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FAULT IDENTIFICATION AND LOCALIZATION FOR MOVING WHEELS BASED ON DE-DOPPLERIZATION BEAMFORMING KURTOSIS METHOD

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ABSTRACT

During the railway system operating, impact noise can be generated due to the fault on the surface structure of the wheels, but it is often very difficult to determine the position of fault in real-time. In this paper, a fault detection approach is proposed to identify and localize the wheel with different kinds of fault with the interference of wheel without fault and high background noise during the rolling movement. In such cases, the impulsive signal generated by fault is totally merged in rolling and background noise. Time-domain beamforming with de-dopplerization is used to accomplish moving sources localization and beamforming kurtosis is used to search for the temporal feature and as an indicator of the impulsive signals. Since the beamforming kurtosis can extract the impulsive feature from original signals and locate the position of specific sound source, the location of the wheel with fault can be identified and localized by observing the sound map of beamforming kurtosis.

1 INTRODUCTION

In the modern city, wheel/rail system is commonly utilized in order to improve the transport efficiency. The damage or fault on the surface structure of the wheels can cause impact noise lead to great environmental pollution or even cause fatal railway accident. Therefore, it is necessary to develop a structural condition monitoring system in order to improve the operability and reliability of the wheels in service. Various methods have been employed to monitor the condition of wheel/rail system, such as acoustic emission [1, 2] (AE), ultrasonic wave [3, 4], and magnetic testing [5, 6]. Meanwhile, various time-frequency techniques have been proposed for faults detection in this area, for example, Short-Time-Fourier-Transform (STFT), Wigner-Ville transform, and wavelet transform (WT) [7]. However, these methods can only indicate the existence of faults, but they cannot determine the position of the fault wheel. Since these existing techniques only rely on contact inspection methods and periodical maintenance to eliminate the potential security issues. This paper proposes an integrated fault detection and localization method for wheel/rail system with flexible monitoring position. The localization of a moving source can be achieved by time-domain beamforming with de-Dopplerization method [8] which can obtain both temporal and spatial information of the moving sources. Meanwhile, during the train operation, the impulsive features generated by fault on wheel surface can be extracted from the original signals. By utilizing the time-domain beamforming integrated with kurtosis [9], the fault detection and localization system can be developed, which can be regarded as a non-contact monitoring system to detect the fault at early stage.

2 TIME-DOMAIN BEAMFORMING WITH DE-DOPPLERIZATION

The time-domain delay-and-sum (DAS) beamforming [10] is a conventional and efficient way to visualize the sound field. Consider an arbitrary time-domain acoustic signal is measured by a linear array of *m* microphones. In scanning sound field introducing a scan vector:

$$\mathbf{w}(\theta,t)=[w_2(\theta,t) \quad w_1(\theta,t) \quad \cdots \quad w_m(\theta,t)]^T \tag{1}$$

It can extract the original sound features by analysing the wavefront which only depends by sound source location and acoustical model. Assume that the Direction-of-Arrival (DOA) of the plane wave source is θ_0. The sound pressure signals received at the microphone array can be expressed as:

$$\mathbf{p}(t)=[p_1(t) \quad p_2(t) \quad \cdots \quad p_m(t)]^T \tag{2}$$

Then the conventional DAS beamformer output can be written as:

$$b_{DAS}(\theta,t)=\mathbf{w}(\theta)^T\mathbf{p}(t) \tag{3}$$

For moving sound signal whose position in sound field, as it is shown in Figure 1, is continuously changing with respect to time τ, two main distortions in time-domain should be considered in the localization approach. First is the arrival time of sound signal and the second is Doppler amplification. For a linear motion with a speed v_0, the measured sound pressure at observation position $\mathbf{r}=[x,y,z]$ is given by:

$$p(\mathbf{r},t)=\frac{q_0(\tau)}{4\pi\left|\mathbf{r}-\mathbf{r}_0(\tau)\right|}\frac{1}{\left|1-M_0(\tau)\right|} \tag{4}$$

in which q_0 is the time signal, $\mathbf{r}_0=[v_0\tau_j,0,0]$ is the position of source and M_0 is the Mach number term:

$$M_0(\tau)=\frac{v_0}{c}\frac{x-v_0\tau}{\sqrt{\left(x-v_0\tau\right)^2+y^2+z^2}} \tag{5}$$

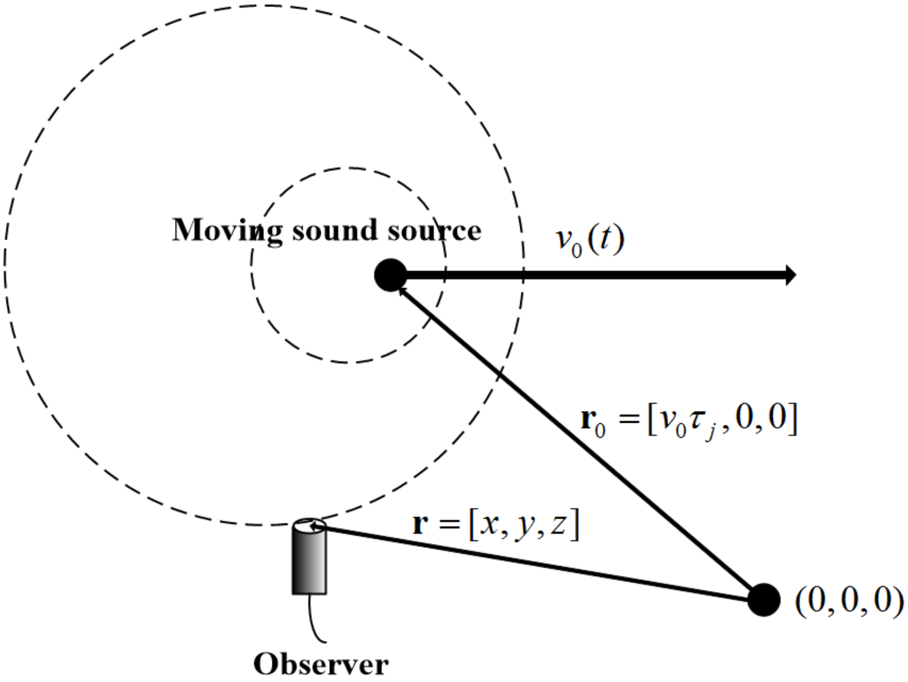

Fig. 1.Propagation wavefront produced by a moving sound source.

To neutralize the distortion of Doppler amplification, a method called de-Dopplerization can be adopted in beamforming localization approach. Use the relation of Eq. (4), the source signal can be estimated as:

$$q_0(\tau)=4\pi\left|\mathbf{r}-\mathbf{r}_0(\tau)\right|\left|1-M_0(\tau)\right| p(\mathbf{r},\tau+\frac{\left|\mathbf{r}-\mathbf{r}_0(\tau)\right|}{c}) \quad (6)$$

in which the sound pressure is assumed to be measured by a fixed microphone array.

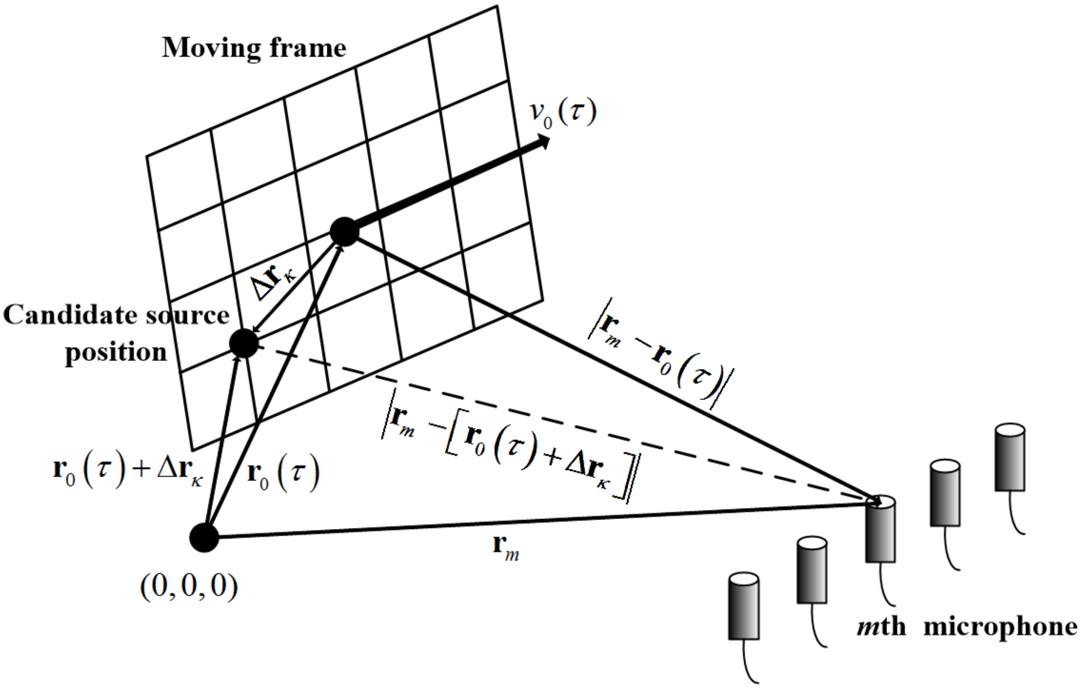

Fig. 2. De-Dopplerization beamforming approach with sound source on a moving frame.

Assume K source signals in a moving frame as it is shown in Figure 2 with a centre $\mathbf{r}_0(\tau)$ and the speed v_0 is estimated by m microphones. Each position of the source signals can be expressed as $\mathbf{r}_0(\tau)+\Delta\mathbf{r}_\kappa$ $(\kappa=1,\ldots,K)$, the de-Dopplerized time-domain beamforming output can be written as:

$$b(\Delta\mathbf{r}_\kappa,\tau)=\frac{1}{M}\sum_{m=1}^{M}4\pi\left|\mathbf{r}_m-\left[\mathbf{r}_0(\tau)+\Delta\mathbf{r}_\kappa\right]\right|\left|1-\frac{|v_0(\tau)|}{c}\cos\varphi_{m\kappa}(\tau)\right|p(\mathbf{r}_m,\frac{\tau+\left|\mathbf{r}_m-\left[\mathbf{r}_0(\tau)+\Delta\mathbf{r}_\kappa\right]\right|}{c}) \tag{7}$$

in which c is speed of sound, $\mathbf{r}_m$ is the position of mth microphone and $\cos\varphi_{m\kappa}(\tau)$ is the angle between the direction of $\mathbf{v}_0$ and $\mathbf{r}_m-\left[\mathbf{r}_0(\tau)+\Delta\mathbf{r}_\kappa\right]$.

3 BEAMFORMING KURTOSIS METHOD

Kurtosis is a statistic measurement for the ‘peakedness’ of one statistical distribution, and the beamforming kurtosis method can perform well even in the environment with low signal to noise ratio (SNR), due to background noise and interference distributions are typically lower kurtosis value signals. It is expressed as:

$$Kurt(x)=\frac{E\{[x-\mu(x)]^4\}}{[\sigma(x)]^4}-3 \tag{8}$$

in which $\mu(x)$ is the mean value of x, $\sigma(x)$ is the standard deviation of x, and E represents the expected value of the quantity. The “minus 3” at the end of Eq. (8) is to normalize the kurtosis of the normal distribution equal to zero.

By Combining Eq. (7) and (8), the time domain beamforming kurtosis can be defined and calculated by:

$$Kurt(r_m)=\frac{E\{[b(\Delta\mathbf{r}_\kappa,\tau)-\mu(\Delta\mathbf{r}_\kappa,\tau)]^4\}}{[\sigma(\Delta\mathbf{r}_\kappa,\tau)]^4} \tag{9}$$

in which $\mu(\Delta\mathbf{r}_\kappa,\tau)$ is the mean of $b(\Delta\mathbf{r}_\kappa,\tau)$, $\sigma(\Delta\mathbf{r}_\kappa,\tau)$ is the standard deviation of $b(\Delta\mathbf{r}_\kappa,\tau)$.

Eq. (9) can be used to design as a beamformer output to extract the impulsive feature of faults. Here, a different approach apart from traditional time-domain DAS beamforming is proposed. The integration between acoustic imaging and kurtosis will bring the visualization of impulsiveness as a function of space in new kind of mapping.

4 APPLICATION TO FAULT IDENTIFICATION AND LOCALIZATION FOR MOVING WHEELS

To imitate the wheel/rail system operating, a belt track carried a plastic stand with three loudspeakers was utilized in the following experiment. The belt was driven by a servo motor (57hbm20-1000), which can be controlled by a touch screen control panel. A lineal microphone array containing 16 microelectrical-mechanical system (MEMS) microphones was used in the experiment, with a 0.1m gap between each two adjacent microphones. All sound sources were arranged in a 3m × 3m plane, hence the beamforming scan area is 3m ×

3m as well. The lineal microphone array is regarded as X-axis and the first MEMS microphone is regarded as zero point in the whole geography. The reflections and reverberation effect was not considered in this article. Thus, all the experiments were conducted in anechoic chamber. The whole experimental setup was shown in Figure 3. Three different kind of sound signals were transmitted by loudspeakers, including the background white noise, wheel with fault and wheel without fault.

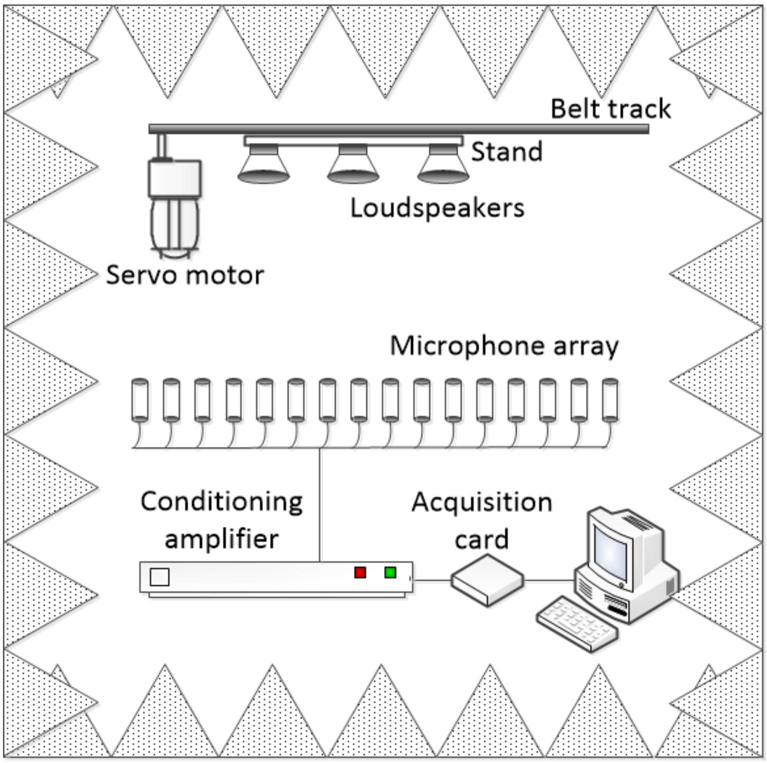

Fig. 3. Experimental setup.

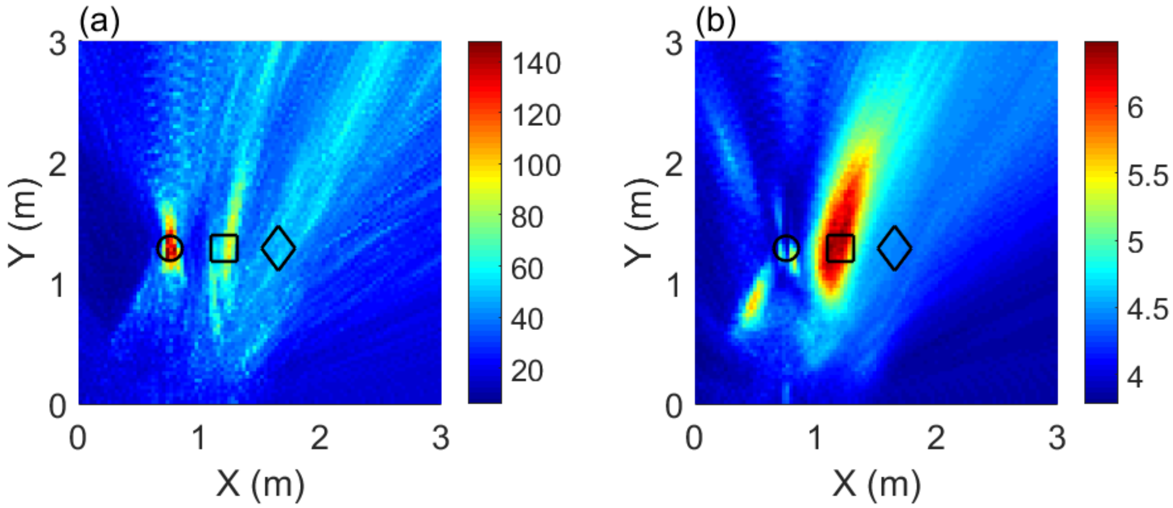

Fig. 4. Fault detection and localization results at $\tau = 2s$ *(○: location of background white noise, □: location of wheel with fault, and ◇: location of wheel without fault). (a) Beamforming power (W), (b) Beamforming kurtosis.*

Figure 4 showed the sound maps after 2s, in which the stand carrying three loudspeakers moved at a speed of 0.2m/s. Two clear sound sources: (○ and □) and one indistinct sound source (◇) can be discovered in Figure 4(a) from the sound map. This is mainly because the sound power level of background noise was set rather higher than the other two signals to verify the effectiveness of the new method. Figure 4(b) showed the beamforming kurtosis sound map. In this improved map the background noise (○) were suppressed and the wheel with fault (□) was protruded.

In Figure 5 the two sound maps were calculated after 4s. Obviously the de-dopplerization and beamforming kurtosis approach were still effective. Since the moving speed of the sources was 0.2m/s in this case, all the sound sources locations translated 0.4m compared with Figure 4.

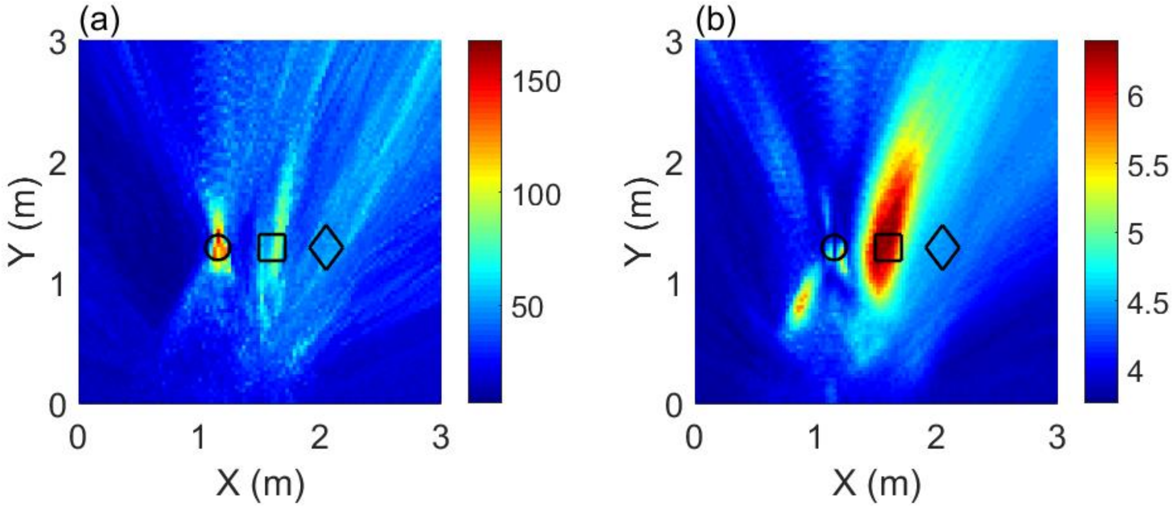

Fig. 5. Fault detection and localization results at $\tau = 4s$ *(○: location of background white noise, □: location of wheel with fault, and ◇: location of wheel without fault). (a) Beamforming power (W), (b) Beamforming kurtosis.*

5 CONCLUSIONS

In this paper, the de-Dopplerization beamforming kurtosis method for fault identification and localization in wheel/rail system was developed, which can extract the impulsive feature from original sound signals and locate the position of specific sound source. To localise the moving sound source, de-Dopplerization approach were introduced and applied in section 2. To identify the fault, beamforming kurtosis were intergrated with de-Dopplerization approach in section 3. In the experimental section the calculated results presented in sound maps had a good matching with the actual conditions in terms of localizing and identifying. In the first place the localization results for three moving sources were acceptable, furthermore the improved sound maps can identify wheel fault with the interference of background noise.

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