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A METHOD FOR A MODAL MEASUREMENT OF ELECTRICAL MACHINES

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Sebastian Fingerhuth[1]; Roman Scharrer[1]; Knut Kasper[2]
[1)] Institute of Technical Acoustics
RWTH Aachen University
Neustr. 50
52066 Aachen. Germany
sfi@akustik.rwth-aachen.de
+49 241 8097984
[2)] Institute for Power Electronics and Electrical Drives
RWTH Aachen University
Jägerstr. 17/19
52066 Aachen. Germany

ABSTRACT

One important acoustic and vibration analysis carried out on electrical machines is experimental modal analysis. A well known method for this measurement is using an impulse hammer or shaker, but those have some important disadvantages.
In this work a method of electrical machine modal measurement is presented, where the machines electromagnetic forces are used to excite the machine while halted. By exciting the machine with a known current signal a reproducible and controlled measurement procedure is obtained. The modal characteristic of the machine as well as the transfer function between force and surface vibration are determined.

INTRODUCTION

For the engineer involved in the design and construction of products using electrical motors, it is of great importance to know the vibration and noise radiation characteristic of the motor. It is even more significant in applications where the sound quality of the product is important, as in household appliances or in the car industry (electric car). The noise and vibration produced, transmitted and radiated is investigated by the NVH (noise, vibration and harshness) engineer and then used for example, to optimize the design and construction of a motor, by trying to reduce the vibration and also by defining the mounting and clamping of the machine. One method to obtain the vibroacoustic characteristic of the motor is the modal analysis. It permits to obtain the vibration amplitude and form (mode) of the structure and its corresponding frequency.

MODAL ANALYSIS METHODS

For a modal analysis some different methods can be used, each one with some advantages and drawbacks. For very simple geometric structures (plates, cylinders, boxes, etc.) with simple material parameters an analytical method could be used as a first approximation without practical importance. If the material parameters of the structure that should be analyzed are known, precise results can be obtained with the numerical methods, as the finite element method (FEM). One advantage is that the modal analysis can be computed in the design state

of the machine, before it is constructed. The drawback is the amount of computational power required to calculate the modal analysis of structures with a high detail level.
In the experimental modal analysis mainly two methods are used: impulse force hammer and modal exciter (shaker). With both methods, the structure is excited with a known broad band force signal [1] [2]. In the case of the force hammer the force applied is measured while force impulses are applied to the structure under test. A similar setup is used with the shaker. The shaker is attached to the structure and excited with a broad band signal while the force is measured. In both setups, the vibration, mostly velocity or acceleration, is registered simultaneously on one or more points on the structure. Using both signals (input and output) the vibration characteristic (modes, resonance frequencies, damping, transfer function, etc.) can be computed. One disadvantage of both methods is that normally it is not possible to apply the forces in the inner structure of the stator, where the forces are present during normal operation. With the hammer or shaker the force is applied on the outside of the housing and the vibration measurement is also realized on the outside.

In this paper an alternative method for modal analysis of electrical machine is presented. The big difference and advantage is that the force for the modal analysis is applied on the stator teeth, on a place where the force is applied in normal operation. A switched reluctance motor (SRM) will be used as a case study to present the proposed measurement method. A good overview of modal analysis methods (measurement and numerical) for electrical machines is presented in [2].

MODE OF OPERATION OF AN SRM

The operation of the SRM will be presented briefly, because the results presented here are from the modal analysis on a motor of this type. In an SRM, the current applied to one electrical phase of a machine (see phase A on Figure 1Figure 1Figure 1 as an example) produces a magnetic flux that crosses the stator and rotor of the machine. Forces are produced on boundaries of low reluctance (reluctance is the magnetic equivalent to the electric resistance) that generate torque but also radial forces. The electrical phases of an SRM are switched sequentially to make the rotor turn. The windings consist on concentrated coils on each stator tooth. The rotor of an SRM also has teeth, but no coils. In the left hand side plot on Figure 1Figure 1Figure 1, phase A is active and the reluctance force makes the rotor rotate clockwise. The required current form is obtained by applying a positive, negative or zero voltage to the machine. This is controlled and regulated by a microcontroller and power converter unit depending on the actual rotor angular position and the target operating point (torque and speed). At an optimal angular position the control unit *switches on* the next phase (phase D) while the phase current of Phase A is set to zero. For an overview on electrical drives and power converters refer to [3].

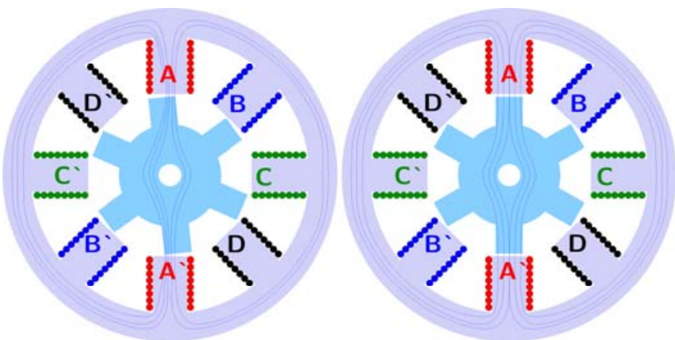

Figure 1: Schematic representation of a switched reluctance machine (SRM)

MODAL ANALYSIS USING ELECTROMAGNETIC FORCES

The response (output) of a linear, time-invariant system to any given input signal is completely described by its impulse response. Transforming the impulse response into the frequency domain, the transfer function is obtained. The proposed method consists in measuring the impulse response of the machine, using the phase current as the input signal and the surface vibration as the output. Due to the fact, that the relation between the phase current and the resulting force is nonlinear (see Figure 2Figure 2Figure 2) a finite element (FE) electromagnetic model of the stator was used to compute the force produced by different current levels for an aligned rotor position.

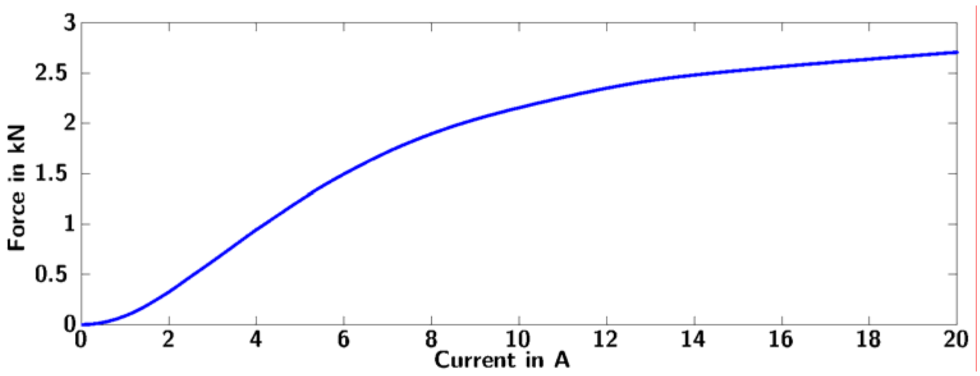

Figure 2: Relation between phase current and radial force

The relation between the force and the surface vibration is linear and time invariant (LTI system), so that the transfer function between force and surface velocity can be computed by dividing the measured vibration by the applied force in the frequency domain as presented in the block diagram of **¡Error! No se encuentra el origen de la referencia.Fehler! Verweisquelle konnte nicht gefunden werden.Fehler! Verweisquelle konnte nicht gefunden werden.**. Since the input magnitude of the system is the phase current (and not the force), the nonlinear relation between current and force has to be included in the lower branch of Figure 3Figure 3Figure 3 (input signal).

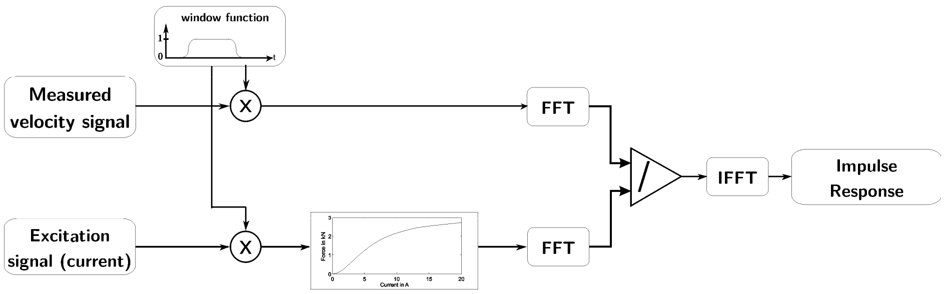

Figure 3: Diagram of the impulse response (transfer function) calculation

For the modal measurement, three different broadband current signals were user-programmed on the power converter control unit: a pulse, a sweep [4] and a pseudo-random noise signal [5]. The three current signals are plotted in Figure 4Figure 4Figure 4. The spectrum of the three force signals are plotted in Figure 5Figure 5Figure 5. It can be seen, that the different signals have a different spectral energy distribution, but the resulting transfer functions were very similar for the three signal types.

The measurement of the surface vibration of the stator can be realized with different methods, for example using accelerometer sensors on points of interest on the stator surface. A more efficient and faster measurement of the surface velocity on several points is achieved using a scanning laser vibrometer. For the analysis presented in this paper a laser vibrometer was used. The broad band current signal was repeatedly applied to the machine, every few seconds, while the scanning point was changed to measure the surface velocity on the points previously defined on the stator surface.

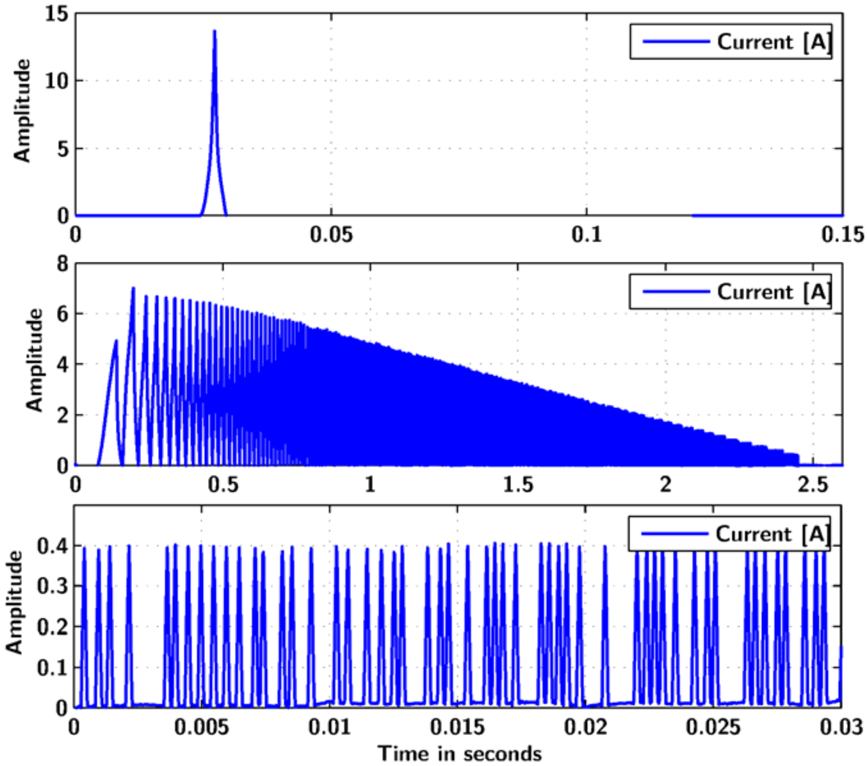

Figure 4: Broad band current signals used for the measurement. From top to bottom: pulse, sweep, pseudo-random noise (only a short window of the pseudo-random noise signal is plotted).

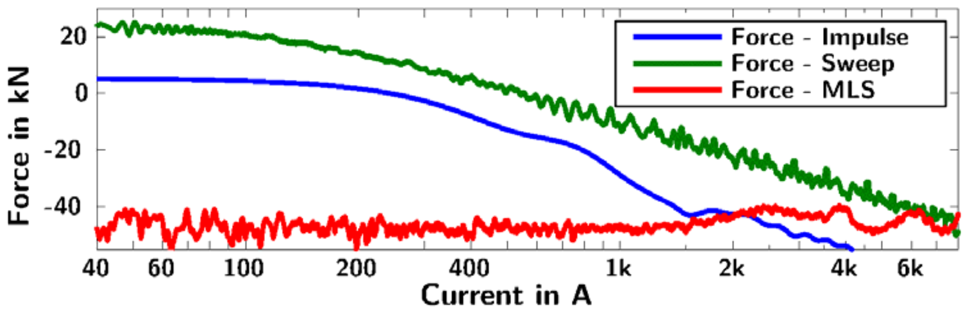

Figure 5: Spectrum of the three broad band force excitation signals

This procedure was then repeated for all the four phases of the machine to finally obtain a set of transfer functions between force and surface velocity for all points on the machine surface. Since the mechanical system is linear, the result from the measurement of each point for each of the four phases can be superimposed.

RESULTS

The results from the measurement will be presented for only two of the four electrical phases of the machine.

First a plot of the transfer function between force and surface velocity for several points around the machine will be presented.

Figure 6Figure 6Figure 6 shows the measured transfer function in a frequency range around the main resonance of the stator for several measurement points around the stator. Due to symmetry properties of the motor, only 180° were measured. On top is the result for $Phase_{el,1}$ (the notation: $Phase_{el,N}$ will be used for the Nth electrical phase). On the bottom plot the result for $Phase_{el,2}$ (which is geometrically shifted by 45°) is presented.

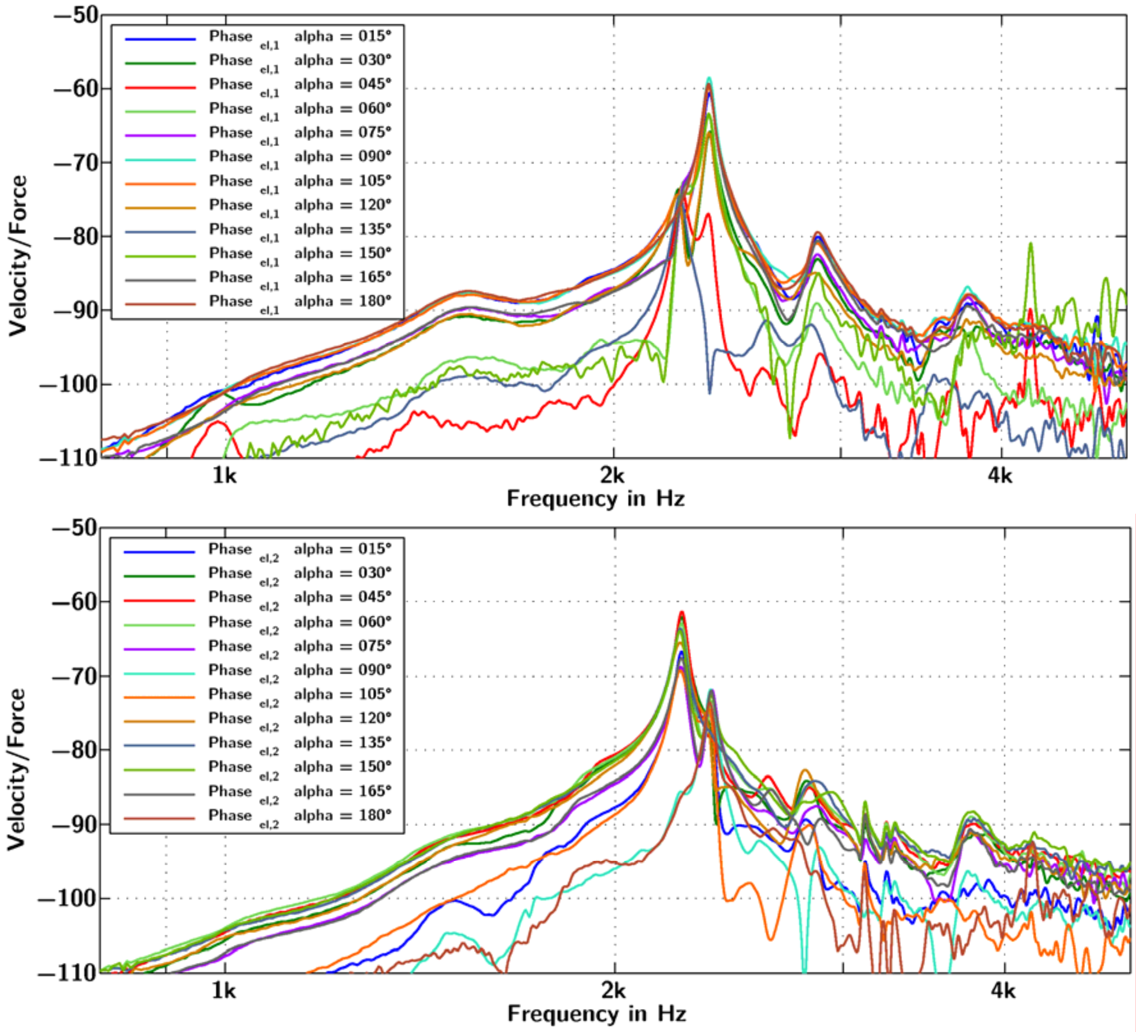

Figure 6: Measured transfer function for the first electrical phase (top) and for the second electrical phase (bottom)

From both plots it can be seen, that $Phase_{el,1}$ excites mainly a mode with a maximum at about 2.37 kHz. $Phase_{el,2}$ excites the stator at a slightly lower resonance frequency, namely 2.25 kHz. In this latter case, the vibration at 2.37 kHz is still present, but is not as pronounced as with $Phase_{el,1}$ (-12 dB). The vibration intensity and frequency is not constant for the different positions around the machine. Observing the color code in the legend, it can be seen, that the change is periodic, repeating after 90°. From the results of the measurement it can be concluded that there are two important resonances. Both are cylindrical mode-2 resonances at slightly different frequencies (2.25 kHz and 2.37 kHz) and rotated (shifted) by 45°.

This can also be seen in the cylindrical plots of Figure 7Figure 7Figure 7. Again, only the measurement results of exciting two of the four electrical phases are shown. The plots show the surface velocity for the frequencies of main vibration found before. The two plots on the left hand side for a frequency of 2.25 kHz and for 2.37 kHz on the right. The legend shows which phase was excited with the broad band current signal. Exciting $Phase_{el,1}$, produces vibration mainly at 2.37 kHz. Using $Phase_{el,2}$, this is, applying the radial force at a different place (shifted by 45°) also produces a mode-2 stator vibration (at 2.25 kHz), rotated by 45°.

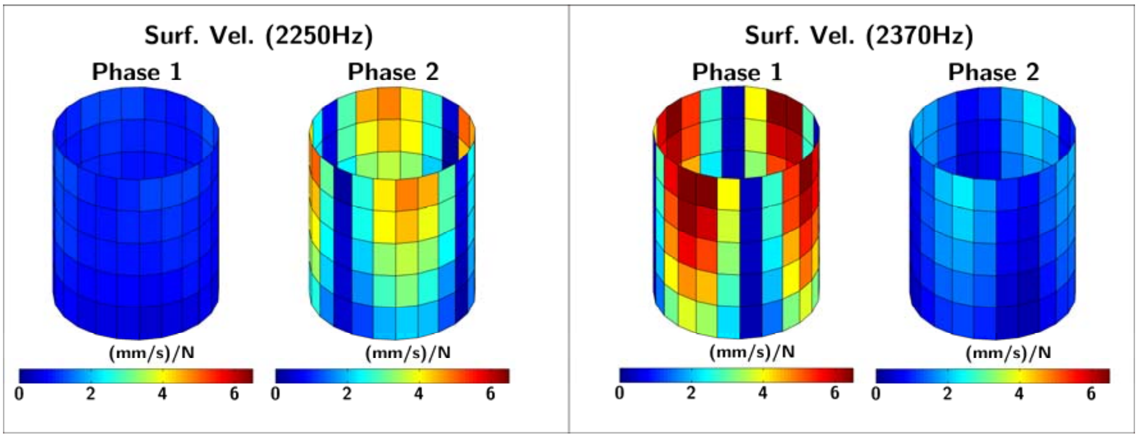

Figure 7: Plot of the measured surface velocity on a cylinder representing the stator. Of the four measurements (applying the current signal to one of the four electrical phases), only the results for two of them are plotted. On the left-hand side plot are for a frequency of 2250 Hz, on the right hand side for 2370 Hz.

With these cylindrical plots it is possible to describe the vibration modes for different frequencies, showing for example, that the vibration is not constant in the axial direction ($Phase_{el,1}$ at 2.37 kHz).

The measurement procedure was also used to simultaneously measure the radiated sound of the machine at a certain distance. This expanded the transfer function presented before by one link so that the complete chain, from the phase current to the sound in far field, is recorded. This can be used to compare the noise produced by the machine for different machine control strategies.

CONCLUSIONS

A modal analysis measurement method that uses the circuit and power electronics of the machine was presented in this paper. Therefore a broadband input force signal is produced and applied to the machine stator. The main advantage of this method is that the force is applied exactly at the same place as in normal operation. With other methods (impulse hammer and shaker) this is usually not possible. Therefore, the control unit of the machine is programmed to produce a broad band signal. The surface vibration (or even the radiated sound) is measured to obtain the transfer function, between phase current and velocity (or sound) with simple post processing.

The transfer functions can then be used: i) to describe the modal characteristic of the machine, ii) to simulate the surface vibration for any operation point, iii) to define motor control strategies that are optimized from a vibroacoustic point of view, iv) to simulate the radiated sound for noise evaluation purposes.

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