The Influence of Stacking Technologies on Structural Dynamic Properties of Electric Motors Iron Cores

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This paper is dedicated to the lifetime work of Professor Andrzej Demenko and Professor Lech Nowak in recognition of their contributions in the field of Electrical Machines

***Abstract*—It is essential to understand the structural dynamic behavior of electrical machines to predict their acoustic and vibrational behavior. Since soft magnetic cores of electrical machines consist of laminated steel sheets, they exhibit anisotropic mechanical properties. Stacking technology, which is used to manufacture soft magnetic cores, has a strong influence on the material properties. In this paper the stacking technology of welding and bonding with bake varnish are compared. Eigenfrequencies, mode shapes and modal damping ratios are extracted from measurements and used in a finite element simulation model. The approach and achieved accuracy of the simulated frequency response functions are discussed.**

***Index Terms*—Acoustics, Modal Analysis, Electric Machines, Magnetic Cores, Damping, Vibrations**

I. INTRODUCTION

To predict the acoustic behavior of an electric machine or drive train a simulation of the structural dynamic behavior is necessary. To prevent losses due to eddy currents the soft magnetic cores of electrical machines are constructed from laminated metal sheets. The mainly used construction technologies are connection by welding, punch-bundling with interlocks or bonded via bake-hardening varnish during production. In mass production the first two methods are favored due to long processing times and high cost of the baking process. However welding and interlocking only connect the layers at certain points. This potentially allows micro-slip inbetween layers involving friction and variations of the surface contact area while vibrating [7].

The modeling of structural dynamics is state of the art performed by using methods of modal analysis; a detailed description can be found in EWINS [3] and theoretical and practical short studies in the extensive article series in AVITABILE [5]. Basic principle of the modal analysis is the transformation of the system of coupled equations of motion into the modal space to a system of uncoupled single degree of freedom (DOF) equations.

The simulation of modal characteristics with numerical approaches requires the discretization of the geometry. Due to the high amount of layers in soft magnetic cores, small dimensions of sheet metal thickness (in the magnitude of $0.2\,\mathrm{mm}$) and varnish thickness (in the magnitude of $10\,\mu\mathrm{m}$) it is not suitable to discretize each layer, hence this approach leads to equation systems with too many degrees of freedom to be practically solvable. Therefore homogenization techniques are used which can be found in the literature [8][10][1][9][12]. These approaches reduce the multi-material composite to a homogenized equivalent material with appropriate anisotropic properties. The anisotropic properties are accounted for by the material model. The geometric discretization can thus be coarser which decreases the computational effort needed to solve the equation system. However, the homogenization approach assumes a fully bonded material, which is not the case with welded or punch-bundled iron cores. As a result the homogenization approach has to be tested.

In this paper, the differences between bonded and welded iron cores are analyzed, at the example of a stator iron core which is depicted in fig. 1. It is shown that modal analysis is feasible for this problem and leads to good measurement results which demonstrate the effect of different stacking technologies on the structural dynamic behavior. Extracting modal parameters and especially reliable damping coefficients from a frequency response function can be troublesome, therefore various methods have been developed [2]. Four of these methods are chosen, briefly described and their feasibility on this problem and results are compared. The obtained parameters are then used in a simulation with a homogenized material model. The approach and its results are compared to the measurements and discussed.

II. MEASUREMENT

The structural dynamic characteristics of the iron cores are determined using the impact hammer method [3]. An impact hammer with a force sensor on its tip is used to excite the stator cores. The response is measured with vibration sensors on the surface of the stator. The stator itself is suspended in a frame which minimizes the interaction between the frame and the stator, approximating a free-free boundary condition. Receptances are calculated from the force spectrum F and the acceleration spectrum A.

Fig. 1. The analyzed stator core.

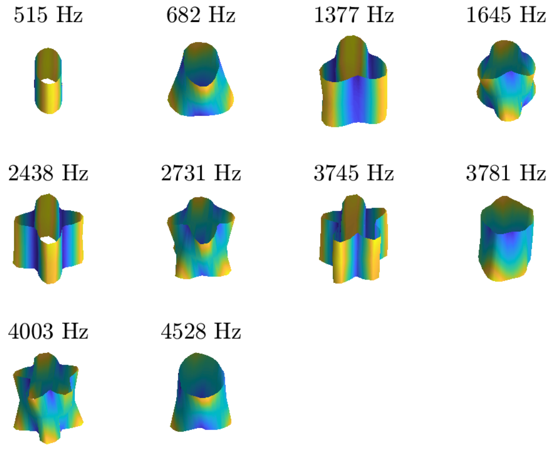

Fig. 2. Measured mode shapes of the bonded stator.

$$H(\omega) = -\frac{1}{\omega^2}\frac{A}{F} \tag{1}$$

To obtain the receptances, from which the modeshapes can be extracted, the roving sensor method was used as shown in fig. 3. While the excitation remains at the same location the acceleration sensor is moved through 30 equidistant positions on three rings on the stator. By this multiple frequency response functions of the system matrix are measured.

A. Mode Shape and Eigenfrequency

Initially both stators, the welded and the bonded one, are characterized with the impact hammer method. Exemplary receptances calculated from the measurements can be seen in fig. 5. To locate the eigenfrequencies, the Mode Indicator Function (MIF) is applied [5]. The MIF takes advantage of the fact that the real part of the receptance crosses the x-axis while it passes a resonance. A resonance is therefore indicated by a drop in the MIF.

$$MIF = \frac{|Re(H)|^2}{|H|^2} \tag{2}$$

At the discovered eigenfrequencies the modeshapes are extracted, which are shown in fig. 2 and fig. 4. Modes with pure bending deformation are present in both stators at similar frequencies. Peaks that correspond to pure bending modes are as pronounced as in the receptance of the bonded stator, which indicates that there is no significant difference in the modal damping ratios. The stators differ significantly at modes with shear deformation. The mode of the bonded stator with pure shear deformation at 3781 Hz is also present in the welded stator, but at a significantly lower frequency 424 Hz. Peaks that correspond to modes with shear deformation are less pronounced than in the bonded stator. This indicates high modal damping ratios.

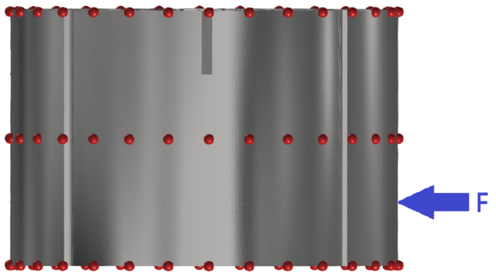

Fig. 3. Excitation and measurement positions on stator.

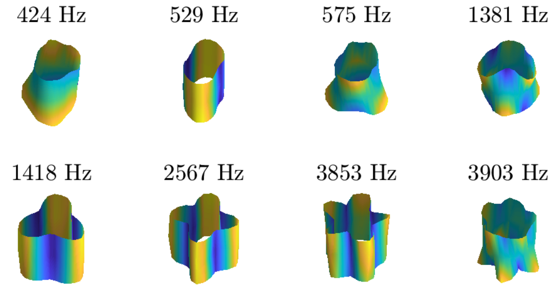

Fig. 4. Measured mode shapes of the welded stator.

B. Methods for Extraction of Damping Coefficients

Several methods to extract modal damping parameters from measurements exist [2]. They can be divided into Single Degree Of Freedom methods (SDOF) and Multi Degree Of Freedom methods (MDOF). While SDOF methods take into account only one DOF at a time for the extraction of modal parameters, MDOF methods consider multiple DOF simultaneously which allows for better parameter estimation. To achieve reliable damping coefficients in case of the expected highly damped welded core, two simpler methods (3dB method, Circle Fit method) are compared with two more sophisticated methods (Rational Fractional Polynomial method, Least Squares Rational Fit method [6]).

1) 3dB Method: The 3dB method is a simple SDOF method to estimate the modal damping ratio. It depends on methods, which can extract the Eigenfrequencies like the MIF. The 3dB method uses the 3dB falloff of a peak to estimate its corresponding modal damping ratio. [3]

2) Circle Fit Method: The Circle Fit method fits a circle to one peak of the FRF and calculates the corresponding damping ratio from characteristic parameters of the fitted circle. As with the 3dB method only one DOF is treated at a time. Therefore the Circle-Fit method is a SDOF method. [3]

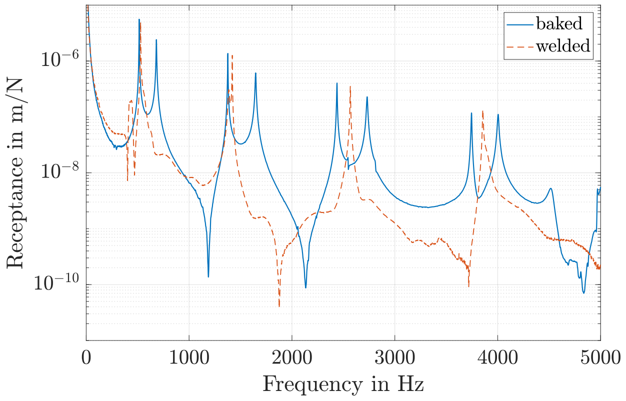

Fig. 5. Measured receptances of the bonded and the welded stator.

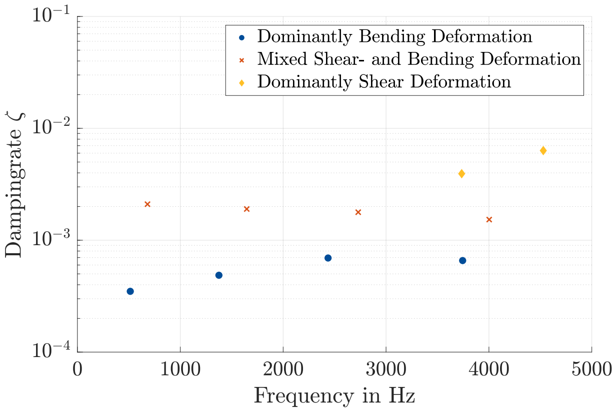

Fig. 6. Damping coefficients of the bonded stator with dominant deformation.

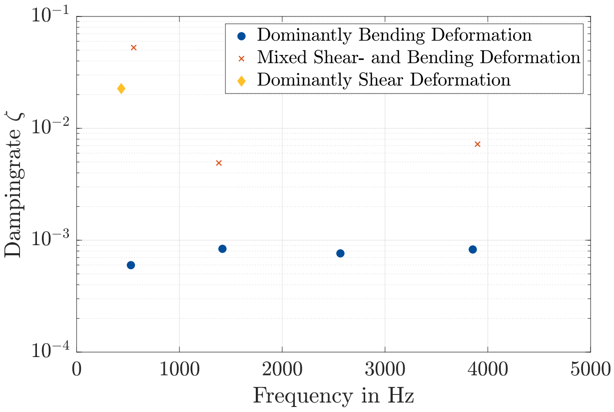

Fig. 8. Damping coefficients of the welded stator with dominant deformation.

3) Rational Fraction Polynomial Method: The Rational Fraction Polynomial (RFP) method fits a curve to the measured receptance. The coefficients of the fit are the modal parameters. The method considers multiple DOFs at once and belongs to the MDOF methods. [2].

4) Least Squares Rational Fit Method: The Least Squares Rational Fit (LSRF) method uses a Sanathanan and Koerner iteration [6] to estimate initial parameters for an instrumental-variable iteration. Sanathanan Koerner iterations are based on a rational polynomial which is fitted to the measurement data by a least squares method. Due to better convergence behavior of the instrumental-variable iteration these parameters are used as starting parameters for an instrumental-variable iteration wich extracts the modal parameters. [6].

C. *Comparison of Methods and Results*

The applicability of the methods described above is tested by analyzing the receptance of a bonded stator package. The receptance can be seen in fig. 5 and the estimated modal damping ratios are given in fig. 7. All tested methods agree well on most modal damping ratios except for the shear mode at 3720 Hz. Neither the 3dB nor the circle fit method are able to calculate the modal damping ratio in this case, because the eigenfrequencies of the modes are too close together.

Both MDOF methods take a frequency range and an initial guess of the expected eigenfrequencies as input. The LSRF method turned out to be more robust than the RFP method when varying these boundary conditions. Therefore the LSRF method is used for parameter extraction in this paper.

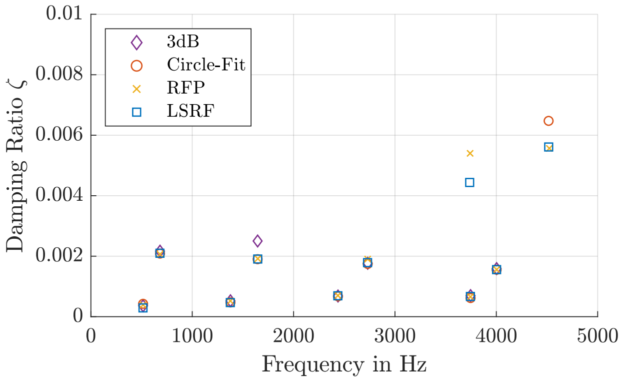

Fig. 7. Comparison of the damping estimation methods for the bonded Stator.

D. *Damping Comparison for Welded and Bonded Stator*

In fig. 6 the modal damping ratios of the bonded stator are shown. The stator is a compact machine element whose layers are in full contact due to the adhesive properties of the bake hardening varnish. A noticeable pattern emerges when comparing the modeshapes with their corresponding modal damping ratios. Modeshapes that exhibit shear deformation show significantly higher damping ratios than modes without shear deformation. The pure shear mode at 3781 Hz exhibits the highest damping ratio in the observed frequency range. This measurement demonstrates the anisotropic damping behavior of the bonded stator, where shear deformation correlates to higher damping ratios. The bake hardening varnish layer has a higher material damping than steel [11]. Shear deformation leads to a higher participation of the varnish in the deformation and thus to higher modal damping ratios.

The layers of the welded stator are only connected via small cross sections at the welding seam. Unlike in the bonded stator no adhesive force acts between the layers, but only normal contact pressure and friction. The friction mechanism is connected to high energy dissipation, which is demonstrated by the damping ratio estimations for the welded stator in fig. 8. All modes with shear deformation exhibit modal damping ratios which are up to two orders of magnitude higher than those exhibited by similar modes in the bonded stator. Modes without shear deformation experience almost no relative motion between the layers so the friction mechanism does only have a small effect on the modal damping ratios. The damping ratios of these modes are comparable to those in the bonded stator.

III. SIMULATION

The stator geometry is modeled as a compact object. The anisotropic material properties which are introduced by the stacking methods are described by the homogenization approach in [12]. A modal analysis is conducted with this model in ANSYS$^{\text{TM}}$ and a subsequent harmonic analysis is used to determine the receptance.

A. Homogenization

	Bonded	Welded	
E_p	186,820	186,820	N/mm^2
E_z	65,822	65,822	N/mm^2
G_p	71,851	71,851	N/mm^2
G_{zp}	24,689	240	N/mm^2
ν_z	0.3	0.3	
ν_{zp}	0.11	0.11	

TABLE I
IDENTIFIED HOMOGENIZED MATERIAL PROPERTIES.

The homogenization approach given in [12] was used to determine the anisotropic material properties of the bonded and the welded stator. As a result the material properties given in the table above were used to define orthotropic material models in ANSYS. In contrast to the bonded stator the layers of the welded stator are only connected to each other via the small cross sections of the welding seams. An equivalent shear modulus was calculated using formula 3, using the relation between the crosssection of the welding seam A_{seam} and the bonded contact area A_{bonded}. All other material properties are left unchanged.

$$G_{zp,welded} = G_{zp,bonded} * \frac{A_{seam}}{A_{bonded}} \tag{3}$$

B. Simulated Eigenfrequencies and Mode Shapes

The simulated eigenfrequencies of the bonded stator match the eigenfrequencies extracted from the measurement as can be seen in fig. 10. The MAC Matrix shows, that the simulated modeshapes correlate well with the ones extracted from measurements. The model is able to predict eigenfrequencies and modeshapes of the welded stator as well. But due to the low equivalent shear modulus a high density of eigenfrequencies is obtained by the simulation in the frequency range up to 5000 Hz. 139 Modes are predicted by the simulation. Most of these modes do not exhibit peaks in the measured receptance due to their high modal damping ratio. The mode at 424 Hz could be measured and predicted by the simulation.

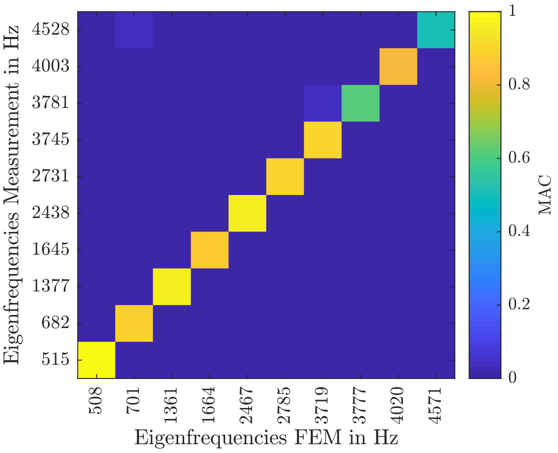

Fig. 9. Modal assurance criterion of measurement versus simulation for the bonded stator.

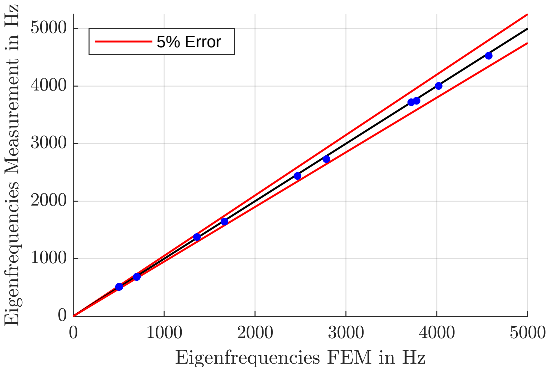

Fig. 10. Comparison of the measured and simulated eigenfrequencies for the bonded stator.

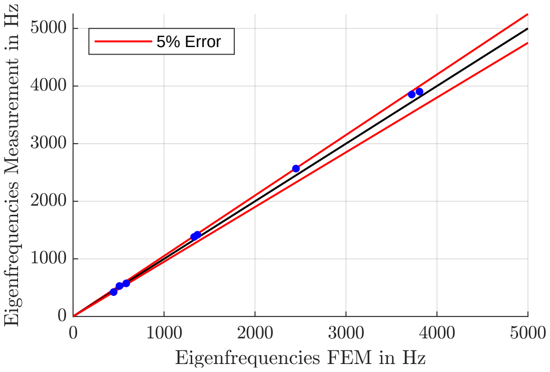

Fig. 11. Comparison of the measured and simulated eigenfrequencies for the welded stator.

The MAC matrix demonstrates the good match between simulated mode shapes and those extracted from measurements for the bonded stator. Only the modes at 3781 Hz and 4528 Hz are attributed with a low MAC value. In the case of the welded stator the modes with pure bending deformation also agree well with the simulation results. Modes with shear deformation on the other hand show lower MAC values when compared to the simulation. A visual comparison between the simulated and the measured modeshapes with shear deformation shows a good agreement. The reduced MAC values stem from deformations in the

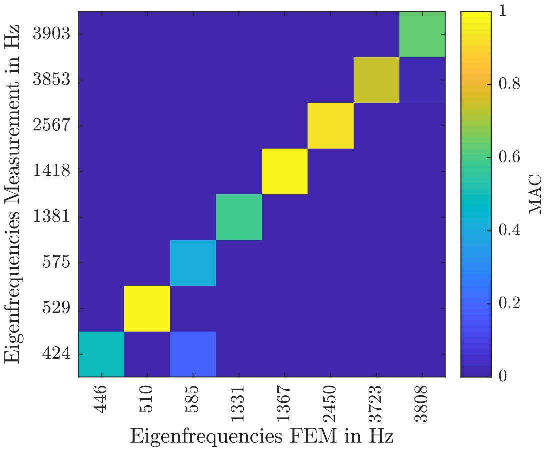

Fig. 12. Modal assurance criterion of measurement versus simulation for the welded stator.

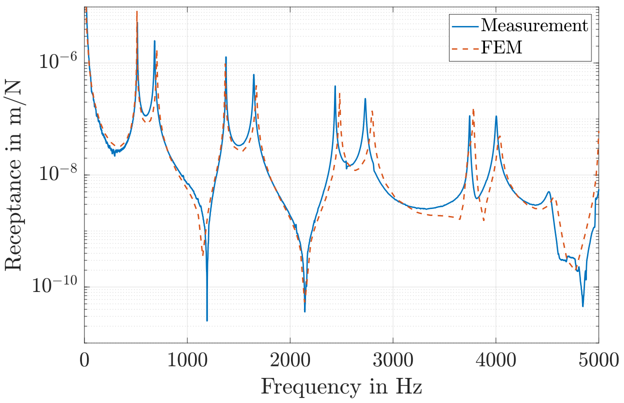

Fig. 13. Comparison of measurement and simulation for an exemplary frequency response function of the bonded stator.

measured mode shapes.

C. *Simulated Frequency Response*

The Harmonic analysis was conducted by exciting and measuring at the same locations on the FE model as in the exemplary measurements shown in fig. 5. But instead of an impact a sinusoidal frequency is used as excitation signal. The frequency is varied from 0 Hz to 5000 Hz and the amplitude is chosen to be 1 N so that the resulting FRF is the receptance. The modal damping ratios are taken from the measurements. Modal damping ratios can not be obtained for the majority of the simulated modes from the welded stator measurements. Since the simulation relies on those damping ratios the harmonic analysis is only conducted for the bonded stator.

The simulated receptance of the bonded stator fits very well to the measured receptance as fig.13 shows. For simulation of the welded stator, the damping coefficients of the highly damped modes have to be known. Future work could deal with alternative measurement techniques to extract modal damping ratios from the welded stator to allow simulation of the receptance. The strain energy method could also be used to determine modal damping ratios as shown in SCHWARZER [1].

IV. CONCLUSION

This paper demonstrates the influence of stacking technologies on the structural dynamic behavior of iron cores of electrical machines. The correlation between mode shapes and their respective damping ratios is shown. The main differences between the bonded and the welded stator from a structural dynamic perspective are the lower shear stiffness and higher damping ratios in the welded stator.

A comparison between damping extraction methods demonstrates that SDOF methods are not able to calculate damping ratios of modes with similar eigenfrequencies. Both MDOF methods are able to estimate damping ratios of these modes. The results of the LSRF method are more stable than those of the RFP method when varying the frequency range and the expected eigenfrequencies. Therefore the LSRF method is chosen in this paper to extract modal parameters from the measurements.

The modal analysis of the stators shows that modes with pure bending deformation are very similar in eigenfrequency, mode shape and damping ratio in both stators. A variation of the stacking technology has only a small effect on these modes. The reduced shear stiffness in the welded stator however leads to significantly lower eigenfrequencies in pure shear modes. The friction between the steel sheets in the welded stator results in damping ratios an order of magnitude larger when compared to pure bending modes. The simulation shows a high density of modes with shear deformation which can not be extracted from the measurements. Receptances extracted from the measurements show now a significant peak for most of these modes, which is also indicative of their high modal damping ratio. The modes with shear deformation that can be extracted from the measurements of the welded stator match the modes predicted by the simulation.

The behavior of the bonded stator can be reproduced very well with a FE simulation, as the comparison between simulated and measured receptance shows. The simulation of the welded stator shows a high density of modes with shear deformation due to the low shear stiffness. Four modes with shear deformation can be extracted from the measurements which fit the predictions made by the simulation. The majority of the simulated modes with shear deformation can not be extracted from the measurements, most probably due to their high damping ratios and low axial spatial resolution of the measurements.

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