Usage of acoustic camera for condition monitoring of electric motors

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***Abstract*—The paper presents a method of analysis of electric motors based on acoustic measurements. Acoustic signals were measured by microphones arranged in circular shape array called acoustic camera. Measurements by acoustic camera allow localization of sound source and by that separate sounds of interests from background noise can be obtained. Typically acoustic camera measurements are accompanied by a photography associated with acoustic measurement scene which is used for mapping of sound sources on the monitored area. As a reference, acoustic analysis is compared with vibration measurements. Vibration signals were measured by piezoelectric accelerometers and data collector dedicated for condition monitoring of electric motors. As presented in the result section, acoustic analysis appears as a valuable technique for condition monitoring of electric motors even in noisy industrial environment.**

Keywords—induction machine; acoustic analysis; acoustic camera; sound source localization; vibration analysis

I. INTRODUCTION

Most of induction machine condition monitoring methods are based on analysis of electric current or vibration monitoring. Many methods exist that allow for analyzing of currents or vibration to identify fault type or just separate healthy machine from faulty one [1]. In most of industrial applications, the desired method for condition monitoring of electrical equipment is one which would not affect industry process - such methods are called passive methods. Passive methods of condition monitoring are using measured quantities and derive certain fault indicators [2]. These methods do not influence the actual operating condition of the electric motor, and therefore they are mostly desired in industrial application where any interruption in the manufacturing process can cause a serious financial loss. Those passive condition monitoring techniques are often also called non-invasive [2]. Methods which utilize current measurements are popular because many of fault types are easily visible in current spectrum [3]-[7]. However often in industrial application condition monitoring is required for large induction machine supplied by medium voltage. Due to safety reason it might be impossible for current sensors to be installed on cables with such a voltage level. On the other hand vibration analysis which is also a popular method for condition monitoring requires dedicated sensors to be attached to the body of the motor. Similarly it might often not be realistic in case were motor is not reachable. Additionally connecting vibration sensors to motor body is time consuming and it might be complicated in industry environment to attach sensor or sensors in proper place.

For many years the diagnostic in the industry was performed by human ear and subsequent assessment of the emitted sound. Method was popular in the past because often in the case of motor fault what site engineers were noticing was the machine abnormal sound. However this method requires highly experienced people since the quality of acoustic monitoring is very much dependent on the background noise of the environment the machine is operated in. 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 the 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 the industry environment. As it is shown in Global Employment Trend document [8] or in the list of the top 10 jobs forecast for next decade [9] this situation will be even more visible in the future. Availability of data collectors and sensors as accelerometers or current probes cause appearance of many condition monitoring systems based on those measurements and human-based acoustic analysis was no longer widely accepted in industry environment. However, still there is a necessity of doing the initial investigation of objects to localize the abnormal sound to pin-point the exact location where further analysis should be conducted.

Recently acoustic analysis has attracted more and more attention and it has been applied in many fields for example speech recognition, nevertheless still very rarely it is applied in industrial environment for condition monitoring purposes. In past few years there were some attempts to create a condition monitoring methods based on acoustic analysis [10]-[13] however the number of works related to acoustic analysis compared with the number of works related to analysis based on vibration or electric current is negligible. This shows that still acoustic analysis is not that popular in industry environment.

A variety of faults which can occur in induction machines, have been extensively studied and many monitoring methods have been proposed to detect problems [6]. The presented paper shows the possibility of utilization of acoustic camera for detection of faulty condition of electric motor. The work is focused on detection of static eccentricity as it is one of the

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most common faulty conditions of induction motor. Presented concept of acoustic based condition monitoring system is not limited to only induction machine and static eccentricity as it can be easily extended to other fault or machine types. Presented acoustic camera based measurements are compared with vibration analysis as a benchmark method.

II. ACOUSTIC CAMERA

Acoustic camera comprises an array of microphones arranged in a way so it is possible to localize the specific sound components and by that remove the influence of the background noise [14], [15]. The idea of acoustic camera is to do sound source identification, quantification and record a picture of acoustic environment by processing of multidimensional acoustic signals received by microphone array and to map the resultant acoustic picture to the video picture [14]. Acoustic camera is currently mostly used in automotive industry however there are many applications for non-destructive measurements for sound identification in interior as well as exterior [14]-[19]. Recently the availability of multichannel low-cost data collectors allowed building acoustic cameras which in terms of price can be competitive with the more popular measurement techniques. In this work circular shape acoustic camera with video camera localized in center was used for sound measurements. Parameters of the microphone are presented in Table 1.

TABLE I. ACOUSTIC CAMERA MICROPHONE CHARACTERISTIC

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

III. SOUND SOURCE LOCALIZATION ALOGRITHM

For the analysis of sound source beamforming technique can be used. Beamforming technique is a method that is used to estimate the sound field in a distance from 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 [20] and [21], while the current chapter outlines only the basic principles.

Fig. 1 presents a schematic illustration of main principle of acoustic camera. As one can see the sound source 1 is exactly in the center of the video camera view. The distance between microphone 1 and microphone 2 from sound source 1 is equal (*d1* = *d2*). This means sound wave phase *φ1* will be equal to sound wave phase *φ2*. In case of sound source 2 distance *d4* to microphone 2 is smaller than distance to microphone 1 *d4* which means there will be difference in sound wave phases *φ3* and *φ4* between microphones 1 and 2 because sound wave will reach microphone 2 earlier in time than microphone 1.

Shift introduced by distance can be computed based on wavelength of given frequency according to the following formula:

$$\varphi_k = \frac{d_k \cdot \lambda}{\lambda} * 2\pi \qquad (1)$$

Where, k is integer number, $\lambda = \frac{v}{f}$, ν is sound speed and f is frequency of interests. This means that phase of frequency of interest from each microphone needs to be calculated in order to estimate the position of the sound source. It is easy to notice that if there is no phase shift between sound waves of each microphone the sound source is located in the center of camera view. In case when electric motor is a sound source of interest, it will typically emit stationary signal so the frequencies are constant in time. This is especially true in case of electric motor supplied direct-on-line. Calculation of phase of signal which is stationary is trivial and can be conducted by many methods [22].

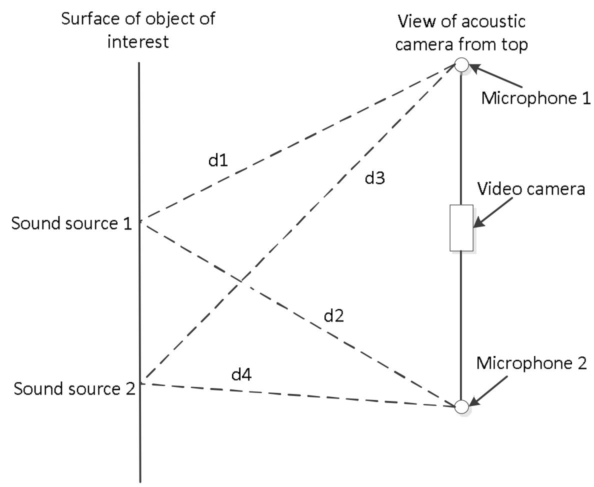


Fig. 1. View of acoustic camera from top, schematic ilustration of principale of acoustic camera

Localization of the sound source allows separation of the sound of object of interest from the background noise which is always present in industry environment. Paper [10] presents method where before operating the induction machine, a measurement of just the background noise is conducted. The spectrum of this measurement is later subtracted from the measured spectrum with the induction machine in operation. At the same time separation of sound source by acoustic camera does not influence the process in any way which makes presented method much more desirable in industry.

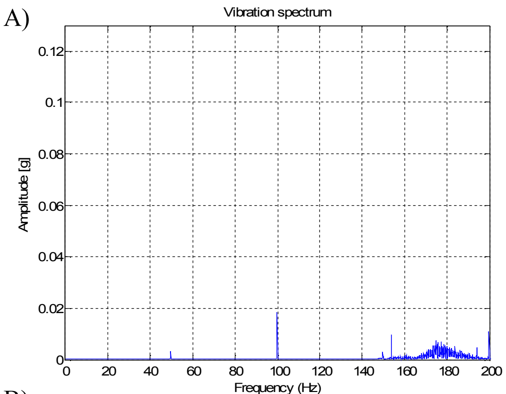
IV. EXPERIMENTAL MEASUREMETNS AND ANALYSIS

A. Vibration measurements and analysis

Vibration analysis is a popular method for condition monitoring of electric motors and is well accepted by the industry society. Because of that and because vibration signals are relatively similar to acoustic signal they were used as a reference for assessment of the value of acoustic measurements. Typically vibration signals are measured by piezoelectric accelerometers. In this work vibrations were collected by ABB MACHsense-P - portable condition monitoring tool dedicated for analysis of electric motors.

As a test case two motors of same type were use. Motor 1 was considered to be healthy while motor 2 was a known static eccentricity case. Both motors were running at the same operating condition: 75% of load, driving centrifugal pumps. Nameplate parameters of motors are presented in table 2 in appendix. For both of the cases vibration sensors were located horizontally on the center of the body of the motors. Fig. 2A presents vibration spectrum of healthy motor case while Fig. 2B presents vibration spectrum of static eccentricity case. Typically static eccentricity can be visible in low frequency range therefore both figures are zoomed into frequencies from 0 Hz to 200 Hz.

A)



B)

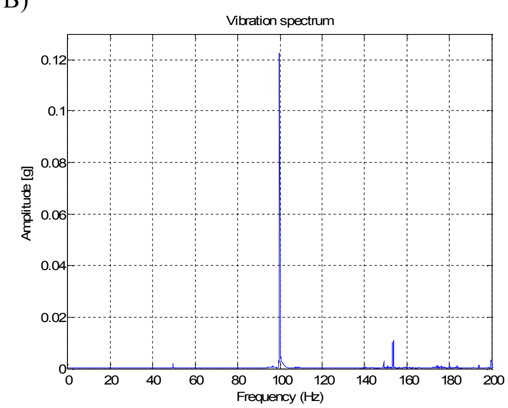


Fig. 2. A – vibration spectrum for healthy case; B – vibration spectrum for static eccentricity case.

According to work [12] static eccentricity results in additional forces visible in vibration at frequency equal to twice the powers supply:

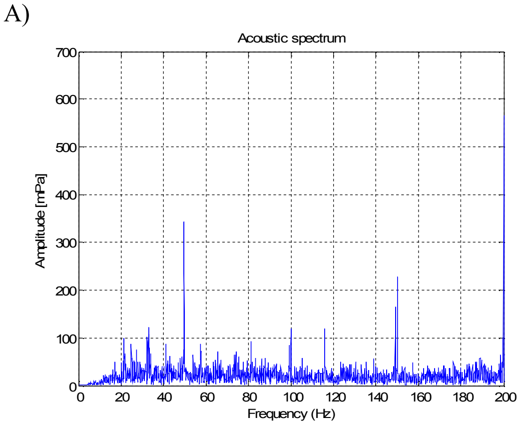
$$f_{ecc} = 2 \cdot f_{line} \tag{2}$$

where f_{line} is power supply frequency. In the presented case, both motors were supplied by 50 Hz, which results in $f_{ecc} \approx 100Hz$. As it is visible in Fig. 2A and Fig. 2B both motors generate a peak at f_{ecc} frequency. Value of f_{ecc} related peak in case of static eccentricity (Fig. 2B) is above 0.12 g's, while in case of healthy motor (Fig. 2A) this peak is smaller than 0.02 g's. The amplitude of f_{ecc} frequency is a commonly used static eccentricity indicator. ABB MACHsense-P portable condition monitoring system is isolating frequency of interest in a similar way as described in paper [5]. Calculating in automatic way motor eccentricity level based on f_{ecc} frequency is one of many embedded functionalities of ABB MACHsense-P.

B. Acoustic measurements and analysis

For both motor cases acoustic camera was located 0.5 m from the motor body pointing towards its center. Fig. 3 presents acoustic spectrum of average signal from microphones array. Fig. 3A presents acoustic spectrum of healthy motor case while Fig. 3B presents acoustic spectrum of static eccentricity motor case. Both figures are zoomed in for frequencies range from 0 Hz to 200 Hz so the f_{ecc} frequency should be visible in center of figure. Similar as in vibration cases in Fig. 3B static eccentricity related frequency f_{ecc} is much higher than in the case of healthy motor from Fig. 3A. Value of f_{ecc} frequency related peak is above 600 mPa, while on the Fig. 3A this peak is smaller than 350 mPa. Therefore this it is possible to say that comparison of f_{ecc} frequency in acoustic spectrum can be used as an indicator of static eccentricity in a similar way as in case of vibration analysis.

A)



B)

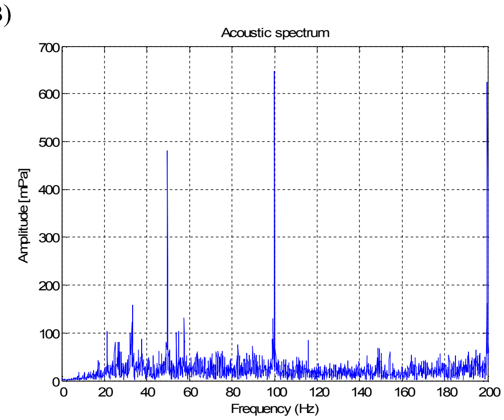


Fig. 3. A – acoustic spectrum for healthy case; B – acoustic spectrum for static eccentricity case.

A general limitation inherent in majority of acoustic monitoring methods is that there is no certainty of the origin of frequency of interest. Acoustic camera however gives the opportunity to localize the noise source and by that visualize that the frequency of interest comes from motor not from its background. For the measurements of faulty motor the biggest difference in phase of 100 Hz between microphones was 6×10^{-5} radians. For camera of 75 cm diameter and distance of half meter from object this indicates a negligible shift of sound source from the center of the camera view. In Fig. 4 there is a graphical illustration of results of 100 Hz sound source location by beamforming algorithm.

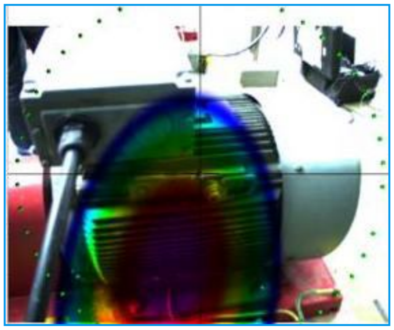


Fig. 4. Visualization of sound source

Sound intensity of 100Hz is marked by the color and as it is easy to notice that the highest amplitude comes from motor body, which means that this particular frequency is not caused by any background noise but its origin is motor itself.

V. Conclusion

In this paper, an acoustic based technique for condition monitoring of electric motors was presented. Acoustic measurements were performed by circular shape acoustic camera. Vibration analysis was used as a reference for assessment of the value of acoustic measurements. Two induction motor cases were examined – healthy motor case and rotor static eccentricity case.

The presented results may suggest that acoustic signals can be successfully used for condition monitoring of electric motors in noisy industrial application. Presented acoustic analysis can be performed quickly due to the fact that acoustic sensors do not need to be located directly on motors, which sometimes is difficult to achieve in industrial applications. Additionally diagnostic system based on acoustic camera solves directly the most often reported problem – find the source of abnormal noise.

The authors consider the presented method as a powerful tool which can significantly improve the ease of any known existing diagnostic technique of the electric motors

Appendix

TABLE II. Nameplate parameters 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

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