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NUMERICAL AND EXPERIMENTAL MODAL ANALYSIS OF AN INDUCTION ELECTRIC MOTOR

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Abstract: *The presented work deals with the modal analysis of the components of the two-pole induction motor and its subassemblies. For the vibration study, it is challenging to build up the computational model of the assemblies of the electric motor magnetic circuits. The design uncertainties in the computational model are inherent; therefore, reasonable simplifications of the rotor and stator assemblies with the tuned and experimentally identified mechanical parameters are applied. The computational model of the induction motor for the modal analysis is developed using the finite element approach. The experimental and computational modal analyses are performed for the shaft, frame, shields, parts of terminal box, and assemblies of the winding, rotor and stator stack, frame with stator stack, terminal box, and the whole motor. The results show that the computed and measured modal parameters of components such as shaft, shields, and frame have almost the same mode shapes and natural frequencies.*

Keywords: Induction motor, Natural frequency and mode shape, Finite element method, Computational modelling, Measurement.

1. Introduction

In electrical motors, there are mechanical, aerodynamical, and electromagnetic force sources (Toliyat, Kliman, 2006) which lead to undesirable vibration. The computational modelling method allows investigating the vibration response of different excitations either separately or as their mutual relations with a multiphysical approach. Therefore, it is necessary to develop a computational model for the modal analysis in order to evaluate vibration resonances due to the excitation forces.

The induction motor is a complex structure with many components. In particular, it is winding, rotor and stator stack which are assemblies composed of materials with different mechanical properties. As a result, the stiffness of the assemblies significantly differs from the solid ones.

Some researchers employed the experimental measurements for the evaluation of the mechanical properties of the assemblies. The Young's modulus of the winding in the grooves and the winding ends of the induction motor was experimentally obtained by Itori et al., (2002). The ultrasonic non-destructive method (Tang et al., 2004) is utilized for the measurement of the Young's modulus of the laminated stator stack and that is used in the computational modal analysis of a switched reluctance motor.

The computed and measured results of the modal analysis of the laminated squirrel cage rotor were presented by Batiha et al., (2021). The pre-stress analysis caused by the contraction force on the rotor stack as well as interference fit connection between the shaft and squirrel cage with rotor stack was considered in the computational model. Prem et al., (2019) investigated the effect of random variations of the Young's modulus along the rotor axis to the first natural frequency of the laminated rotor stack. The dynamical features of the rotor were computed with the Monte Carlo Simulation method.

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The goal of the presented work is the development of the computational model of the induction motor, which will be used in the future to predict a rotordynamic vibration and acoustic noise emission due to the electromagnetic force excitation. In this paper, the results of an experimental and computational modal analysis of an electric motor are presented. The assumption of a solid body in the computational model is employed for the winding, the laminated rotor and stator stack. The computed and experimentally measured results lead to a good agreement.

2. Description of the investigated motor, developed computational models, solutions, and measurements

The three-phase asynchronous motor with the IE3 efficiency class, IMB3 type of construction, axis height of 315 mm, nominal speed of 2986 rpm, power of 315 kW, and total weight of 1510 kg was investigated. The frame, shields, bearings cover, and terminal box are made of the low-grade EN-GJL-200 grey cast iron, the fan and the rotor squirrel cage are made of aluminium, the rotor and the stator sheets are made of the M530-50A steel grade, and on the sheet surfaces, there is approximately 1 µm-thin layer of resin. The fan cover is made of PA6-GF30 material, the shaft is made of the 11600 steel grade, and the winding is made of copper, insulation material, and epoxy impregnation.

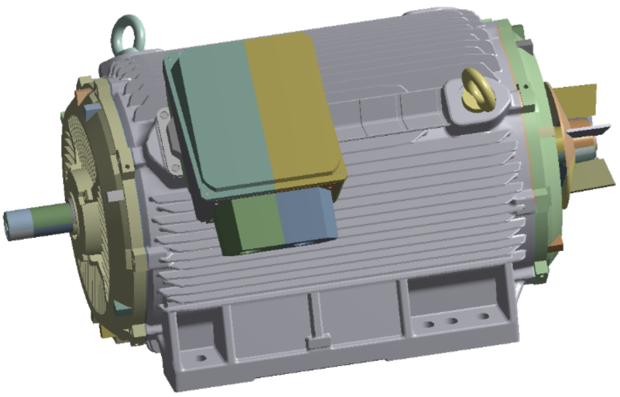


Fig. 1: Simplified geometry of the induction motor.

The geometry of the studied motor is depicted in Fig. 1. Some small fillets, holes, and others have been removed to simplify the computational model, which do not change the overall stiffness. The complicated shape of the windings ends (see left Fig. 2) was simplified into envelope shape based on the 3D scanning results (see right Fig. 2).

The manufacturing processes of the rotor and stator stack and winding mounted in the stator lead to variations in the mechanical parameters of these assemblies. The rotor and stator stack stiffness may vary significantly along the rotor axis due to air gaps, local deformations, and effects of the contact conditions between sheets. The vibration characteristics of the winding (see Fig. 2) are influenced by an epoxy material for the impregnation of wires, forces of drawstring tightening, and contact conditions between the wires and slots.

Therefore, in the developed computational model of the motor the winding, the laminated rotor and stator stack are considered as solid bodies. Its mechanical parameters for the computational model are identified and tuned considering the results obtained with the experimental modal analysis. The bending stiffness of the rotor and stator stack is modified by the bodies grouping connected with a no separation contact type.

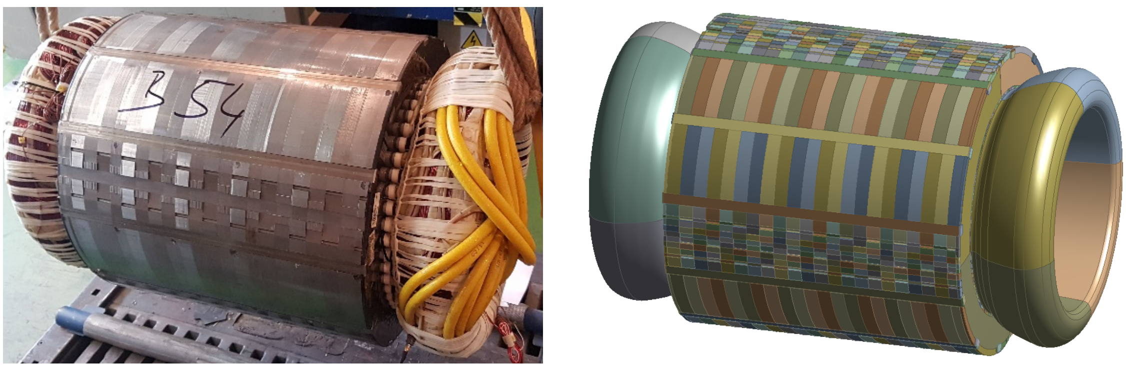


Fig. 2: Photography of the stator stack with winding (left) and its simplified geometry (right).

A transversely isotropic material was proposed for the laminated rotor, see (Batiha et al., 2021) and stator stack and for the winding on the ends and in the stator slots. On the other hand, for the winding in the stator slots and in the winding ends the isotropic material model with the Young's modulus, determined according to the article of Itori et al. (2002) was tested. In the computational model, the mass of the components and assemblies was stated according to the measurement.

Modal properties are computed with the assumption of the undamped system, and the mechanical contacts and joints are modelled with linear elements. The computational model of the investigated motor is created and solved in the Ansys Workbench software.

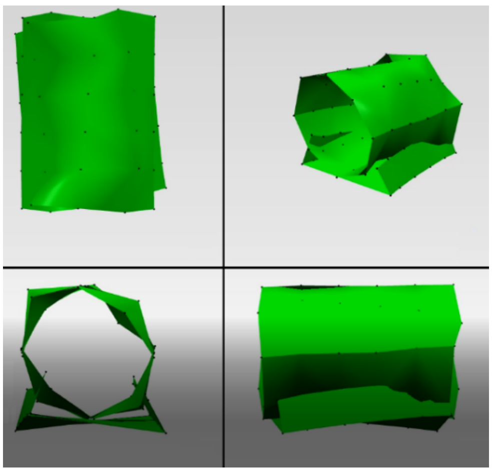
The experimental modal analysis was done with a force impulse hammer in a single location of excitation, and the position of an acceleration sensor varied between the locations on the test structure. Signals of the piezoelectric three-axis acceleration sensor PCB 356A02 and the impulse hammer PCB 086D20 were connected to the four channels of the data acquisition device NI 9234, and the notebook with installed software ME Scope was used. The modal properties of the test structure were recognized from the poles of the measured transfer function. The fixed suspension of the tested structure was achieved with mounting to the base plate, and the free-free one was realized on an elastic rope.

3. Results of the computations and measurements

Table 1 shows the computed and measured natural frequencies of the electric motor frame for two kinds of boundary conditions, a free-free and fixed to the base frame. The relative errors between the computed and measured natural frequencies are up to 5 % for all components of the motor. Fig. 3 shows the measured and computed 3rd mode shape with dominant radial vibration of the frame ends in the opposite direction.

Table 1: Comparison of the measured and computed eigenfrequencies of the frame.

Eigenfrequency order [-]	Free-free / fixed-base suspension		
	Measured eigenfrequency [Hz]	Computed eigenfrequency [Hz]	Relative error [%]
1	96.0 / 79.1	94.8 / 78.9	-1.3 / -0.3
2	122.3 / 164.0	120.7 / 167.2	-1.3 / +2.0
3	131.1 / 187.4	130.1 / 188.7	-0.8 / +0.7
4	188.5 / 268.3	190.2 / 272.6	+0.9 / +1.6
5	296.3 / -	283.4 / 294.6	-4.4 / -
6	317.6 / 398.0	324.6 / 403.4	+2.2 / +1.4
7	379.7 / 455.9	380.3 / 451.9	+0.2 / -0.9



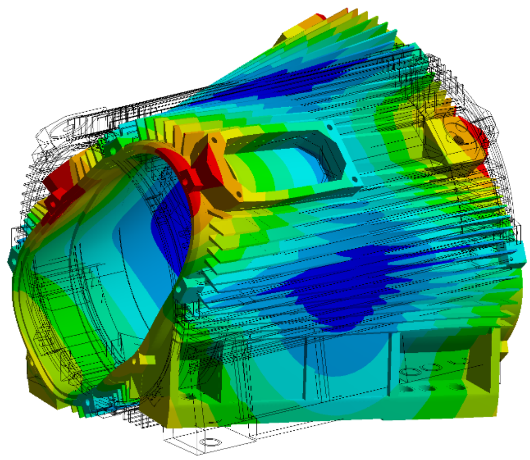


Fig. 3: Measured (left) and computed (right) 3rd mode shape of the frame for free-free suspension.

The computed and measured natural frequencies of the whole motor for the fixed-base suspension are summarised in Table 2, and the relative errors between the computed and measured natural frequencies are, except the first frequency, up to 5 %. The mode shape of the first natural frequency corresponds to the dominant rotor axial vibration and the difference between the measured and computed natural frequency is caused by the variation of the bearing's stiffness. The higher natural frequencies correspond to the complex mode shapes of combined vibrations of the frame, winding attached to the stator and the rotor.

Table 2: Measured and computed eigenfrequencies of the whole motor.

Eigenfrequency order [-]	Measured eigenfrequency [Hz]	Computed eigenfrequency [Hz]	Relative error [%]
1	60.8	54.5	-10.4
2	141.5	146.5	+3.5
3	201.1	208.3	+3.6
4	220.9	221.0	+0.1
5	271.7	283.3	+4.3
6	352.6	353.1	+0.1
7	431.2	434.3	+0.7

4. Conclusions

The computational models of the essential components and assemblies for the 2-pole asynchronous electric motor with nominal power of 315 kW were developed by the finite element method. The comparison of the experimentally and numerically computed mode shapes and natural frequencies is presented. The results show that a relative error between the measured and computed natural frequencies for all components of the motor is up to 5 %. The stiffness properties of the assemblies such as the winding, rotor, and stator stack, which are composed of many parts, are identified with the support of the experimental modal analysis. The proposed transversal isotropic material model helps to set properties of the winding, rotor and stator stack to ensure the accuracy of the computational modal analysis. However, for the motor assemblies, small discrepancies of up to 15 % for the measured and computed modal results were found.

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