ICSV14
Cairns • Australia
9-12 July, 2007
14th International Congress on Sound & Vibration

AN INVESTIGATION INTO THE FAULT DETECTION OF MACHINES BASED ON ACOUSTIC ARRAY SYSTEMS

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Abstract
Acoustic condition monitoring (CM) has a number of significant merits such as remote measurement and rich information content. In recent years it has been gaining increasing attention because of the rapid development in sensing and processing methods for interference noise suppression and demands for accurate CM. In this paper, a new acoustic detection scheme is investigated based on array technology. The scheme uses only a small number of microphones (about 5), which is easy and realistic to implement in CM, compared with conventional array applications. The capabilities of different small array configurations are studied theoretically in terms of detection accuracy and potential diagnosis capabilities. Numerical simulations have shown that a 5-sensor tetrahedron array produces high accuracy for source identification and fault detection. Based on this array configuration, an acoustic CM system is developed and embedded with array technologies, advanced signal processing and pattern recognition. Experimental results show that this system has a great potential in detecting machine faults in an industrial environment.

1. INTRODUCTION

Condition monitoring (CM) provides necessary techniques to prevent unexpected breakdowns including catastrophic accidents and thus to promote the economical benefits for industry. Many effective approaches [1, 2] have been investigated and utilised in industry. Among these approaches, airborne acoustic related methods [3-7] have been paid an increasing amount of attention recently, due to their remarkable merits, including information richness, remote measurement, low cost sensing system and high dependency on modern signal processing technologies. Many projects were carried out to make use of these merits and showed the effectiveness of acoustic CM methods, such as those conducted by Boeing and Rolls-Royce, which intend to diagnosis faults of various engines by acoustic signals [5, 6, 8].

Most of the previous investigations are based on an assumption that the location of the source is known in advance and then the fault detection and diagnosis is conducted by finding the changes in the source [5, 6]. Unfortunately, the source location is often unknown in most of the practical applications especially when an unexpected fault occurs. This means that the

* Partially supported by NSFC project 60654002

techniques developed may not be so generic for a wide variety of applications.

In this study a novel acoustic CM scheme is investigated based on a microphone array system to achieve both the localisation of the sound source and the enhancement of the desired signals for condition monitoring. For this purpose four key tasks will be conducted :1) to gain knowledge of the acoustic characteristics of the machine at both healthy and faulty operation; 2) to develop source localisation techniques based on an small array system; 3) to enhance acoustic signals using array beam-forming according to the pre-localisation result; and 4) to perform fault diagnosis using acoustic signals. Among these tasks, array based accurate localisation is the most critical one because all the subsequent processes that are based on its result.

According to CM practice, array development must consider the following special requirements.

- Easy implementation;
- Good localisation performance in near field conditions (2 to 10m from the source);
- Implementation in a full 3-D space;
- Robustness to noise including reverberant influences;
- Powerful signal processing capability;
- Remote measurement;
- Real time implementation in some special cases; and
- Minimal cost.

Based on these requirements, a new scheme is proposed to use a small scale acoustic array (SSAA) in which the knowledge of the source characteristics is embedded with advanced signal processing techniques. The SSAA system will confine its sensor number to 4 or 5 which is the minimum required in theory to locate the source in a 3-D space. The data acquisition for these sensors can be achieved easily by a common 8-channel data acquisition board and a PC at reasonable cost. However, it is difficult to match the accuracy of localisation with a large number of sensors because such array systems ensure the accuracy by using a large number of sensors to gain the benefit of information redundancy. The work reported in [9] focused on this subject and can only provide an acceptable level of accuracy in the far field condition which is about 50m away from the sources, where usually these conditions can not be met in CM applications.

Although some noise suppression methods and pre-knowledge of machine sources can be applied to enhance the signal to noise ratio and hence possibly to improve the localisation accuracy, two main sources may degrade the performance of SSAA significantly. These two sources are the configuration of the array system and the error of time delay estimation (TDE). TDE is one of the most popular subjects of signal processing and has been investigated for years[10]. Comparatively, little attention has been paid to the analysis of array configurations. This should not be neglected however as an unsuitable array configuration may magnify the error of TDE, especially when a small scale array system is employed. Therefore, the focus of this paper is on the analysis of array configurations to build theoretical basis for SSAA systems.

The rest of this paper is structured as follows. In the second section, a theoretical analysis of SSAA configurations is presented. A 5-sensor array system is mainly discussed. In the third section, a numerical simulation is conduct to test the accuracy of different configurations. In the fourth section, an initial experiment is conducted to show the potential of array based CM systems. A summary will be presented in the fifth section.

2. THEORETICAL ANALYSIS OF ARRAY CONFIGURATIONS

In practice, it is difficult for a SSAA system to achieve accuracy in locating a source obtained by a large scale array system consisting of a large number of sensors such as 64. However, its development has still interested researchers recently due to its distinctive merits such as easy use and low cost implementation. This interest is further increased with the recent advances in sensor and signal processing which is providing more potential to develop a SSAA system with good accuracy. In particular, a 4-sensor cross array and a 4-sensor tetrahedron array were investigated in [9, 11]. Also a number of the latest algorithms in adaptive calculations and subspace decompositions have been used to improve the accuracy in time delay estimation. The results in tracking moving objects such as different vehicles and localising special acoustic sources such as explosions are very promising.

In theory, a 4-sensor cross array can be applied in only half the space which is partitioned by the plane where the array is fixed in. Its performance is poor when the elevation is larger than 75°. However, with a 4-sensor tetrahedron array the localisation of sources is likely to be achieved in the whole 3-D space. Unfortunately, it can not develop a complete equation set for solving the necessary unknowns in a space. Some simplifications must be introduced in solving the equations. These simplifications may lead to a large error in source location. This is particularly true in the near field conditions where CM is concerned.

Therefore, based on previous investigations, a SSAA consisting of 5 sensors is advocated in this paper. A 5-sensor array owns a complete set of localisation equations and can be applied in a full 3-D space. These theoretical advantages make it much more promising for the application of CM. To show these advantages this section conducts a detailed analysis of several candidate array configurations with just 5 sensors.

2.1 Configurations for 5-snesor Array

There are many possible configurations with 5 sensors in space. For easy construction and simple computation three candidate configurations are studied. As shown in Figure 1 they are referred to as T-shape, diamond shape and tetrahedron shape respectively. As shown in the figure, these configurations have the following features: (1) sensors are distributed around a spherical surface as uniformly as possible; (2) the distance between each sensor to the centre of array is kept the same apart from the tetrahedron configuration and (3) the sensors are arranged to be symmetric to the centre or around a particular axis These features. help to develop localisation formulas and to obtain an analytic expression for accurate analysis.

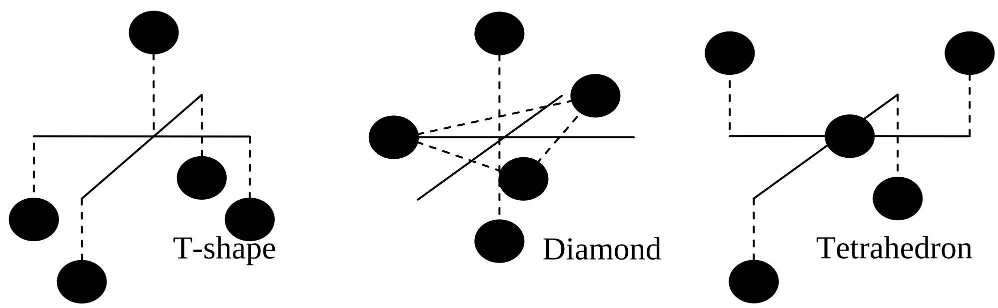

Figure 1. Different configuration shapes for a 5-sensor array

2.2 Localisation Formulas for 5-sensor Array

In spite of the difference in sensor positions, the localisation equations can be developed uniformly. For one of the configurations, Figure 2 shows the details of the sensors distributed in the reference space. 5 sensors are positioned at $S_1\ (x_1, y_1, z_1)$, $S_2\ (x_2, y_2, z_2)$, $S_3\ (x_3, y_3, z_3)$, $S_4\ (x_4, y_4, z_4)$ and $S_5\ (x_5, y_5, z_5)$. Assuming a source is located at $P\ (x, y, z)$, it can be represented by an elevation θ, azimuth φ and radius R. R_i is the distance between the source P and ith sensor S_i. d is the diameter of the array.

Based on the geometrical relationship shown in Figure 2, the following equations can be derived .

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = R_i^2 \quad (i = 1, 2, 3, 4, 5) \tag{1}$$

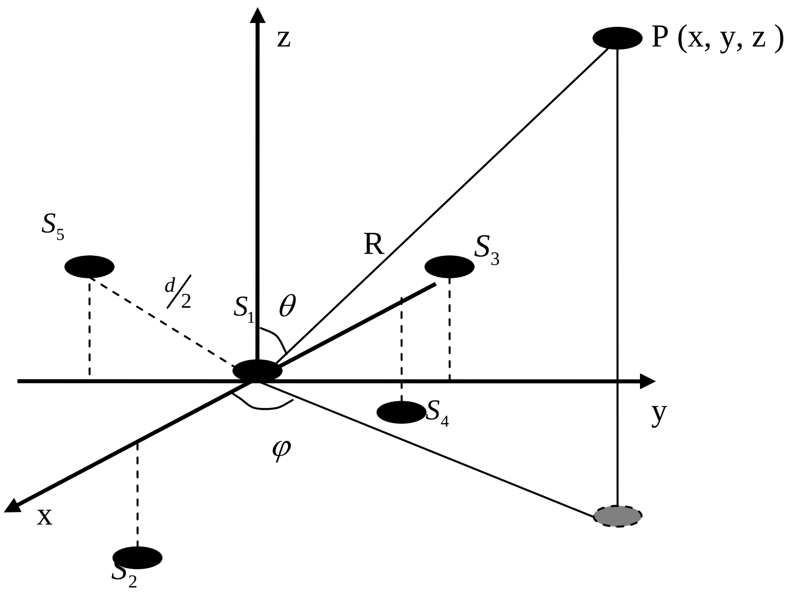

Figure 2. 5-sensor tetrahedron array configuration

Taking S_1 as a reference sensor, R_i in (1) can be replaced by

$$R_i = R_1 + ct_{i1} \tag{2}$$

where t_{ij} is the time delay between the ith and the jth sensor, c is the speed of sound.

Subtracting ith equation by the 1st equation in (1) forms equation set (3):

$$AL = C \tag{3}$$

where,

$$A = \begin{bmatrix} 2(x_1 - x_2) & 2(y_1 - y_2) & 2(z_1 - z_2) & -2ct_{12} \\ 2(x_1 - x_3) & 2(y_1 - y_3) & 2(z_1 - z_3) & -2ct_{13} \\ 2(x_1 - x_4) & 2(y_1 - y_4) & 2(z_1 - z_4) & -2ct_{14} \\ 2(x_1 - x_5) & 2(y_1 - y_5) & 2(z_1 - z_5) & -2ct_{15} \end{bmatrix} \tag{4}$$

$$L = \begin{bmatrix} x & y & z & R_1 \end{bmatrix}^T \tag{5}$$

$$C = \begin{bmatrix} c^2 t_{21}^2 - (x_2^2 + y_2^2 + z_2^2) + (x_1^2 + y_1^2 + z_1^2) \\ c^2 t_{31}^2 - (x_3^2 + y_3^2 + z_3^2) + (x_1^2 + y_1^2 + z_1^2) \\ c^2 t_{41}^2 - (x_4^2 + y_4^2 + z_4^2) + (x_1^2 + y_1^2 + z_1^2) \\ c^2 t_{51}^2 - (x_5^2 + y_5^2 + z_5^2) + (x_1^2 + y_1^2 + z_1^2) \end{bmatrix} \tag{6}$$

The location of sound source $P\ (x, y, z)$ can then be obtained by solving (3).

Based on the theoretical analysis, the accuracy of localisation is fluctuating with the geometrical parameters and the time delay estimation. However, their standard deviations are difficult to express in a simple format for analysis due to the complexity of the formulas. Therefore, a numerical study has to be carried out to find the performance of the array configurations in locating the source.

3. NUMERICAL STUDY

Due to the complexity of the expression, it is difficult to compare the errors of different array configurations by the theoretical error analysis result. In order to show the influences of the errors for various array configurations, the error of localisation is defined as the Euclidean distance between the true source position and that predicted by the array:

$$\delta = \left\| P_{predicted} - P_{true} \right\| \tag{7}$$

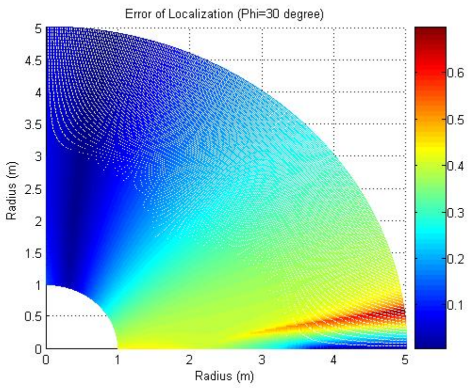

Figure 3. Error of localisation
(azimuth=30° , 4-sensor cross array)

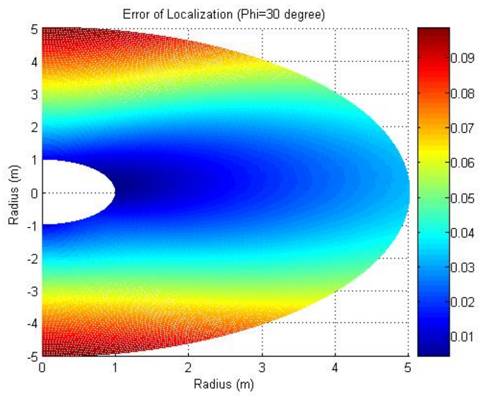

Figure 4. Error of localisation
(azimuth =30°, 5-sensor tetrahedron array,)

Figure 3 and 4 show the localisation errors of a 4-sensor cross array and a 5-sensor tetrahedron array when the azimuth angle of the predicted source is equal to 30° and the time delay is given with an error of 1% which is the normal value of TDE. The 4-sensor cross array can only be used in a half 3-D space and the localisation error increases sharply when the elevation is larger than 75°. The mean error is around 0.3m. However, the 5-sensor tetrahedron array can be used in the entire 3-D space with a mean error of 0.05m. Its maximum error is no more than 0.1m.

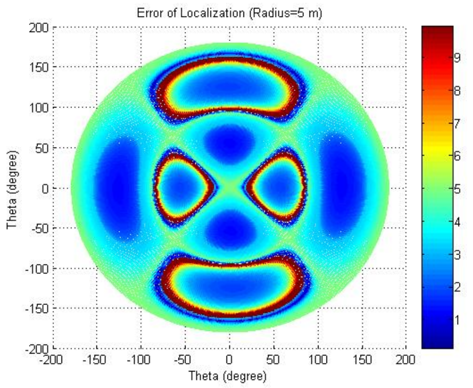

Figure 5. Error of localisation
(radius=5m , 4-sensor tetrahedron array)

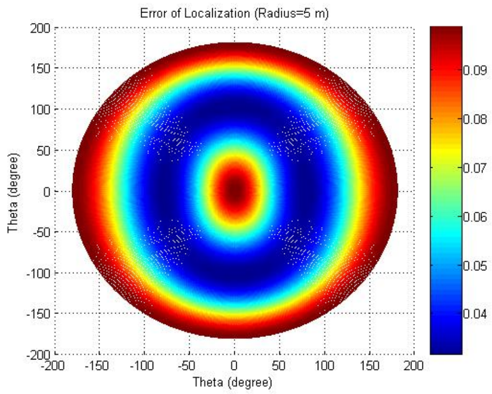

Figure 6. Error of localisation
(radius =5m, 5-sensor tetrahedron array,)

Figure 5 and 6 show the localisation errors of a 4-sensor tetrahedron array and a 5-sensor tetrahedron array when the radius of the predicted source is fixed at 5m. Despite the error fluctuation in different directions, the error of a 4-sensor tetrahedron array is far larger than that of 5-sensor tetrahedron array. The mean error of the 4-sensor tetrahedron array is larger than 3.8m, even if the peaks which are larger than 10m have been eliminated. That means the 4-sensor tetrahedron array can not provide an acceptable localisation result in the near field condition, though it performs well in far field conditions as shown in [9].

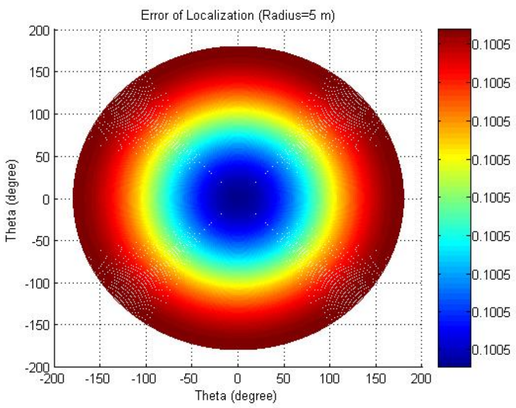

Figure 7. Error of localisation
(radius=5m , 5-sensor T-shape array)

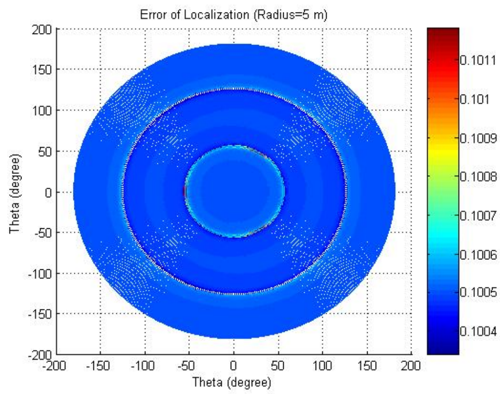

Figure 8. Error of localisation
(radius=5m , 5-sensor diamond array)

Figure 7 and 8 show the localisation errors of a 5-sensor T-shape array and a 5-sensor diamond array when the radius of a source is 5m and the error of time delay is 1%. The error of a 5-sensor T-shape array has some extreme peaks when the azimuth angle is equal to 45°, 135°, 225° and 315°. Also for a 5-sensor diamond array the error of localisation has extreme peaks when elevation equals 57° and 127°. Despite these extreme values, the error fluctuation of a T-shape array and a diamond array is far less than tetrahedron array. However, the mean error values of these two arrays are even larger than the maximum error of the tetrahedron array.

It is obvious that the localisation error of different configurations is also influenced by the error of time delay. When the error of time delay is increasing from 0 to 10% of the real value, despite the 4-ssensor tetrahedron array which is not applicable for near field conditions, the error changes of the other 4 configurations are shown in Figure 9. Although the 4 errors increase respectively, the 5-sensor tetrahedron array seems perform best to suppress the error of time delay.

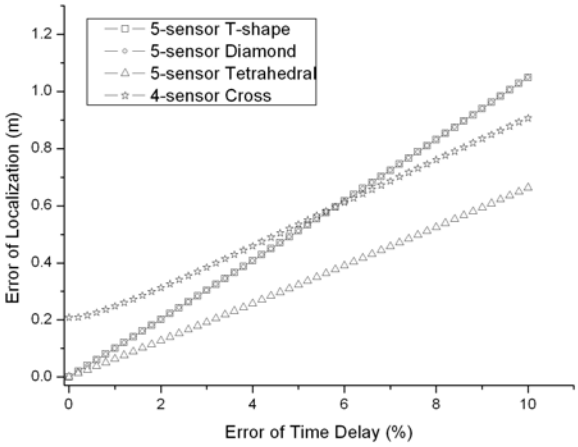

Figure 9. Errors of different configurations (Radius=5m)

Figure 10. Experimental facilities

As a result of the simulation, a 5-sensor array performs better than a 4-sensor array especially in the near field condition. Among the three 5-sensor array shapes, the tetrahedron array performs the best. The 5-sensor tetrahedron array is not disturbed by the extreme values and owns a low localisation error in the desired area. It can satisfy the demands of CM and is suitable to be used to establish a novel CM scheme.

4. EXPERIMENTAL RESULT

According to the results of theoretical and numerical studies, experiments were conducted based on a 5-sensor tetrahedron array. 5 high accuracy microphones were used to take the acoustic information from a weak reverberant environment (T60=0.15s) with a SNR of 12.3 dB. The data was acquired by a NI 4472 DAQ board. A recorded noise of diesel engine running at 2500 rpm was replayed as the sound source by a speaker which is positioned at 2.11m in radius, 100.35° in elevation and 24.8° in azimuth, away from the centre of the array. The experimental facilities are shown in Figure 10. In this initial experiment, due to the characteristics of sound source and simplicity of the measurement environment, a bandwidth filter and generalised cross correlation method in signal processing was employed and can provide an acceptable result. A PHAT algorithm was used to estimate the time delay between microphones. The localisation results are shown below.

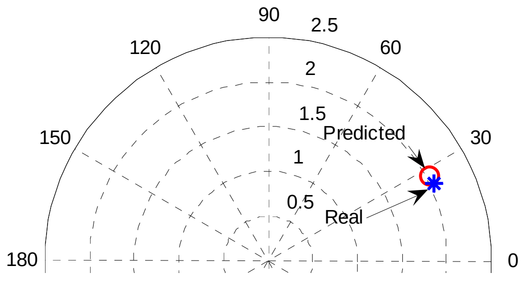

Figure 11. Localisation result (Radius × Azimuth)

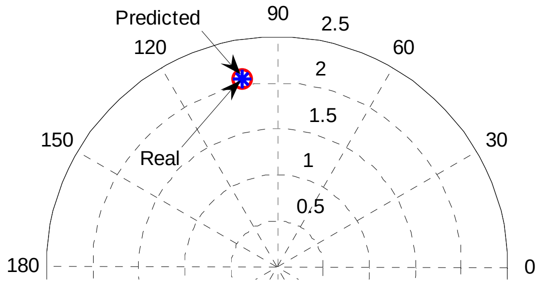

Figure 12. Localization result (Radius × Elevation)

The results show that the predicted position has a difference in distance of 0.03m with the real position. This error is caused by 1) the measurement error of practical microphone locations; 2) the nature phase delay between any two of those 5 microphones; and 3) the accuracy of time delay estimation algorithms. From these 3 factors, the last is the most important since the accuracy of localisation will increase sharply with the decrease of TDE error. Therefore the investigation of accurate TDE method will be the focus of the next step.

5. CONCLUSIONS

A novel machine condition monitoring and fault diagnosis scheme based on a small scale acoustic array system is studied in this paper. It focused on the analysis of different SSAA configurations, which is one of the key factors causing the localisation error. 5 different small scale array configurations, including a 4-sensor cross array, 4-sensor tetrahedron array, 5-sensor T-shape array, 5-sensor diamond array and a 5-sensor tetrahedron array, are introduced. The localisation formulas of the 5-sensor array are derived from the geometrical relationships. Based on the numerical simulation results, accuracy of the 5 array configurations was fully analysed and compared. The results show that the error of the 4-sensor array is far larger than that of the 5-sensor array especially in the near field condition. The 5-sensor tetrahedron array has the best performance compared to the other four different array configurations. A preliminary test was conducted with a basic correlation algorithm in a common environment. It has produced source localisation results with less than 1% error in the entire 3-D space, which is suitable for condition monitoring purposes.

In addition to the array configuration, error of time delay estimation is also an important factor influencing the accuracy of localisation. The accurate time delay estimation method needs to be further investigated. The signal enhancement algorithms which are used to suppress the noise and reverberation of environment also need to be taken into account in the future.

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