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Acoustic analysis of electric motors in noisy industrial environment

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Abstract- This paper presents a method of acoustic analysis of electric motors in noisy industrial environment. Acoustic signals were measured by the microphones arrays called acoustic camera. Measurements by acoustic camera allow localization of sound source and by that separate sounds of interests from background noise. Results of acoustic analysis are compared with vibration measurements. Vibration monitoring is a well-known technique used in condition monitoring and in this work vibration measurements were used as a reference signal for assessment of the value of acoustic measurements. Vibration signals were measured by piezoelectric accelerometers. Two induction motor cases were examined – healthy motor case and combination of static eccentricity with soft foot case. As presented in result section acoustic analyses appear as valuable techniques for condition monitoring of electric motors even in noisy industrial environment.

I. Introduction

Since any interruption in the manufacturing process can cause a serious financial loss for the company it is very important to prevent unplanned shut downs of electric machines. Hence the diagnosing of the health of electric motor is crucial and is still receiving more and more attention. One of the possibilities or performing diagnostic of electric machines is by analysing sound emitted by object of interests. The quality of acoustic monitoring is very much dependent on the background noise of the environment, the machine is operated in. Some attempts to create a condition monitoring methods based on acoustic analysis were made in the past ([1], [2], [3] and [4]). Recently acoustic analysis has attracted more and more attention and it has been applied in many fields for example speech recognition. However condition monitoring methods based on acoustic analysis are still considered difficult to implement in an industrial environment due to the background noise.

Availability of data collectors and sensors as accelerometers or current probes cause appearance of many condition monitoring systems based on those measurements. However still very often case where site engineers are asking for inspection of the machine is when they notice abnormal sound. Instead of localization of the sound and its analysis typical solution is to is perform measurements of vibration, current, temperature or voltages which not always are reflecting the problem. Even though what was reported was the abnormal sound, existing solutions are trying to detect the fault by various types of measurements as opposed to showing that sound is emitted by specific part in the first place. This, in turn, might decrease the amount of the possible diagnostic decisions, decreasing the amount of required effort. For this reason in many cases the first diagnostic attempt is made by highly experience engineers who are able to initially diagnose the problem by listening of object sound. For many years the diagnostic in the industry was performed by human ear and subsequent assessment of the emitted sound. Still, however, the influence of the background noise may strongly affect the quality of such a judgment.

Today's trends in the job market lead to situation where there is less and less people who are experienced enough to judge the condition of object by listening to the sound of it. It is the results of the fact that many people prefer to do the office work instead of working in industry environment. As it is shown in Global Employment Trend document [5] or in the list of the top 10 jobs forecast for next decade [6] this situation will be even more visible in the future. However, still there is a necessity of doing the initial investigation of objects to localize the abnormal sound to perform immediate action.

A solution of the described problems might lie in the usage of acoustic analysis for diagnostic of objects of interest. So far it was relatively hard to create a reliable acoustic-based condition monitoring system due to the fact that sound measurements are always affected by the background noise. However, recent technologies like acoustic cameras are able to successfully localize the specific sound components and by that remove the influence of the background noise [7], [8].

A variety of faults which can occur in induction machines, have been extensively studied and many monitoring methods have been proposed to detect problems [9]. Most of those methods for condition monitoring of electric motors utilized vibration or Motor Current Signature Analysis (MCSA) [9], [10], [11]. While vibration or current signature analysis based monitoring techniques are well known and well accepted acoustic measurements are not so popular in industrial application. Presented work contains description of diagnostic method for induction motor based on acoustic measurements while vibration analysis is used as a reference for assessment of the value of acoustic measurements.

II. Measurements tools

A. Acoustic camera

The idea of acoustic camera is to do sound source identification, quantification and perform a picture of acoustic environment by processing of multidimensional acoustic signals received by microphone array and to overlay that acoustic picture to the video picture [7]. Acoustic camera possible applications as test equipment are non-destructive measurements for sound identification in interior and exterior of vehicles [7], [8], [12], trains and airplanes [13], [14], measurement in wind tunnels, etc. Additionally some studies show the application of acoustic camera for underwater unmanned vehicles [15], robots and robotized platforms etc. It can be also used for passive acoustical sensing in battlefield [16].
In this work 48 microphones acoustic camera was used for sound measurements. Parameters of the microphone are presented in Table 1.

Table 1. Microphone characteristic

Parameter	Value
Equivalent noise level:	27 dB(A)
Maximum equivalent sound level:	130 dB
Microphone Frequency response:	20 Hz-20 kHz

For the analysis of sound source Acoustic Holography technique was used. Acoustic Holography technique is a method that is used to estimate the sound field near a source by measuring acoustic parameters away from the source via an array of microphones. This is a well-known technique and its description can be found in the following papers [16] and [17].

B. Vibration Measurements

Vibration measurements are one of the most popular methods for condition monitoring of electric motors. Typically piezoelectric accelerometers are used for measurements of the vibration. For the purpose of this work vibration measurements were taken as a reference for the sound measurements. Vibrations were collected by ABB MACHsense-P condition monitoring tool. ABB MACHsense-P is a walk around condition monitoring service tool provided by ABB which specifically focuses on electric motors.
Vibration signals were measured using 4 simultaneous data capture channels and analyzed for mechanical and electromagnetic defects. Frequency range which is used for analysis by MACHsense-P tool is from 0 Hz to 12800 Hz. Vibration analysis presented in this paper is embedded functionality in ABB MACHsense-P tool.

II. Measurements analysis and comparison

All vibration and acoustic measurements where done in an industrial environment. Since induction machines are the most popular motors in industry [18] as an objects of interest two of the same type three-phase induction motors were chosen. Nameplate details of motors are presented in Table 2.

Table 2. Nameplate of motors

Parameter	Value
Active power [kW]	75
Nominal voltage [V]	690
Nominal current [A]	77.5
Nominal power factor [-]	0.86
Nominal speed [rpm]	1480
Winding connection [-]	Y

Number of poles per phase winding [-]	2
Nominal frequency [Hz]	50

Both motors were localized relatively close to each other and both of them were driving centrifugal pumps of the same type through direct coupling. Both motors where operating at the same load level. Motor case 1 is considered to be healthy while motor case 2 is considered to have a combination of static eccentricity and soft foot. As soft foot typically results in static eccentricity this combination of faults is very common.

A. Results based on vibration measurements

For both of the motor cases vibration sensors were located horizontally on the center of the body of the motors. Figure 1A presents vibration spectrum of healthy motor case while Figure 1B presents vibration spectrum of combination of static eccentricity and soft foot motor case. Since static eccentric can be typically visible in low frequency range both figures present frequencies from 0 Hz to 200 Hz.
It is possible to notice that Figure 1B contains a high peak at around 100 Hz. Value of this peak is above 0.12 g's, while on the Figure 1A this peak is smaller than 0.02 g's. As it is presented in work [12], static eccentricity cause additional forces visible in vibration at frequency f_{ecc} given by following equation:

$$f_{ecc} = 2 \cdot f_{line} \quad (1)$$

where f_{line} is power supply frequency. In above case, both motors were supplied by 50 Hz, therefore static eccentric related frequency f_{ecc} is visible at 100 Hz. By taking the amplitude of f_{ecc} frequency as static eccentricity indicator it is clearly visible that the motor in case 2 got higher level of static eccentricity than healthy motor from case 1. In ABB MACHsense-P this indicator of static eccentricity is calculated in automatic way.

A B

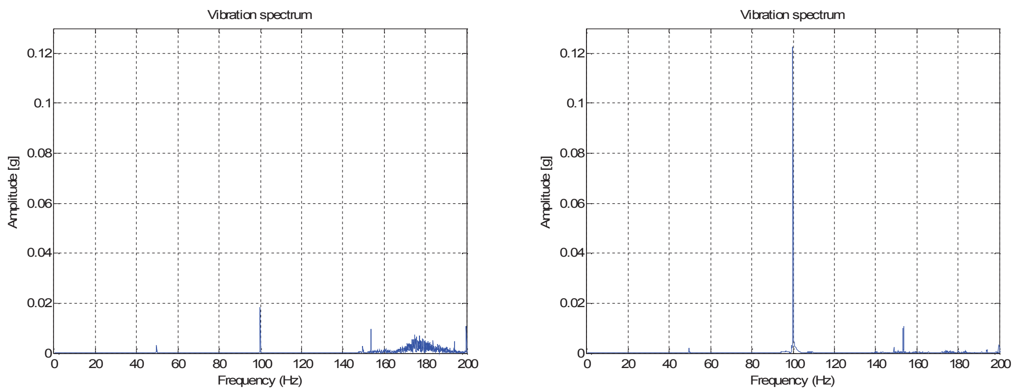

Figure 1. A – vibration spectrum for healthy case; B – vibration spectrum for combination of static eccentricity and soft foot.

A. Results based on acoustic measurements

In industrial applications, by performing measurements using a microphone the background noise cannot be avoided. The background noise can be filtered out by post-processing methods of the measured signals. This is possible due to the different nature of the measured sound. The background noise (including the aerodynamic noise of the cooling device) is usually a broad-band signal with a more or less constant spectrum [1]. On the contrary, the induction machine generates sound that is characterized by many pure tones (at least for the sound produced by electromagnetic origin). Paper [1] presents method where before operating the induction machine, a measurement of just the background noise is conducted. This spectrum of the measurements is later subtracted from the measured spectrum with the induction machine in operation. However this approach of noise filtering cannot be accepted in the industry, because it affects the industrial process.
Paper [11] describes method which isolates the frequencies related to the motor presented in electric current measurements. The same approach can be applied for vibration or acoustic signal. As presented in [11] by

knowing motor parameters and motor slip all the frequencies related to motor condition can be identified. In the same way all the motor related frequencies can be found and identified in acoustic signal even if signal contains background noise.
Figure 2 presents acoustic spectrum of average signal from microphones array. Figure 2A presents acoustic spectrum of healthy motor case while Figure 2B presents acoustic spectrum of combination of static eccentricity and soft foot motor case. Both figures are obtained for frequencies range from 0 Hz to 200 Hz. Similar as in vibration cases it is possible to notice that Figure 2B consist of high peak at around 100 Hz while Figure 2A did not. Value of this peak is above 600 mPa, while on the Figure 2A this peak is smaller than 350 mPa. Those results are very similar to vibration based results and they are clearly indicating static eccentricity however in case of acoustic signal there is no assurance that this frequency comes from motor.

A B

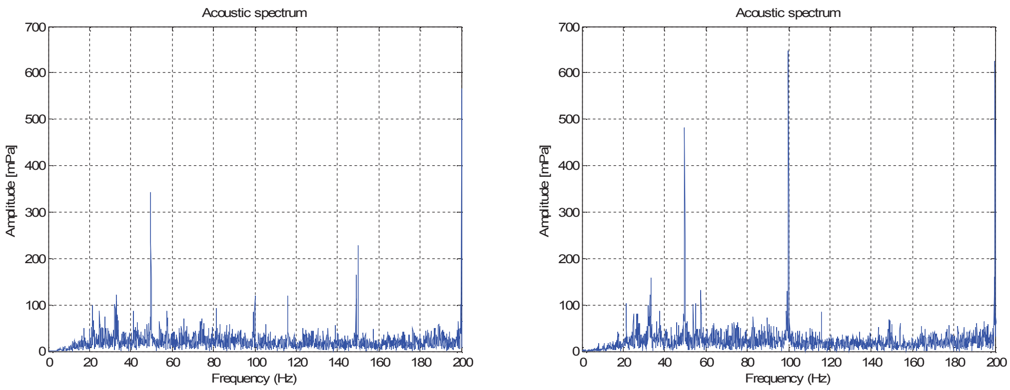

Figure 2. A – acoustic spectrum for healthy case; B – acoustic spectrum for combination of static eccentricity and soft foot

To solve this problem, Acoustic Holography technique can be applied to find sound source of frequency of interest – in this case 100 Hz. Figure 3 presents results of the Acoustic Holography technique applied for the 48 microphones acoustic camera. Sound intensity is marked by the color and as it is easy to notice highest amplitude of 100 Hz comes from motor body, which means that this particular frequency is not caused by any background noise but its origin is motor itself.

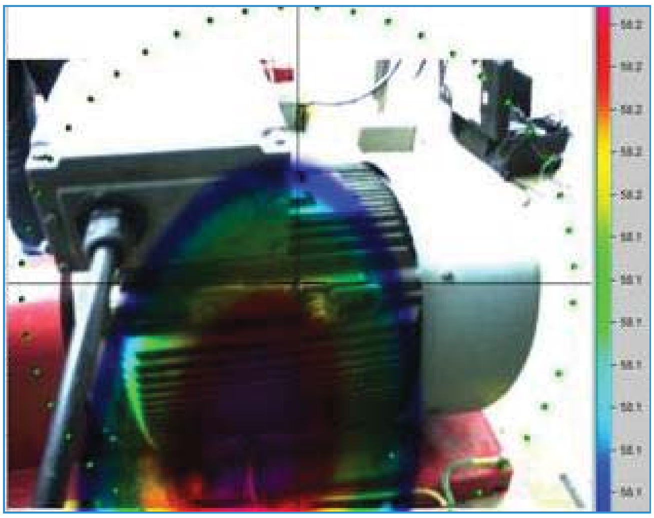

Figure 3. Localization of 100 Hz by Acoustic Holography technique.

IV. Conclusions

In this paper, an acoustic based technique for condition monitoring of electric motors was presented. Vibration analysis was used as a reference for assessment of the value of acoustic measurements. Acoustic measurements were performed by 48 microphones acoustic camera.
Two induction motor cases were examined – healthy motor case and combination of static eccentricity with soft foot case. For fault case respective frequencies were identified in both vibration and acoustic signal. Based on Acoustic Holography technique fault related acoustic frequency source was localized in the center of the body of faulty machine.
As it was presented in the results section, it is possible to say that acoustic signals can be successfully used for condition monitoring of electric motors in noisy industrial application. Obviously single acoustic signal is disturbed and noisy compared to vibration signals therefore sound localization technique based on acoustic camera needed to be applied to solve this problem. Additional fact that the acoustic sensors do not need to be located directly on motors, which sometimes is difficult to achieve in industrial applications, is one of the strengths of the sound analysis.

References

[1] Van Riesen D., Schlensok C., Henrotte F., Hameyer K.: “Acoustic measurement for detecting manufacturing faults in electrical machines”, *17th International Conference on Electrical Machines ICEM*, (2006)
[2] Verma S. P.: “Noise and vibrations of electrical machines and drives; their production and means of reduction”, *International Conference on Power Electronics*, Drives and Energy Systems for Industrial Growth, Vol. 2, pp.1031, 1996
[3] Verma S. P., W. Li: “Measurement of vibrations and radiated acoustic noise of electrical machines“, *Sixth International Conference on Electrical Machines and Systems ICEMS*, Vol. 2 (2003), pp. 861
[4] Gaylard, A., Meyer, A., Landy, C., A. “Acoustic evaluation of faults in electrical machines “, *Seventh International Conference on (Conf. Publ. No. 412)*, Durham, p. 147 -150
[5] Employment Trends unit of the ILO Employment Sector, “Global Employment Trends 2012: Preventing a deeper jobs crisis”, *International Labor Office,* Geneva, 2012.
[6] WorldWideLearn “Top ten jobs”, *WorldWideLearn.com Copyright*, Quinstreet Inc., 2012.
[7] Miljko M.Eric.,2011, Some Research Challenges of Acoustic Camera, *19th Telecommunications forum Telfor*,Page(s):1036-1039
[8] Ulf Michel, “History of acoustic beamforming”, *Berlin Beamforming Conference (BeBeC)* 2006, 21-22. Nov.2006
[9] Tavner P.J., 2008, Review of condition monitoring of rotating electrical machines, *IET Electrical Power Applications*, Vol 2(4), Page(s): 215-247
[10] Orman M., Orkisz M., Pinto C. T., 2011, Slip Estimation of a Large Induction Machine Based on MCSA, *Diagnostics for Electric Machines, Power Electronics & Drives (SDEMPED),* IEEE International Symposium on, Bologna, pp. 568 – 572, 2011
[11] Orman M., Orkisz M., Pinto C. T., 2011, Parameter identification and slip estimation of induction machine, Elsevier, *Mechanical Systems and Signal Processing*, Vol 25, Page(s): 1408-1416
[12] S.Guidati, "Advanced beamforming techniques in vehicle acoustic",Berlin *Beamforming Conference (BeBeC)* 2010.
[13] C.Cariou, O.Delvedier "Localizing aircraft noise sources with large scale acoutic antenna" *27th International congress of the aeronautical sciences*
[14] J.S.Pascal, J.F.Li "Use of double layer beamforming antenna to identify and locate noise in cabins, *EURONOISE*, Finland, 2006
[15] Hans-Elias de Bree, Jelmer Wind, Erik Druyvesteyn, “Battlefield Acoustic", *Microflown ebook*, chapter 21
[16] Korpel Adrianus, “Acoustic imaging and holography”, *IEEE Spectrum*, Volume:5 Issue:10, pp. 45 - 52, 1968.
[17] Mueller, R.K. “Acoustic holography”, *Proceedings of the IEEE,* Volume:59 Issue:9, 1971
[18] Long Wu, “Separating Load Torque Oscillation and Rotor Faults in Stator Current Based-Induction Motor Condition Monitoring”, *Georgia Institute of Technology*, 2007.
[19] M.Mijic, D.Masovic, D.sumarac Pavlovic and M. Adnadevic, “A Model of Planar Microphone Array Realized with Low-cost Multimedia Microphones", *Telecommunications Forum (TELFOR)*, pp. 1040 - 1043, 2011