mesh deformation on the MAC matrix, which now has all the diagonal terms, is significant. Combined, the six considered mesh deformations remove about 80% of the frequency and mode shape differences. This implies that the difference between these two models is due to a limited number of systematic errors. Differences resulting from approximations/simplifications made during the model generation only seem to play a secondary role. These results also confirm that updating the geometry of a CAD-based FE-model using a limited number of discrete geometry measurements is a feasible approach to increase the reliability of the FE-model.

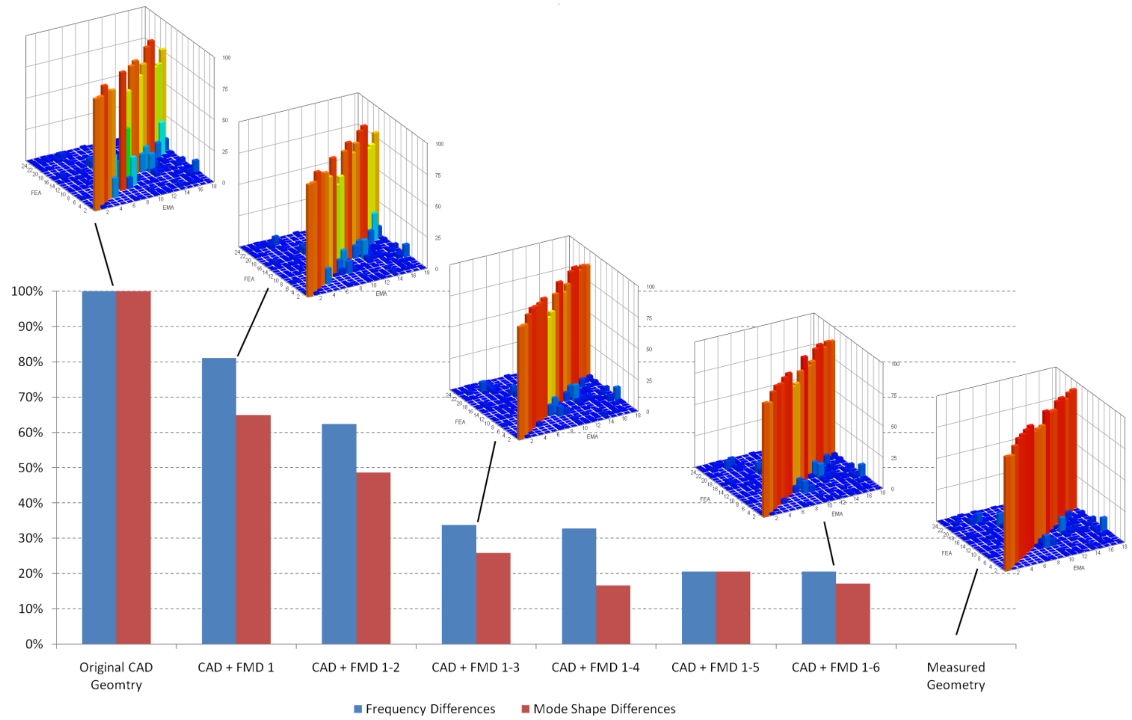


Fig. 9 The impact of the geometry modifications on the modal correlation

5. Conclusions

The presented work evaluates the impact of using a high-fidelity representation of the geometry of a monolithic cast-iron structure on the correlation between measured and simulated responses. The use of the as-built geometry of the structure, obtained by optical scanning of a prototype, provides a significant improvement in the correlation between the measured and simulated mode shapes in a wide frequency range.

It was shown that only a limited number of geometry measurements are needed to update the CAD-based geometry using mesh morphing techniques. With geometry updating it is possible to eliminate most of the uncertainty on the geometry. As such, geometry updating eliminates, or at least reduces, the need for equivalent parameter changes to compensate the effects of geometrical inaccuracies. As the updating process provides parameter changes that are physically more relevant, the application range in which the updated FE-model can be used as a reliable predictive tool for design optimization can be increased.

Acknowledgements

We would like to express our gratitude to Hansen Transmissions N.V. for providing the test data and FE-models of the lantern housing, and to the KULeuven for providing the modal test data.

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