Resynchronization of tonal acoustic field in multi-pass non-stationary microphone array measurements

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Abstract

The geometrical limitations of microphone arrays as well as the unavailability of multiple channel data acquisition systems or their incurred costs fundamentally challenge the sound source identification in acoustic imaging. This can be solved by sequentially scanning the object of study with a moving array with or without fixed references and requires the sound field to be stationary. In rotating machines, the generated vibroacoustic phenomena during a run-up or coast-down are non-stationary, and conventional resynchronization techniques cannot be directly implemented. To solve this problem, this study proposes a novel approach called Angular Speed Resynchronization (ASR). The orders from several sequential measurements are first extracted using time domain order tracking techniques, then synchronized into a single data set over which order based beamforming (OBBF) is performed. OBBF is an acoustic imaging technique that aids in the identification of non-stationary tonal sources. Given that the radiated sound field is determined for a given angular speed, the complex envelopes in the data set are realigned with respect to speed as if they were obtained from the same measurement with a full array. The proposed method is evaluated using an experimental data set collected from an induction motor. The approach demonstrates the capability of OBBF to accommodate with non-synchronous measurements during variable operating speed.

1 Introduction

Acoustic imaging through microphone array measurements is a widely used method for identifying sound sources. The effectiveness of array is influenced by different factors such as the geometry of the array and the spatial density of the microphones used. Typically, increasing the size of the array leads to improved source localization at lower frequencies. On the other hand, densifying the microphone array generally improves localization results at higher frequencies, but these come at the expense of higher instrumentation costs. In recent years, non-synchronous measurements, also known as multi-pass measurements or sequential measurements, have gained popularity as an approach to extend the working frequency range and significantly increasing the size of microphone arrays [1, 2, 3, 5, 6]. This technique is particularly useful in 3D acoustic imaging applications, where it can significantly reduce the costs associated with multiple arrays, multichannel data acquisition systems, and transducers. In non-synchronous measurement, a prototype array is sequentially moved in different directions to scan the object of interest, effectively creating a virtual array that is larger or denser than the prototype array. However, the absence of overlapping times results in the loss of phase relationships between consecutive measurements/positions, which is in contrast to simultaneous array measurements [1]. Therefore, for synchronizing the multi-pass measurements, one must obtain the phase relationships between the consecutive positions of the array. One of the strategies employed in the literature is to have fixed references around the radiating object to indirectly reconstruct the missing phase relationships and, subsequently, facilitate resynchronization. The effectiveness of resynchronization demands a high quality and an adequate number of fixed references to capture the correlation structure of the acoustic field. But, the addition of these extra transducers results in increased costs. Synchronizing the multi-pass measurements without references have been addressed in Refs [2, 3]. Nonetheless, the state-of-art techniques in the literature, whether with or without fixed references, are based on the strong assumption of stationarity of sound field.

For rotating machines running at variable working speed the radiated sound field is a function of shaft rotational frequency, where the measured acoustic signals in the time domain are strictly non-stationary, i.e. amplitude and frequency modulated, and are generally analyzed through orders. As a result, traditional techniques cannot perform resynchronization on non-stationary acoustic fields. In order to address this problem, the paper introduces an original technique known as Angular Speed Resynchronization (ASR) through order based beamforming (OBBF) [4]. OBBF is a novel beamforming technique that identifies the order related noise sources on a rotating machine operating at variable speeds such as run-up and coast-down. By utilizing OBBF, the paper outlines a brief methodology of performing resynchronization of tonal acoustic field in multi-pass non-stationary microphone array measurements.

2 Angular Speed Resynchronization

As previously stated, the objective in this paper is to achieve synchronization among multiple trajectories of varying speeds, such as run-up and coast-down, which differs from the usual synchronization approach where measurements are made at a constant speed between the consecutive positions. Additionally, when analyzing non-stationary sound fields radiated by rotating machines, the analysis is dealt with orders. In general, the complex envelope of an order can be explicitly written as a function of angle θ and angular speed $\dot{\theta}$, i.e. $A(\theta, \dot{\theta})$. Therefore,

$$x(t) = A\left(\theta(t), \dot{\theta}(t)\right) \mathrm{e}^{\mathrm{j}k\theta(t)} \tag{1}$$

for an order k.

This paper addresses a specific scenario where it is assumed that the sound field of a complex envelope in a rotating machine remains approximately constant with respect to the angle, but varies solely based on the angular speed. This assumption can also be attributed to the result of the narrowband filter used in order tracking. In such cases, synchronizing the tonal acoustic fields from multiple array measurements involves realigning the complex envelope vectors of an order sharing the same angular speed and that are order tracked with the instantaneous phase $\theta(t)$ in the carrier signal $\mathrm{e}^{\mathrm{j}k\theta(t)}$ defined with respect to the reference position[1] for every run. From a mathematical point of view,

$$A(\theta, \dot{\theta}) \approx A(\dot{\theta}). \tag{2}$$

The desired order is extracted using any time domain order tracking technique with the angular references for all the sequential measurements. Subsequently, the resulting complex envelopes are concatenated into a single data set, as if they were obtained from a simultaneous measurement with the full array. OBBF is performed on the new data set for identification of the noise sources along the course of the order at any desired angular speed, thus facilitating ASR. Furthermore, this approach is cost-effective as it does not necessitate the use of extra dedicated reference microphones or accelerometers apart from the key phasor to estimate the angular reference.

3 Experimental Validation

Validation of angular speed resynchronization (ASR) is performed on an induction motor in a non-anechoic environment. The experimental setup includes a planar array of 45 analog microphones positioned in front of the electric motor, as shown in Fig. 1. Data acquisition is performed using LMS SCADAS and Simcenter Test Lab software. OBBF performed on the orders extracted from the microphone array responses measured from an induction motor operating at a constant speed, ensured that the sound field of the complex envelopes are almost invariant as a function of angle, which is consistent with the assumption of this technique. To begin with the demonstration of resynchronization, a full array is divided into two partial arrays P_1 and P_2 and the acoustic

[1] In rotating machines, the reference position is where the reference shaft is considered to be in its ”zero” position.

radiation from the induction motor is measured individually for a linear run-up, with P_1 corresponding to run-up 1 and P_2 corresponding to run-up 2. When performing multiple runs, the initial angle of the angular reference varies between each specific run, thus resulting in inconsistency between the reference position of phasor defined over various runs. This is solved by setting the initial angle of the angular reference to zero, which assures that phasor in every run is referenced to the zero position of the shaft. Subsequently, the mechanical order 84, as illustrated in Fig. 2a, corresponding to the 3^{rd} multiple of rotor bar pass order is extracted using baseband demodulation order-tracking technique [4] from both the sets P_1 and P_2. The resulting complex envelopes are resynchronized as discussed in Section 2. The time course of order 84 shows a sharp peak at 1520 rpm corresponding to 2128 Hz, where the OBBF is performed to identify the noise source. The OBBF on resynchronized partial arrays P_1 and P_2 are compared to the OBBF response of a full array measured during a single run. Figs. 3a and 3b shows the OBBF performed with partial arrays and Fig. 3c shows the OBBF performed on the ASR data set, which indeed shows good agreement with the ground truth Fig. 2b. The reconstructed source obtained through the synchronization of partial arrays demonstrates a narrow main lobe, leading to improved spatial resolution when compared to using the partial arrays alone. This demonstrates the concept of ASR to synchronize the multi-pass non-stationary array measurements.

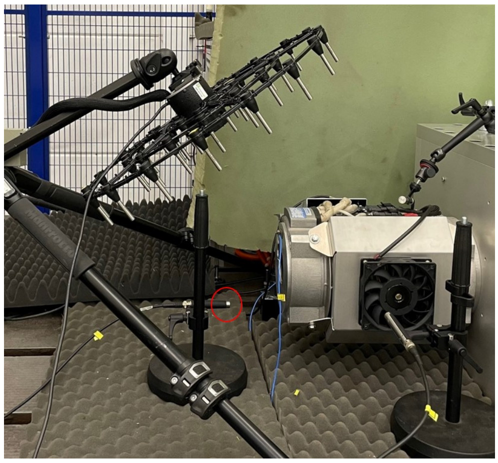
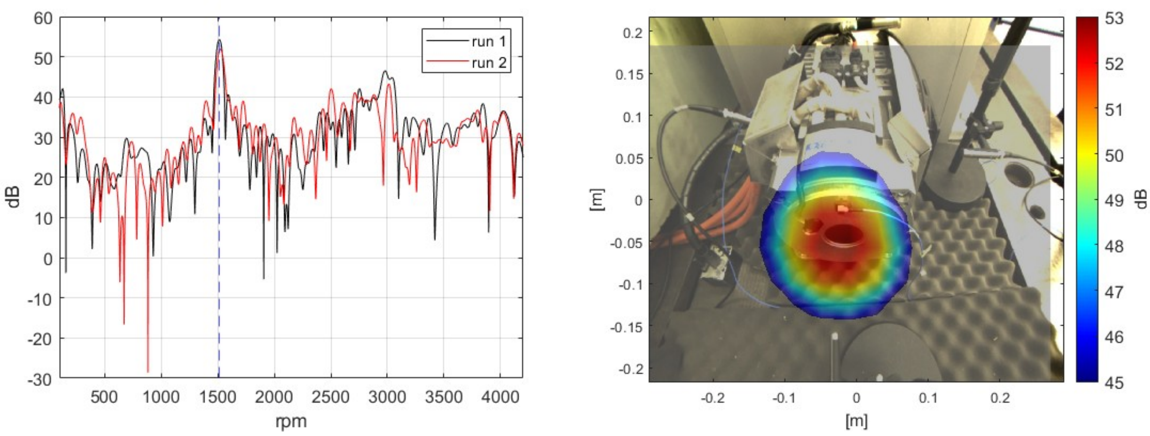


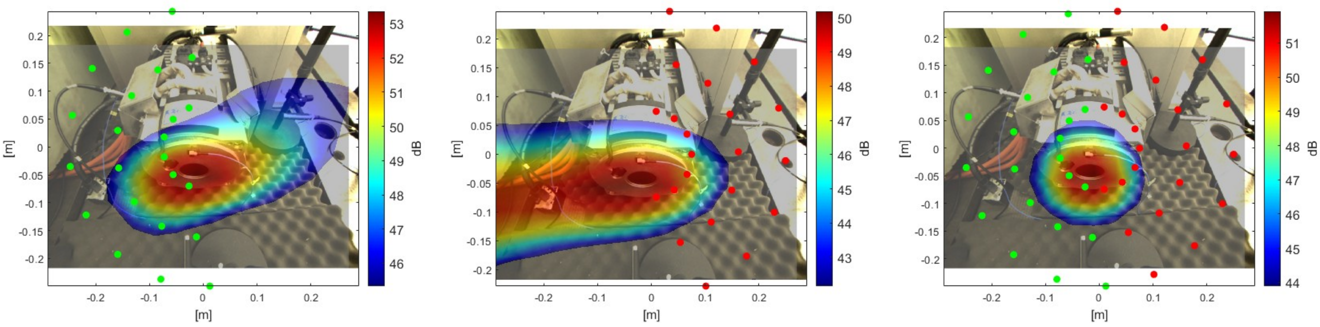
Figure 1: Experimental setup with array facing the induction motor and a reference microphone (marked in red circle).



(a)

(b)

Figure 2: a) Order 84 tracked from the response of a reference microphone b) OBBF performed on order 84 at 1520 rpm with full array (dyn = 8 dB).



(a) (b) (c)

Figure 3: OBBF (dyn = 8 dB) performed on order 84 at 1520 rpm a) with partial array P_1 b) with partial array P_2 c) resynchronization of partial arrays P_1 and P_2.

4 Conclusions

The problem of synchronization of multi-pass non-stationary measurements has been investigated. An original approach, Angular Speed Resynchronization is introduced, which can perform synchronization of tonal sound fields. The resynchronization is based on the premise that sound field of the complex envelope does not vary as a function of angle but solely on angular speed. The potential applications of this method includes all situations where several measurement passes are necessary. This includes all the cases where there are limitations in terms of microphone array size and data acquisition capabilities, such as in 3D acoustic imaging.

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