3D printed acoustic camera for electric motor diagnostics

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Abstract - **This paper focuses on the aspect of performing acoustic analysis for the purpose of electric motors diagnostics. The measurements are performed in noisy industrial environment with the use of a dedicated acoustic camera build by ABB. The acoustic camera comprises a set of microphones arranged in a pre-defined, carefully designed and manufactured shape. The great advantage of acoustic cameras is the sound measurements can be used to pin-point the exact location of the sound source in a monitored scene. This, in turn allows for the frequencies of interest to be separated from the background noise. The paper presents the result of comparing the acoustic camera outputs from two induction motor – a healthy motor and a motor suffering from a broken rotor bar fault. The presented results show that the acoustic camera is capable of detecting the characteristic electric motor fault and robustly localize it in space, which proves its robustness even in noisy industrial environment.**

Keywords- condition monitoring, induction motor, broken bar, acoustic analysis, acoustic camera, sound source localization

1. Introduction

Most of the 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 the accompanying industry process - such methods are called passive methods. These methods of condition monitoring utilize the measured quantities and, as a result of processing them, derive certain fault indicators [2]. These methods do not influence the actual operating condition of the monitored motors, and therefore they are mostly desired in industrial application where any interruption in the manufacturing process can cause a serious financial loss. These passive condition monitoring techniques are often also referred to as non-invasive [2]. Methods which utilize the measurement of the electric currents for the purpose of electric motor condition monitoring are popular because many of fault types are easily visible in electric 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. At the same time vibration analysis, which is also a popular method for motor condition monitoring, requires dedicated sensors to be attached to the body of the motor. Similarly it might often not be feasible in a case were motor is not physically reachable. Additionally connecting the vibration sensors to the body of the motor is time consuming and it might be complicated to attach sensor or sensors in proper place in the industrial environment.

For many years the diagnostics in the industry has been performed by human ear and subsequent assessment of the nature of the emitted sound. However this method requires the expertise of highly experienced technicians since the quality of acoustic monitoring is very much dependent on the background noise of the environment the machine is operated in. Also the condition of the motor might often deteriorate to a severe fault until the awaited sound becomes clearly audible. Today’s trends in the job market lead to situation where there is a continuously decreasing number of people who are experienced enough to judge the condition of the object by listening to the sound of it. It is a result 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. The advent of widely available data acquisition units and sensors such as accelerometers or current probes, decreased the need as well as acceptance of human-based acoustic analysis in industry environment. However, there is a constant necessity of performing the initial investigation of objects in order 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 the analysis based on vibration or electric current is negligible. This shows that still acoustic analysis is not that popular in the industrial applications.

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]. This paper shows the possibility of utilizing the acoustic camera for detection of faulty conditions of electric motor. In this document the cases of healthy motor and a motor with a broken rotor bar fault are compared and discussed.

2. Measurement tools

Acoustic camera principle

The idea behind the acoustic camera is to perform sound source localization based on a number of simultaneously recorded acoustic signals. The phase relationships between the acoustic signals are analyzed and the resultant localization of the sound source is mapped on a photography of the monitored scene. Acoustic camera itself represents just one stage in long history of microphone array technology development [14]. Possible applications of acoustic camera as test equipment include nondestructive measurements for noise/sound of road vehicles [15], trains and airplanes [16], [17], quantification of industrial noise [18], measurement of wind turbines [18], acoustical sensing in battlefield [20], obtaining acoustic images of seafloor hydrothermal flaws [21], underwater unmanned vehicles [20] and even observation of marine fauna [23].

Sound analysis can be an important quality aspect of condition monitoring tool. When faults in machinery and plant installations occur, they can often be detected by a change in their noise emissions. In this way, acoustic camera replaces the human ear into an automated listening process and the results are more likely to be subjective. Current acoustic camera-based systems are in a form of portable systems which can be used to visualize sounds and their sources. Maps of sound sources that look similar to thermo graphic images are created within seconds. Noise sources can be localized rapidly and analyzed according to various criteria. An acoustic camera consists of some sort of video device, such as a video camera, and a series of sound pressure measuring devices, such as microphones, sound pressure being s usually measured in units of Pascal. The microphones are normally arranged in a pre-set shape and precisely designed position with respect to the camera.

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 [24] and [25] 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. 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 [26].

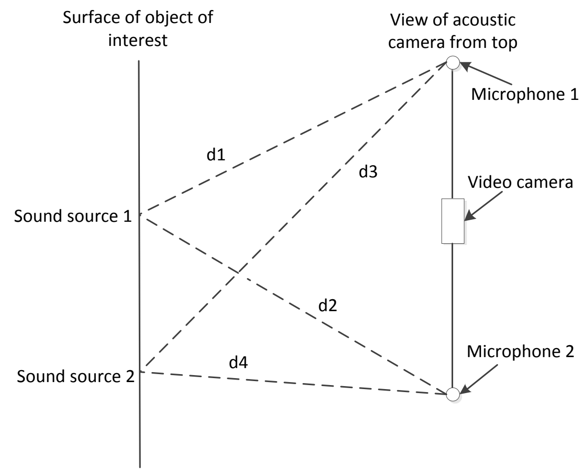


Fig. 1 View of acoustic camera from top, schematic illustration of principles of acoustic camera

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.

Acoustic camera design

Acoustic camera developed in ABB Corporate Research Center was designed in SolidWorks and printed with a 3D printer. The device is based on a circular shape with microphones positioned on its perimeter. There are 8 evenly spaced microphones (distanced at π/4). Each microphone is placed inside a dedicated slot inside of the device casing. All microphones are at a same distance from camera center and all of them are in the same plane. Microphone diameter is 4.75 mm. In addition to the circular front, the camera casing contains a pipe to lead the cables which is also can work as handle. The handle can be connected to a tripod for more stable measurements.

The drawing of the camera design is presented in Fig. 2a), while Fig. 2b) presents photography of 3D printed and assembled camera.

a)

b)

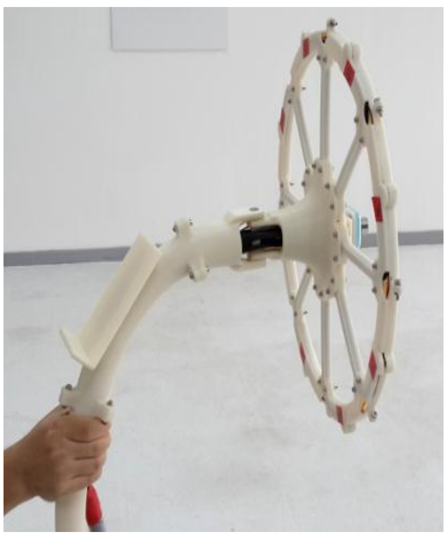


Fig. 2 a) Acoustic camera design – front view. B) 3D printed and assembeld acosutic camera.

3. Measurements analysis and comparison

The presence of broken rotor bar or end ring, causes an unbalance to the rotor magnetic flux, as the current cannot flow through the broken or cracked bar/end-ring. The unbalanced rotor flux can be considered as the combination of positive- and negative-sequence rotor flux, rotating at slip frequency in the opposite directions. It is well know that this results in modulation of current which can be visible in current spectrum as a twice slip sidebands around the line frequency. However it is also known that the broken bar results in sidebands around harmonics of rotation speed in vibration signal. In this chapter a healthy motor case will be compared to a case of a motor with broken rotor bar.

Both motors used as objects of interest were three-phase induction machines of the same type. Nameplate details of motors are presented in Table 1.

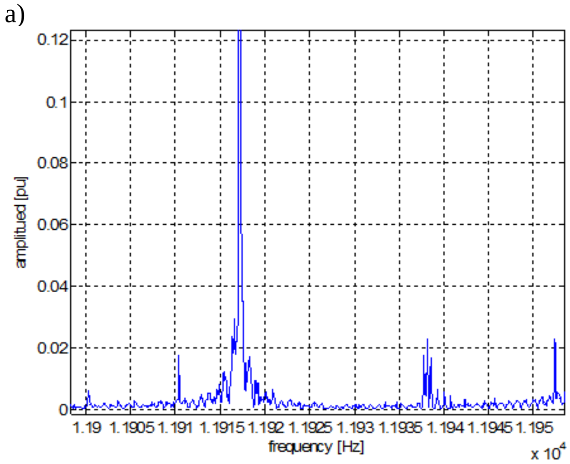
Both motors were operating in exactly the same conditions and environment. Both motors were supplied by variable-frequency-drive. Supply frequency set up by drive was 21 Hz and motors were running at full load.

TABLE I. NAMEPLATE OF MOTORS

Parameter	**Value**
Active power [kW]	0.37
Nominal voltage [V]	230
Nominal current [A]	2.2
Nominal power factor [-]	0.697
Nominal speed [rpm]	2850
Number of poles per phase winding [-]	2
Nominal frequency [Hz]	50

Fig. 3 presents comparison of acoustic spectrum of healthy motor case and faulty one recorded by one of the acoustic camera microphones

a)



b)

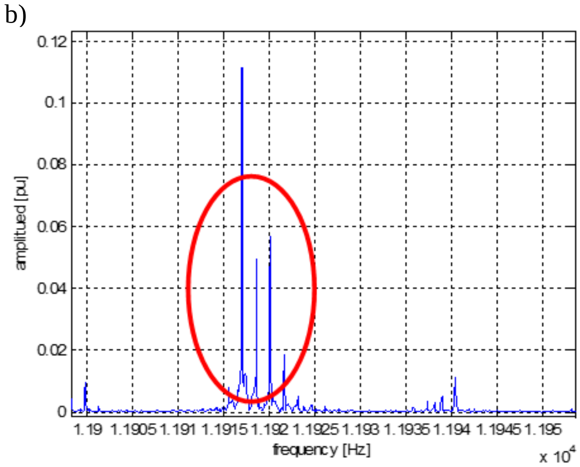


Fig. 3 a) Acoustic spectrum of the healthy motor (a) and the motor with the broken rotor bar (b)

On the contrary in the case of the broken rotor bar the spectrum contains some clearly visible sidebands around the rotational speed harmonics equal to twice the slip (marked by red ellipsis on Fig. 3b). The appearance of these sidebands is a well-known indication of broken rotor bar. A general limitation inherent in the majority of acoustic monitoring methods is that there is no certainty as to the physical origin of the 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 and not from its background.

Fig. 4 and Fig. 5 present the results of sound source localization performed by ABB acoustic camera.

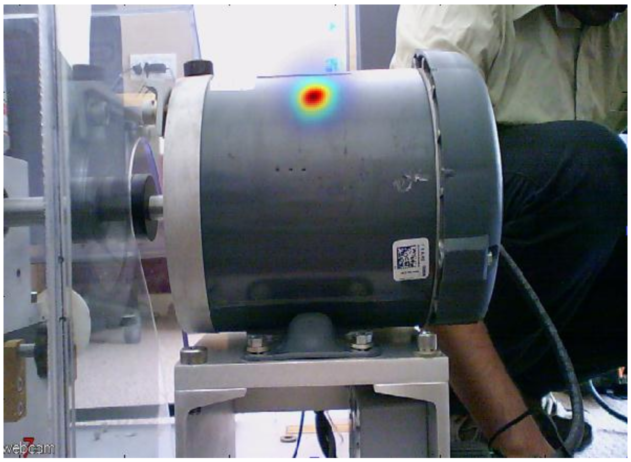


Fig. 4 Localization of frequency components related to broken rotor bar (harmonic of rotor speed + 2 slip frequency)

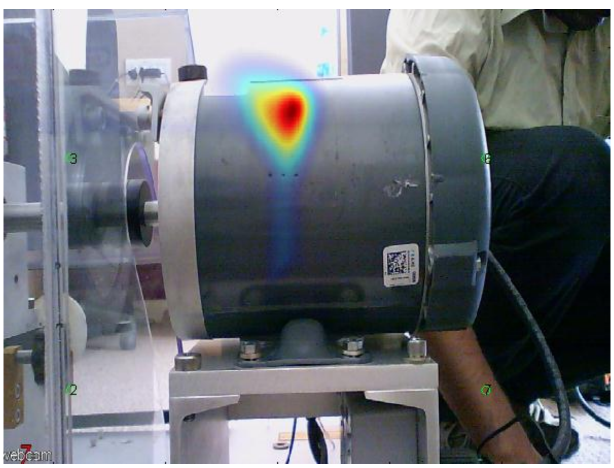


Fig. 5 Localization of frequency components related to broken rotor bar (harmonic of rotor speed + 2 slip frequency)

As it is possible to notice the sound source was localized as originating from the body of the motor in both cases, which means that this particular frequency is not caused by any background noise but it originates from the motor itself.

4. Conclusions

In this paper, an acoustic based technique for condition monitoring of electric motors was presented. Acoustic measurements were performed by low cost circular shape acoustic camera. The entire process from the design stage up to the manufacturing of acoustic camera has been performed in-house.

To show the potential of acoustic camera it was used as a tool for diagnostic of electric motors. Two induction motor cases were examined – healthy motor case and rotor broken bar case. The presented results may suggest that acoustic signals can be successfully used for condition monitoring of electric motors even in noisy industrial application. It has been shown that the frequency of interest is located in the most probable location, in this case at the body of electric motor. 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.

The advent of the 3D printing technique makes it possible for virtually any element of relatively simple design to be created in non-industrial environment. Even though the accuracy of the resultant measurements might be slightly lower compared to the off-the-shelf products, the trade-off between the price and the required precision might often tilt the balance in the cost-saving direction

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