A Frequency Compensation Method to Smooth Frequency Fluctuation for Locating Moving Acoustic Sources

P. Mo, X. Wang and W. Jiang

Abstract The current beamforming approach for locating moving acoustic sources could not correctly evaluate sources with time-dependent frequency fluctuation. The frequency fluctuation is usually caused by the non-constant relative speed between the solid object and the flow. The source frequency varies with time in a certain frequency range, so that the frequency-domain beamforming approach, which only focuses on a fixed narrow frequency band, cannot focus on the fluctuating frequencies. A frequency compensation method is proposed to smooth the frequency fluctuation. Fluctuating frequencies are squeezed into a narrow frequency band, so that a frequency fluctuating source can be treated as a conventional steady source. The method is then integrated into the frequency-domain beamforming approach for moving sources, and is able to identify moving sources with frequency fluctuation. The integrated method is verified by a simulation and an experiment performed on a rotating source.

Keywords Beamforming · Microphone array · Unsteady moving sources
Frequency compensation

1 Introduction

Beamforming is now developed to locate moving acoustic sources by removing the Doppler effect in the microphone signals. The de-Dopplerized signals are specially steered to focus on a group of moving points, so as to give the source strength estimation for a source region. Moving beamforming was extensively applied to identify the aero-acoustic noise sources from the passing-by trains [1], the fly-over

P. Mo · W. Jiang (✉)
State Key Laboratory of Mechanical System and Vibration,
Shanghai Jiao Tong University, Shanghai, China
e-mail: wkjiang@sjtu.edu.cn

X. Wang
China Aerodynamics Research and Development Centre, Mianyang, China

Y. Zhou et al. (eds.), *Fluid-Structure-Sound Interactions and Control*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-10-7542-1_55

aeroplanes [2], and rotating blades [3]. In the current moving beamforming approaches, the moving sources are assumed to be steady and time-independent. However, some of the aero-acoustic noises are actually time-varying. Taking the helicopter rotor noise as example, the frequency fluctuation in the vortex shedding noise is caused by the non-constant relative speed between the blades and the flow. The time-varying source frequencies would disable the current beamforming approaches in determining the source positions and source frequency components. A time-domain frequency compensation method is proposed to smooth the time-dependent frequency fluctuation. The method is integrated into a classic moving beamforming approach [3], so that moving sources with frequency fluctuation could be identified.

2 Frequency Compensation Method

Assume $q(t)$ is the frequency distorted signal following a time-varying frequency shift $f(t)$ with mean frequency $\bar{f}$. The frequency compensation method is performed on the distorted signal as follows.

$$\tilde{q}(t) = q(t)\exp\left(-j2\pi\int_0^t f(\tau)d\tau\right). \tag{1}$$

The frequency compensated signal $\tilde{q}(t)$ is a tonal signal at frequency $\bar{f}$ without frequency fluctuation. To apply this method, the frequency shift $f(\tau)$ should be given in advance. As for the aerodynamic noise induced by the interaction between the blades and the flow, $f(\tau)$ is governed by a physical model that the source frequency is proportional to the normal speed of the relative blade-to-flow speed. The ratio is known as the Strouhal number.

This method is then integrated in the beamforming approach for locating moving sources. A fixed array with M microphones are used record the sound signals, and to scan the moving source region which is discretized into N scanning points. To scan the nth $(n = 1, 2, \ldots, N)$ moving point, the mth $(m = 1, 2, \ldots, M)$ microphone signal $p_m(t)$ is de-Dopplerized to $q_{nm}(t)$ as introduced by Sijtsma et al. [3], so as to remove the Doppler effect caused by the moving source.

$$q_{nm}(\tau) = T_{nm}^{-1}(t, \tau)p_m(t), \tag{2}$$

where T_{nm} is the time-dependent transfer function from the nth moving source to the mth microphone. T_{nm} is defined by

$$T_{nm}(t,\tau) = \frac{1}{4\pi\left|\vec{x}_m - \vec{\xi}_n(\tau) - \vec{U}(t-\tau)\right|\left|1 - M_{mn}(\tau)\right|}$$
$$t - \tau = \frac{1}{c}\left|\vec{x}_m - \vec{\xi}_n(\tau) - \vec{U}(t-\tau)\right|. \tag{3}$$

where $\vec{x}_m$ is the fixed position of the mth microphone, $\vec{\xi}_n(\tau)$ is the moving path of the nth source, $\vec{U}$ is the speed of the uniform flow, and $M_{mn}(\tau)$ is the dimensionless source speed projected on the source-to-microphone direction.

To further remove the frequency fluctuation, the previously mentioned frequency compensation method is applied. The frequency compensated source signal is

$$\tilde{q}_{nm}(t) = q_{nm}(t)\exp\left(-j2\pi\int_0^t f(\vec{x}_n,\tau)d\tau\right), \tag{4}$$

where $f(\vec{x}_n,\tau)$ is proportional to the normal speed of the relative blade-to-flow speed for the scanning point at $\vec{x}_n$. Their ratio is determined by the specific Strouhal number.

Beamforming is then performed on the nth scanning point. The elements of the Cross Spectral Matrix (CSM) are calculated by

$$[G_{mm'}(f)]_n = \sum_{k=1}^{K}\left[Q^*_{nm}(f)Q_{nm'}(f)\right], \tag{5}$$

where $Q_{nm}(f)$ is the frequency bins of $\tilde{q}_{nm}(t)$ processed by FFT (Fast Fourier Transformation). The elements in Eq. (5) constitute the full CSM G_n. The power spectrum output for the nth scanning point is

$$Y_n = \frac{\vec{e}^H G_n \vec{e}}{M^2}, \tag{6}$$

where $\vec{e} = (1 \ \ 1 \ \ \ldots \ \ 1)^T$ is a reduced steering vector with unit elements.

3 Simulation and Experiment

A numerical simulation is conducted on a counter-clockwise rotating source, as in Fig. 1a. The source rotates on a circle of radius 1 m at a constant rotational speed 60 rpm ($f_{rot} = 1\text{Hz}$), and emits a sound with frequency distortion $f(\vec{x}_0,t) = 4000 + 200\ \sin(2\pi f_{rot}t + \theta_0)$. The source strength is 94 dB in sound pressure level (SPL). An array with 56 microphones and 1 m in diameter is placed

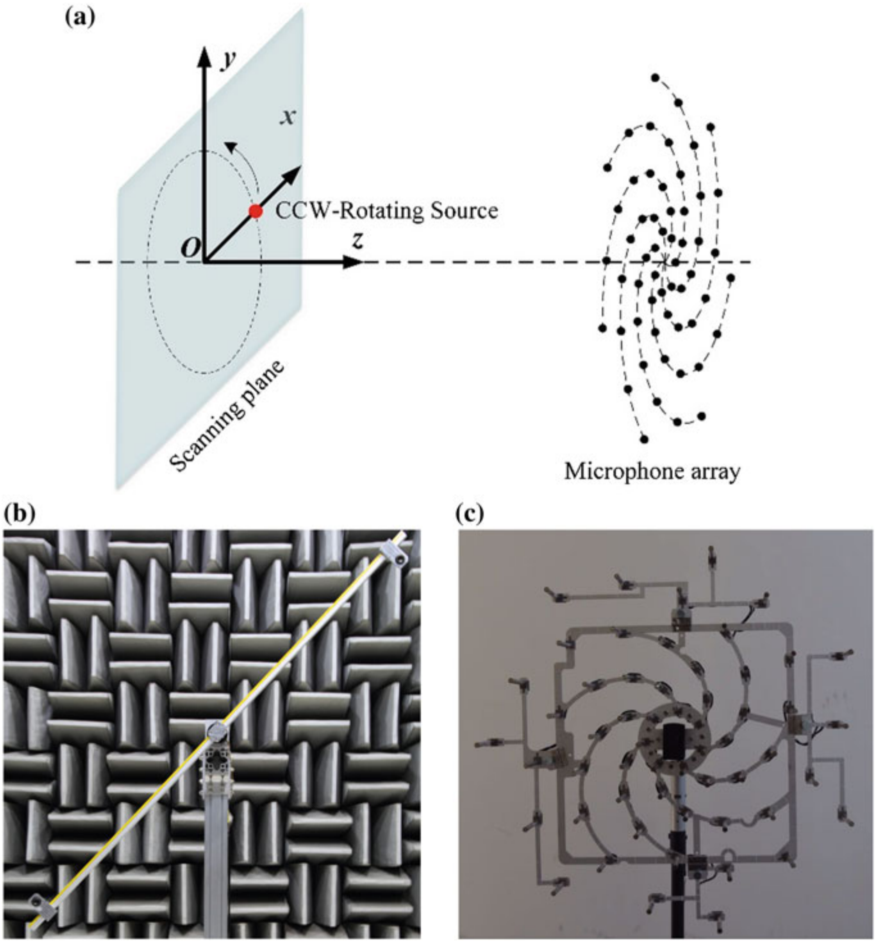

Fig. 1 Setups of beamforming for locating moving sources. **a** schematic description; **b** rotating speakers; **c** an array with 56 microphones and 1 m in diameter

2 m in front of the source plane to record the sound signals. A 2 m × 2 m rectangle scanning plane with a gird size of 0.02 m × 0.02 m is used to cover the rotating source. The sampling rate is 12,800 Hz, and the analyzing time block size is 0.1 s.

On the other hand, a similar experiment is also done in a semi-anechoic chamber, and share the same parameters with the simulation. Two rotating speakers are mounted, but only one actually works, as in Fig. 1b. Figure 1c demonstrates the practical spiral microphone array with 56 half-inch microphones.

The beamforming results of the simulation and the experiment with or without frequency compensation are demonstrated in Fig. 2. Figure 2a is the simulation result without frequency compensation, and Fig. 2b is the beamforming map after

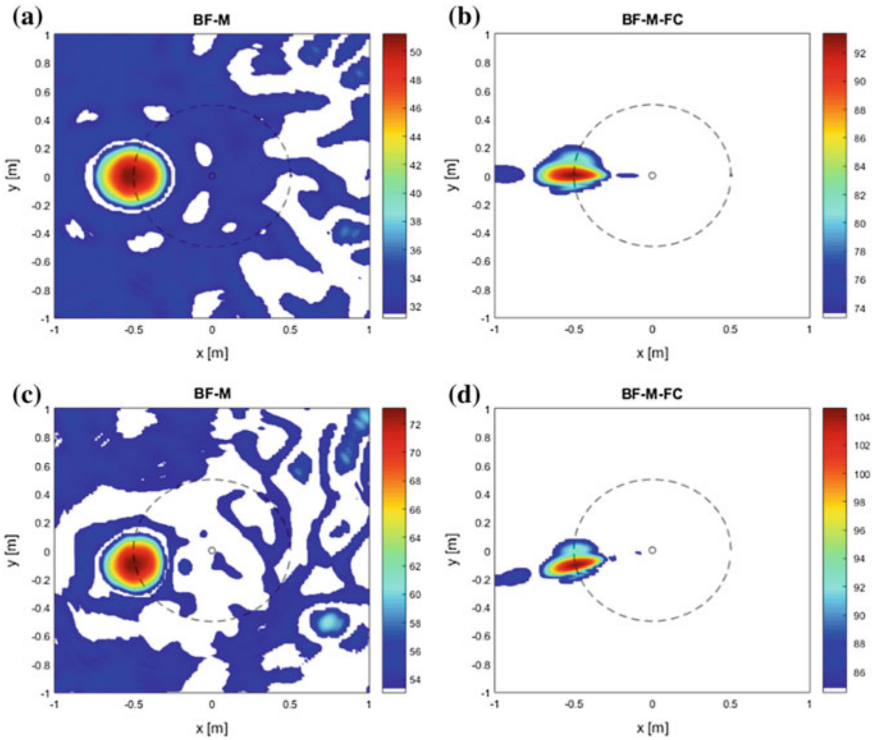

Fig. 2 Beamforming map of a frequency distorted rotating source. **a** simulation without frequency compensation; **b** simulation with frequency compensation; **c** experiment without frequency compensation; **d** experiment with frequency compensation

frequency compensation. By comparing these two figures, it is found that the recovered source strength of the latter map is very close to the actual source strength 94 dB, while the former map has large source leakage in energy. The conventional method only can concentrate on a fixed frequency bin. The other frequency bins are neglected and the frequency components are distorted by performing FFT on the frequency fluctuated signals when applying the conventional method. The frequency compensation method can squeeze the frequencies into a narrow frequency, so that the sources are reconstructed without loss of energy. Similar results are drawn by comparing Fig. 2c, d, which are the experimental results for an actual rotating speaker. The recovered source strength from the source compensation method has less frequency leakage, so its result is more accurate and more reliable.

4 Conclusion

A frequency compensation method is proposed to smooth the frequency fluctuation in moving sources. The integration with the beamforming approach enables it to precisely identify moving sources with frequency fluctuation. The current beamforming approach could only recover a small portion of the source energy, so that the source is likely submerged by large noise. However, the frequency compensation method could recover the fluctuating source with correct source location and strength. It is proved effective and robust to identify moving sources with frequency fluctuation.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 11574212).

References

1. Barsikow B (1996) Experiences with various configurations of microphone arrays used to locate sound sources on railway trains operated by the DB AG. J Sound Vib 193:283–293
2. Brusniak L, Underbrink JR, Stoker RW (2006) Acoustic imaging of aircraft noise sources using large aperture phased arrays. In: Proceedings of the 12th AIAA/CEAS aeroacoustics conference, MA, USA
3. Sijtsma P, Oerlemans S, Holthusen H (2001) Location of rotating sources by phased array measurements. In: Proceedings of the 7th AIAA/CEAS aeroacoustics conference, Maastricht, Netherlands