Acoustic Measurement for detecting Manufacturing Faults in Electrical Machines

D. van Riesen, C. Schlensok, F. Henrotte, K. Hameyer

***Abstract* — The general design goal of electrical machines is to reach high torque-volume and power-volume ratios, while at the same time having low manufacturing costs. Hence, manufacturing tolerances are pushed to or even beyond the limits. In the case of induction machines (IM), this can lead to disturbance of the normal motor operation by eccentricities, broken bars, and other. In a series production, the detection of manufacturing tolerances in the real machine has to be done by measurement. In this paper, the disturbing noise radiated by an IM is measured and analyzed to detect non-tolerable electromagnetic eccentricities due to mechanical reasons of the IM.**

***Index Terms* — induction machine, acoustic noise, eccentricity, measurement.**

I. Introduction

IN general, the design goal of electrical machines is to reach high torque-volume and power-volume ratios, while at the same time having low manufacturing costs. Hence, manufacturing tolerances are pushed to or even beyond the limits. In the case of induction machines (IM), this can lead to disturbance of the regular motor operation by eccentricities, broken bars, and other. Here, the disturbance results in extra noise radiation of the regarded IM. In many cases, the unsatisfactory operation of the motor is stated after the start of the series production. This is due to the fact, that during prototype stage, the manufacturing tolerances are usually kept small. In these cases, measurements have to be used to detect these faults.

Noise and vibrations of electrical machines [1] have to be taken into account, since they are particularly troublesome due to the fact that they are characterized by many pure tones. Standards [2] define tolerable noise levels. But usually, the comfort needs of consumers or costumers are even stricter. Thus, manufacturing tolerances that lead to a higher acoustic noise emission, can lead to complaints, although they might not directly affect the functioning of the machine.

Detecting the tolerances by measurements is troublesome or expensive. Other approaches try to detect them at stand-still [3], by feeding the machine with special excitation signals. Nevertheless, this is not possible to put into practice during normal operation of the machine.

In this paper, the disturbing acoustic noise radiated by an IM during operation is measured and analyzed using an analytical model [4] to detect non-tolerable electromagnetic eccentricities of the IM. First, different machines taking from a series manufacturing process are examined by measurement. They are operated at the 50 Hz-grid. Differences are noted, not only in the measured acoustic spectra, but also as a subjective difference in their noise behavior. Taking the acoustic spectra

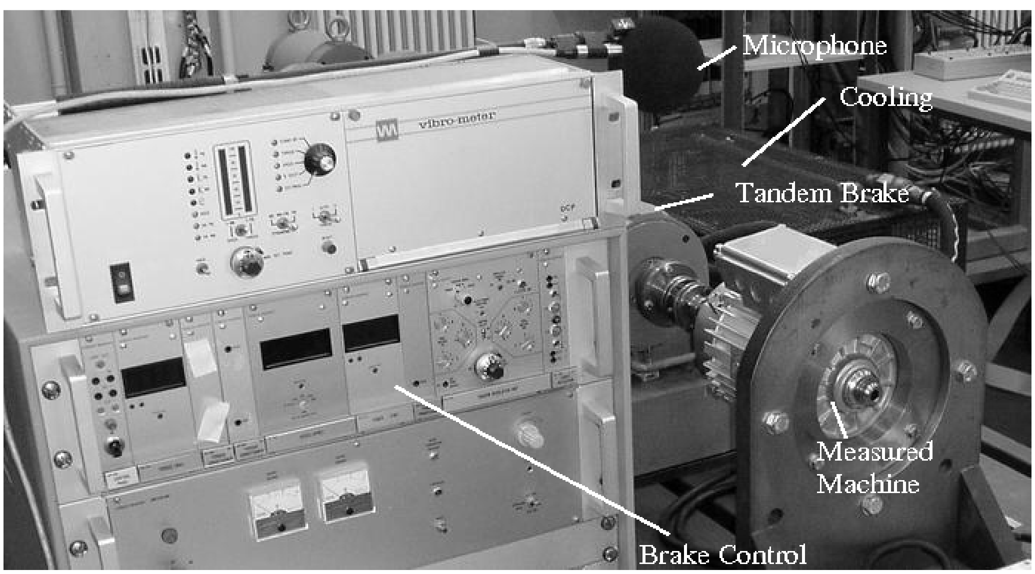

Fig. 1. The test bench setup for the induction machine.

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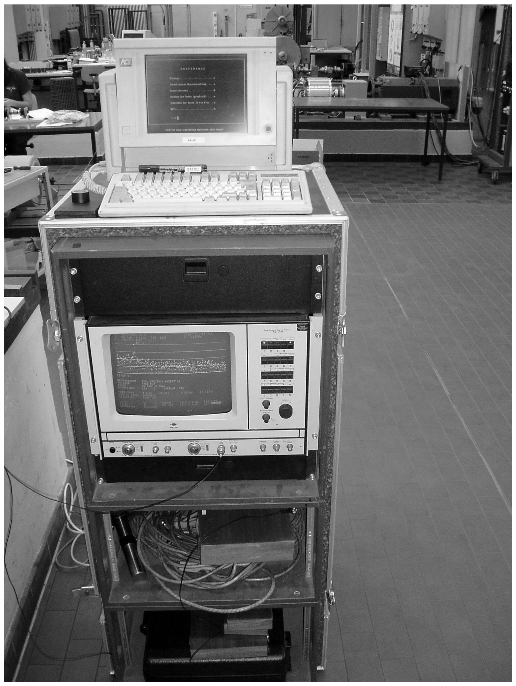

Fig. 2. The utilized 2-channel spectrum analyzer.

as a base, the analytical model is then used to determine the possible causes of the different acoustic behavior of the induction machines. The analytical solutions are validated using a two-dimensional Finite Element (FE) simulation. The determined reason for the differences in the acoustic noise radiated by different machines is then corrected mechanically, and the machine measured again. The obtained results confirm the assumption.

II. Measurement Setup

Fig. 1 shows the test bench used to measure the induction machine. The machine is mounted on a flange and coupled to a tandem brake [5]. This tandem brake, which is electronically controlled, consists of an eddy current brake and a magnetic powder brake. Thus, it is possible to generate a constant braking torque over a wide speed range. A magnetic clutch decouples the powder brake from the system at higher speeds. The control allows operating on constant torque or constant speed. The induction machine is connected directly to the grid. The acoustic noise is measured by a microphone located above the induction machine. Additionally, accelerometers can be fixed on the housing of the machine, to measure the vibration and compare the spectrum obtained with the acoustic measurement. Furthermore, by using a broad-band excitation with a hammer, the eigenfrequencies of the induction machine housing can be obtained.

Microphone and accelerometers are connected to a dual channel spectrum analyzer from Brüel&Kjær [7]. With this, a direct spectrum analysis of the measured signal can be obtained on site. Additionally, the measured data is exported for further processing.

The acoustic measurement is of course superposed with background noise, since the measurement is not conducted in an anechoic chamber. Especially, the cooling device for the tandem brake generates some disturbing noise. The brakes are water-cooled, and the water is pumped through a radiator equipped with fans. These are located just next to the test bench, thus generating an important amount of noise.

Nevertheless, the focus of this paper and the analysis method proposed is to have a simple, yet accurate way of detecting faults in operating machines. Thus, a measurement has to be possible on-site as well, and the measurement setup has to be relatively simple and flexible. Hence, background noise is not avoided, but taken into account through post-processing methods of the measured signals. This is possible due to the different nature of the measured noise. The background noise (including the aerodynamic noise of the cooling device) is usually a broad-band signal with a more or less constant spectrum. On the contrary, the induction machine generates noise that is characterized by many pure tones. This is true at least for the noise produced by an electromagnetic origin. And this is the relevant noise source for the analysis considered here.

Therefore, before operating the induction machine, a measurement of just the background noise (that is, in this case, including the cooling of the tandem brake) is conducted. This spectrum (averaged over a short period of time) is later subtracted from the measured spectrum with the induction machine in operation. As the results presented later will clearly demonstrate, with this strategy it is possible to isolate the noise produced by electromagnetic forces in the induction machine.

III. Measurement Results

Using the above described setup, four induction machines (IM A, B, C, D), taken from a single production series, are measured. The machines are selected to include two with a subjective "good" acoustic behavior, and two with a subjective "bad" acoustic behavior.

The measurements are carried out at different operating points, from no-load to nominal load. The microphone signal is evaluated at a frequency range of 0 – 800 Hz with a resolution of 1 Hz and at a range of 0 – 3200 Hz with a resolution of 4 Hz. Fig. 3 shows the resulting spectrum for one of the "good" machines (IM B), while Fig. 4 shows the same operat-

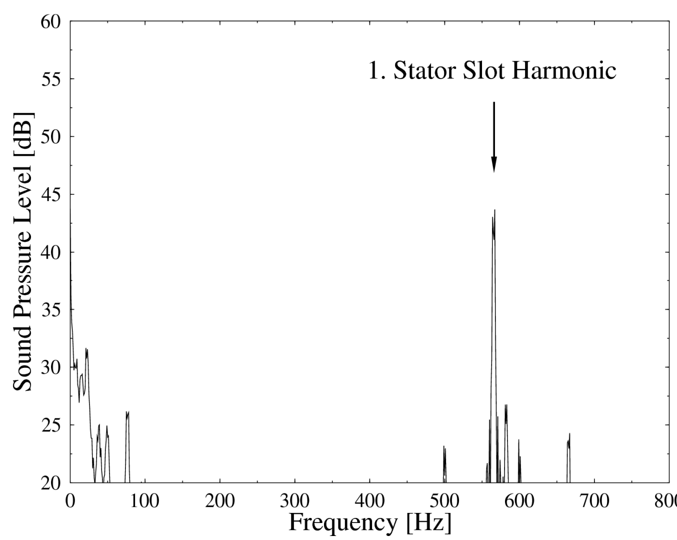

Fig. 3. Spectrum of the sound pressure level of IM B at no-load

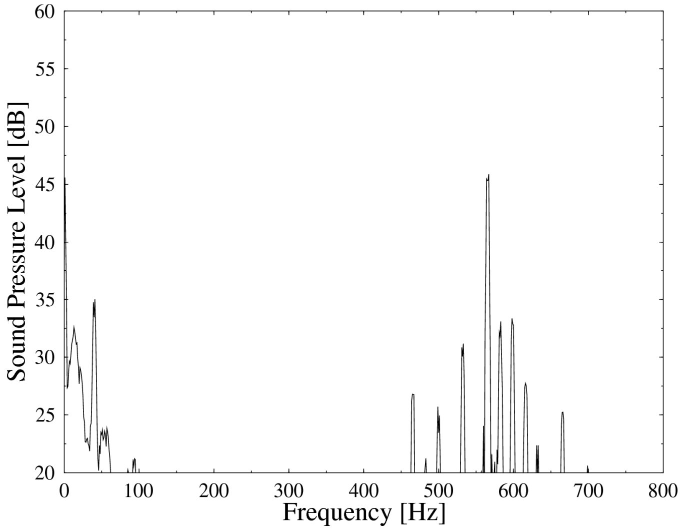

Fig. 4. Spectrum of the sound pressure level of IM C at no-load

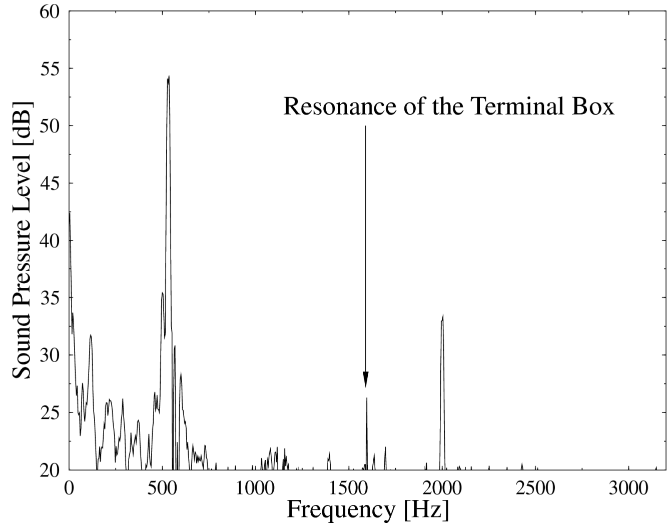

Fig. 6. Spectrum of the sound pressure level of IM C at no-load.

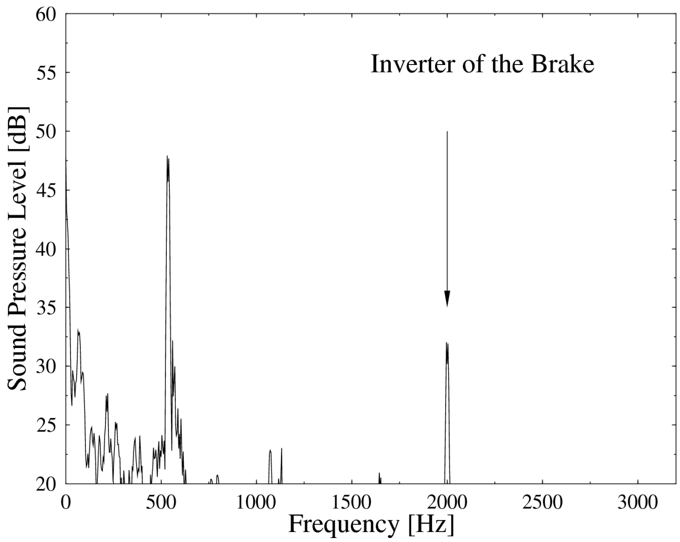

Fig. 5. Spectrum of the sound pressure level of IM B at load

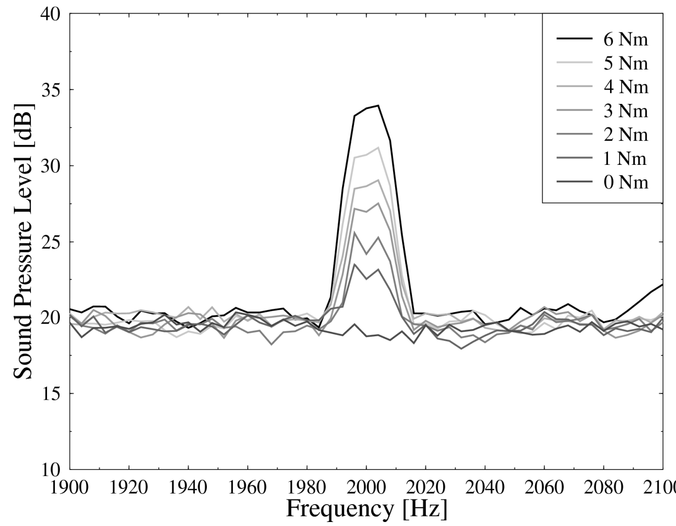

Fig. 7. Spectrum of the sound pressure level of IM A at different loads, zoomed into the 2 kHz peak.

ing point for one of the "bad" machines (IM C). As can be clearly seen, the spectrum of the "bad" machine includes more distinct tones with higher amplitude.

Fig. 5 and 6 show the same machines, loaded at nominal load, and with a resolution up to 3.2 kHz. From these and other measurements, already a certain number of conclusions can be drawn. First, non-relevant frequency results shall be eliminated from the consideration. For instance, each of the measurements carried out with the spectrum up to 3.2 kHz, shows a peak at 2 kHz. But the frequency of this peak is independent of the speed of the machine during the measurement. It is, nevertheless, dependent on the load and disappears when the brake is switched off at no-load (see Fig. 7). The only possible explanation states that this frequency is generated by the inverter controlling the eddy-current brake used to load the machine. It is thus not considered any longer.

Second, measuring the machines at different operating points (speed and torque), the first stator slot harmonic can be identified (see Fig. 3). Fig. 8 shows the sound pressure level generated by the first stator slot harmonic depending on torque and speed. As expected, the frequency of the stator slot harmonic decreases with decreasing speed, since it is dependent on the stator frequency f_1, which is kept constant at 50 Hz, and the slip, which increases with the load. The sound pressure level increases with the load, because of the growing current and thus higher magnetic forces.

Third, a mechanic resonance that was measured in a modal analysis of the housing, as described in the measurement setup, appears as well in the measured acoustic spectrum. Fig. 6 shows the peak corresponding to the resonance frequency of the terminal box of the machine. Since the covering plate of the terminal box is screwed in place manually, this result is not reproducible and thus neglected as well.

The measured frequencies are now analyzed using the analytical model.

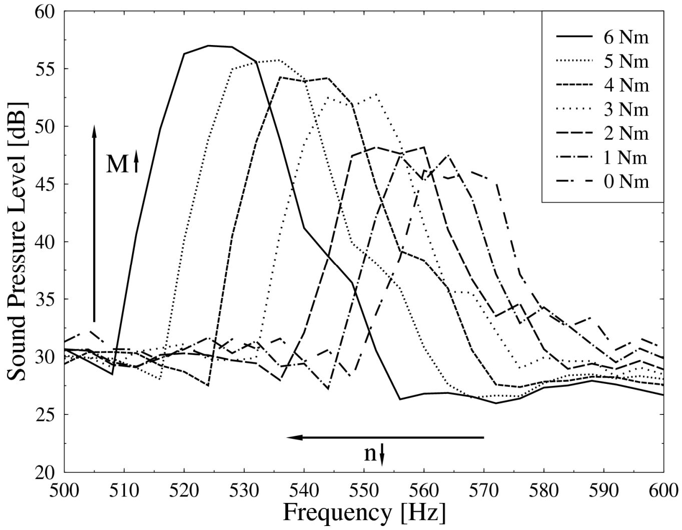

Fig. 8. Sound pressure level generated by the first stator slot harmonic depending on torque and speed.

IV. Analytical Model

The analytical model of [4] is based on the analysis of the force-wave behavior F_r resulting from the normal component of the air-gap flux-density B_n depending on space x and time t:

$$F_r(x,t) = \frac{B_n^2(x,t)}{2\mu_0}$$

with μ_0 being the magnetic field constant. $B_n(x,t)$ results from the fundamental and harmonic field of the stator interacting with the induced field and its harmonics of the rotor. The analysis results in a table of force harmonics, their corresponding frequencies and the predicted oscillation mode numbers. Three major effects are considered in the analytical model: The fundamental of the air-gap field, the saturation of the lamination and static and dynamic eccentricity. Especially, the latter result in specific frequencies.

Fig. 9 shows the output of the analytical tool considering the above described effects, for no-load and nominal load operation. The output is split into oscillation mode numbers for slot and other harmonics, respectively for the fundamental field, saturation field, static and dynamic eccentricity. Only mode numbers 4 and below are considered here, since larger orders do not contribute significantly to the acoustic noise. The first stator slot harmonic is marked in the first column of the fundamental field with a mode number 2. With the output, frequencies resulting from parasitic effects such as saturation and eccentricity can be detected. The detected difference between a "good" (IM B) and a "bad" (IM C) machine lies mainly in frequencies near the first stator slot harmonic (cf. Fig. 3 and Fig. 4). These frequencies can now be identified as resulting from a dynamic eccentricity, like marked in the output in Fig. 9. A static eccentricity can not be detected in a single measurement, since the resulting frequency is identical to the first stator slot harmonic.

With this, an acoustic measurement of an IM allows for the detection of significant eccentric rotor movement and rotor geometry.

f_1 = 50.0 Hz; n = 997.0 rpm.

					ECCENTRICITY			
FREQUENCY	FUNDAMENTAL FIELD		SATURATION		STATIC		DYNAMIC	
	SLOT	OTHER	SLOT	OTHER	SLOT	OTHER	SLOT	OTHER
16.3								1
257.3				2				
341.0								3
357.3		4		4		3		
541.0							3	
557.3	2		2		1, 3			
573.7							1	
657.3			4					

f_1 = 50.0 Hz; n = 927.0 rpm.

					ECCENTRICITY			
FREQUENCY	FUNDAMENTAL FIELD		SATURATION		STATIC		DYNAMIC	
	SLOT	OTHER	SLOT	OTHER	SLOT	OTHER	SLOT	OTHER
15.3								1
229.3				2				
314.0								3
329.3		4		4		3		
514.0							3	
529.3	2		2		1, 3			
544.7							1	
629.3			4					
758.7		4		4		3		
774.0								3

Fig. 9. Output of the analytical tool for the no-load and nominal load operating points.

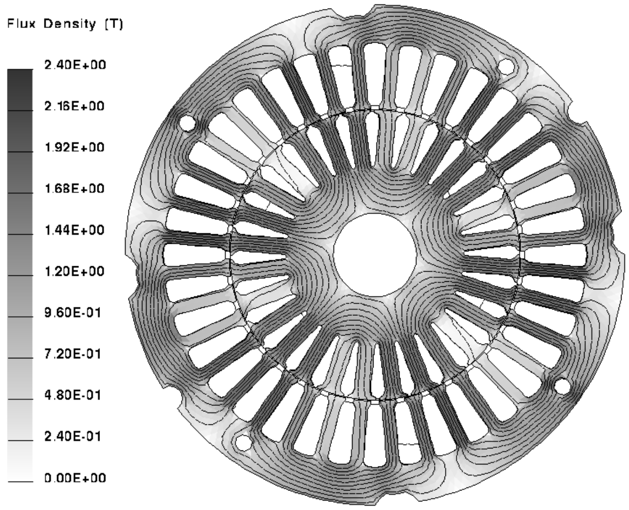

Fig. 10. Flux density and vector potential isolines of the analyzed induction machine.

V. SIMUALTION RESULTS

The measured results are interpreted by means of an analytical model to find the source of the different acoustic behavior of various exemplars of an induction machine series. To consolidate the results, a finite element (FE) simulation of the IM is carried out. A two-dimensional transient analysis is performed using a solver of the iMOOSE [6] package. Fig. 10 shows the model used, with the flux density distribution of one time step and the magnetic field lines, taken from the isolines of the magnetic vector potential. The results of the FE analysis are evaluated with respect to the torque, torque ripple (see Fig. 11) and tooth force (see Fig. 12). The latter is transformed into the frequency domain using a FFT. The results, depicted in Fig. 13, can be used to evaluate the results of the measurements and the analytic consideration. As can be seen, the first stator harmonic is reproduced and is also found in the measured spectra. The FE model is a two-dimensional model, and hence does not take into account skewing. But, the real machine is skewed, and the measured spectra show, that the skewing angle is chosen to suppress all electromagnetic excitation force components except for the first stator slot harmonic.

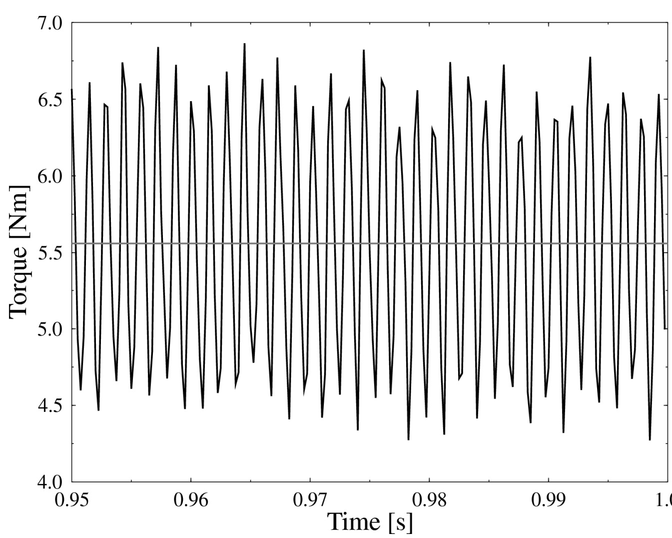

Fig. 11. Torque computation.

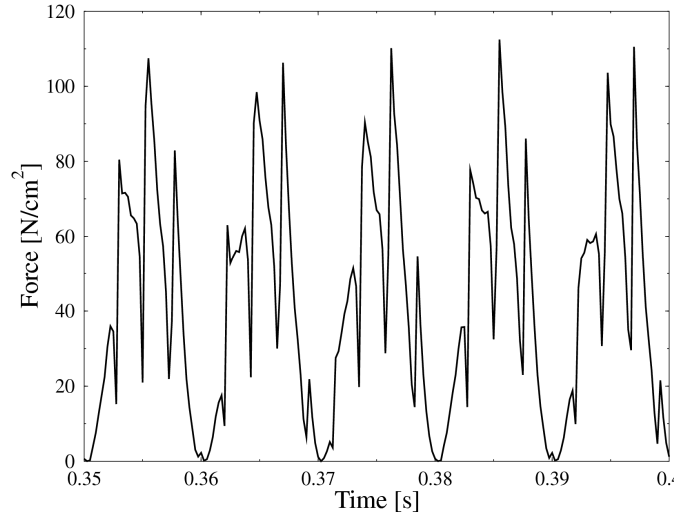

Fig. 12. Stator tooth force for one stator tooth element in the time domain.

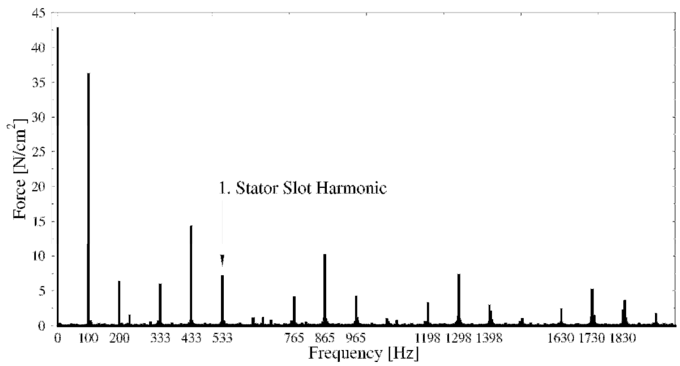

Fig. 13. FFT of the stator tooth forces.

VI. ACOUSTIC DESIGN ANALYSIS

Hence, the assumption of eccentricity generating the additional frequencies and the additional noise endures. To test this, one of the "bad" IM (IM C) is disassembled. The rotor turns out to be mechanically centric. In the manufacturing process, the rotor is turned to size. But due to a misalignment of the squirrel cage within the lamination of IM C, the rotor slots remained closed on one side of the rotor, while being opened on the opposite side. This leads to a magnetic eccentricity. Now, the rotor is turned over again carefully, to ensure that all slots are open. The IM is then re-assembled (now labeled IM C2). The measurements are then repeated. Fig. 14 shows the measured acoustic noise spectrum from IM C before and Fig. 15 after re-assembling. It can be clearly stated, that the additional frequencies around the first stator slot harmonic, have disappeared from the spectrum, hence confirming the theory. The machine is now considered "good" as well regarding its acoustic behavior. Of course, due to the additional turning of the rotor, the air-gap has been widened (by about 20%), resulting in a poorer performance of the machine.

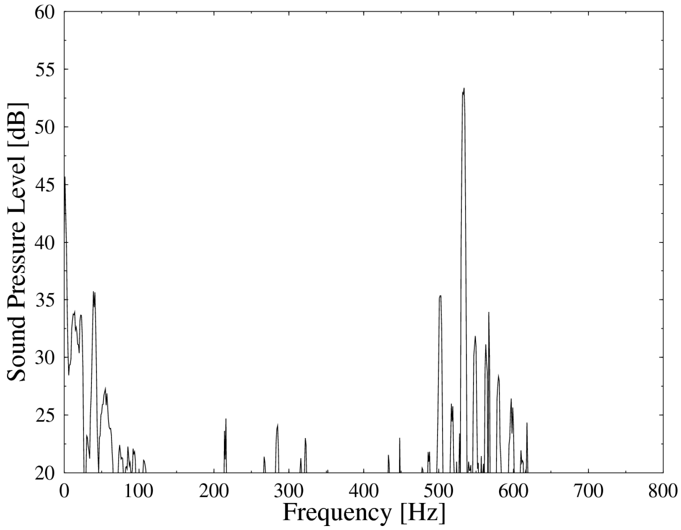

Fig. 14. Spectrum of the sound pressure level of IM C before re-assembling.

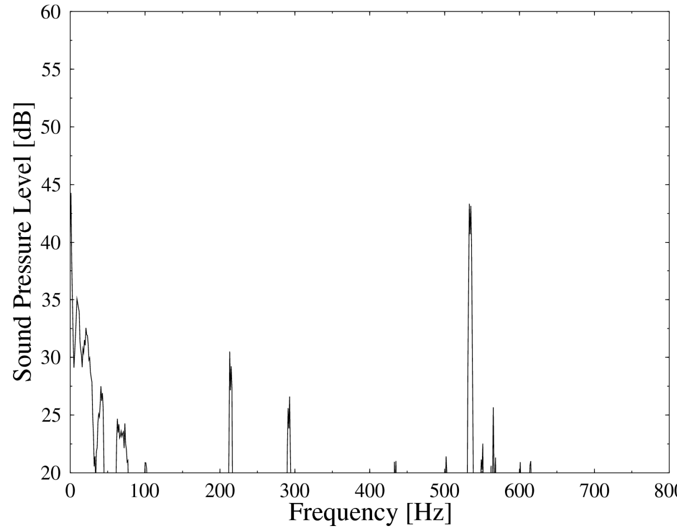

Fig. 15. Spectrum of the sound pressure level of IM C after re-assembling.

VII. CONCLUSIONS

The paper presents the acoustic measurement for detecting manufacturing faults in electrical machines. The goal is to obtain information about manufacturing faults, by analyzing the audible noise of machines during regular operation. A simple measurement setup is presented, which allows even for on-site measurements. Using an analytical tool, the measured acoustic spectrum is analyzed to identify different electromagnetic effects resulting in acoustic noise.

Four induction machines from a series production which differ in their subjective noise perception are studied performing acoustic measurements. The studied operating points are calculated with the analytic tool. Numerical simulations are used to consolidate the measurement data and the results of the analytical model. The results of all three methods are in good concordance. The analytic results allow for the identification of all occurring harmonics in the measured acoustic spectrum, except for those from external sources of the test bench, such as the brake inverter or the cooling fan.

The analysis shows, that the differences in the acoustic behavior of the four machines mainly stem from a dynamic eccentricity. The loudest machine is disassembled, and a reason for this eccentricity found. The dynamic eccentricity is removed and the measurement and analysis are repeated. The results obtained here from confirm the analysis.

The method proves effective, leading to a powerful tool for the analysis of dynamic eccentric machines.

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