Acoustic Noise Characterisation in Dynamic Systems using an Embedded Measurement Platform

Bamidele Adebisi [1], Sunday C. Ekpo [1], Angham Sabagh [1], and Andrew Wells [2]

[1] Department of Electrical & Electronic Engineering
Manchester Metropolitan University, M1 5GD UK
S.Ekpo@mmu.ac.uk, B.Adebisi@mmu.ac.uk, A.Sabagh@mmu.c.uk

[2] Jaguar Land Rover, Warwick, United Kingdom
awells@jaguarlandrover.com

Abstract: The modelling of an acoustic beamforming in a dynamic system characterised by time-variant state variables requires a reliable knowledge of the noise conditions of the environment and sensor subsystems. Such a noise calibration depends on the prevailing noise field(s) for a given acoustic beamforming application. In this paper, an embedded system-based noise modelling platform has been developed to implement a hybrid of the regulated-element Frost (REF) beamformer. The architecture is adaptive and reconfigurable; it has the capability to extract the residual noise of the system better than the conventional Frost beamformer (CFB). A 4-element uniform linear array (ULA) with a 10-cm spacing between the sensors and 4 finite impulse response (FIR) filters per sensor has been simulated to investigate the residual noise extraction capability of the REF beamforming algorithm. The broadside signal-to-noise ratio (SNR)-based array gain for the REF system is over 10-dB better than the CFB.

Keywords: Acoustic Noise Characterisation, Adaptive Beamforming Algorithm, Dynamic, Embedded System, REF

1. Introduction

The noise modelling of a dynamic system (such as an automobile) starts with the characterisation of the prevailing noise field for a measure of correlation between neighbouring onboard and/or deployed sensors; this is referred to as coherence. Mathematically, the coherence function, Γ_{ij}, between incident noise signals at a given frequency, f, is obtained thus:

$$\Gamma_{ij}\left(f\right)\triangleq\left(\frac{\phi_{ij}\left(f\right)}{\sqrt{\phi_{ii}\phi_{ij}}}\right) \tag{1}$$

where ϕ_{ij} is the cross-spectral density between signals i and j. The coherence is a normalised cross-spectral measure. The magnitude squared coherence is bounded by $0 \leq |\Gamma_{ij}(f)|^2 \leq 1$. Three major coherence regimes [1,2] are possible based on the prevailing noise fields. Coherent noise fields (CNFs) have their noise signals propagating to the sensors directly from their excitation sources undisturbed; the acoustic environment limits and eliminates any possible reflection, dispersion or energy loss (dissipation). The noise signals arriving on the sensors are strongly correlated with $\left|\Gamma_{ij}(f)\right|^2 \approx 1$ This is commonly experienced in the environments with no obstacle-posing physical features such as an open air with a minimal wind pressure or thermal disturbance.

Incoherent noise fields (INFs) have their measured spatial location noise signals uncorrelated with the ones measured at all other locations. The coherence factor approximates to zero; $\left|\Gamma_{ij}(f)\right|^2 \approx 0$ Though rarely realisable in practice, the electrical noise in the microphone array elements exhibits a random distribution that lends credence to an incoherent noise behaviour.

The diffuse noise field (DNF) exhibits a synchronised and concurrent sound wavefront or energy that travels in all directions at all times. Propagating noise signals arrive on the microphones with a low correlation relative to their neighbouring array elements. The DNF characterises many practical and real-life noise environments such as office and car noise.

The degree of correlation between noise signals [1,2] at various spatial locations is utilised to qualify the different categories of noise fields.

Mathematically, the coherence function between noise signals in a DNF is given by: [1]

$$\Gamma_{ij}(f) = \sin c\left(\frac{2\pi f d_{ij}}{c}\right) \tag{2}$$

where d_{ij} is the distance between sensors *i* and *j*. The coherence approaches unity for closely spaced sensors and decreases sharply with increasing distance.

2. Acoustic Noise Analysis in Dynamic Systems

The noise energy of dynamic and mobile systems exhibit time-variant and time-invariant acoustic characteristics depending on the prevailing surrounding conditions. Assuming the noise energy is time-invariant and propagates equally in all directions, the array gain [1,2] defines the refinement in signal-to-noise (SNR) ratio and is given by:

$$G_a = \frac{G_d}{G_n} \tag{3}$$

where G_d is the gain in the desired signal and G_n, the average gain to all noise sources.

In a diffuse noise field, the array gain is referred to as the factor of directivity [1] and expressed mathematically as:

$$G_a(f,\theta_o,\phi_o) = \frac{\left|D(f,\theta_o,\phi_o)\right|^2}{\frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}\left|D(f,\theta,\phi)\right|^2 \sin\theta d\theta d\phi} \tag{4}$$

From Eqn. 4, the diffuse noise field for a conventional linear array [1] with sensors is characterised by:

$$\Gamma_c(f,\theta,\phi) = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}\left|D(f,\theta,\phi)\right|^2 \sin\theta d\theta d\phi \tag{5}$$

where $\Gamma_c(f,\theta,\phi)$ is the frequency-dependent diffuse noise function and $D(f,\phi)$, the horizontal directivity pattern. The propagation vector, $d(f)$, [1] is obtained mathematically as:

$$d(f) = [1 \quad \ldots \quad e^{-j\frac{2\pi f}{c}(n-1)d\cos\phi} \quad \ldots \quad e^{-j\frac{2\pi f}{c}(n-1)d\cos\phi}]^T \tag{6}$$

Hence, from Eqns. 5 and 6, the diffuse noise field for a superdirective beamforming aperture system is given by the matrix Γ_s as:

$$\Gamma_s = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} d(f)d(f)^H \sin\theta d\theta d\phi \tag{7}$$

where $(.)^H$ denotes a matrix transpose conjugate. Equation 7 is the governing function for characterising the cross-spectral noise density between array sensors.

3. Acoustic Noise Characterisation Algorithm

The various sources of noise in our case study automobile environment include, but are not limited to, the following: engine noise; fan noise; RF and EM interference; antennae noise (Wi-Fi and RF); electrical sensor noise; channel mismatch; errors in microphone spacing; speaker echo; thermal noise; system dynamics noise (e.g., passenger's movement); infotainment noise (environmental noise/interference from other audio equipment); system operation noise (such as steering, driving, gearing, and clutching) and power supply noise. Since all these noise sources are of varying magnitudes and may not occur simultaneously, the noise energy of the dynamic system is time-variant and an adaptive noise characterisation algorithm is required for real-time (RT) and offline noise performance investigation. The Frost beamforming [3–7] is an adaptive algorithm that incorporates a delay and sum (DAS) network along each sensor path and places FIR sensors with appropriate adjustable weights to control the gain, noise and frequency performance of each ULA sensor.

In this paper, the regulated-element Frost beamforming algorithm has been developed to enable the characterisation of acoustic noise sources in a dynamic system and/or mobile environment. The REF relationship that defines the residual noise, R_n, of the dynamic system for an embedded real-time system noise study is given by:

$$R_n = \frac{\sum_{i=1}^{N} S_r}{N} - F_O \tag{8}$$

The output of the REF algorithm for the SNR determination based on the residual noise function of Eqn. (8) is given by:

$$REF_o = \frac{N(N-1)F_o + \sum_{i=1}^{N}(S_i + n_i)}{N^2} \tag{9}$$

where N is the number of sensors; F_o, the Frost beamformer output; S_i, the desired signal received at each sensor/channel; and n_i, the noise component of the received signal at each sensor.

4. Adaptive Embedded Measurement Design

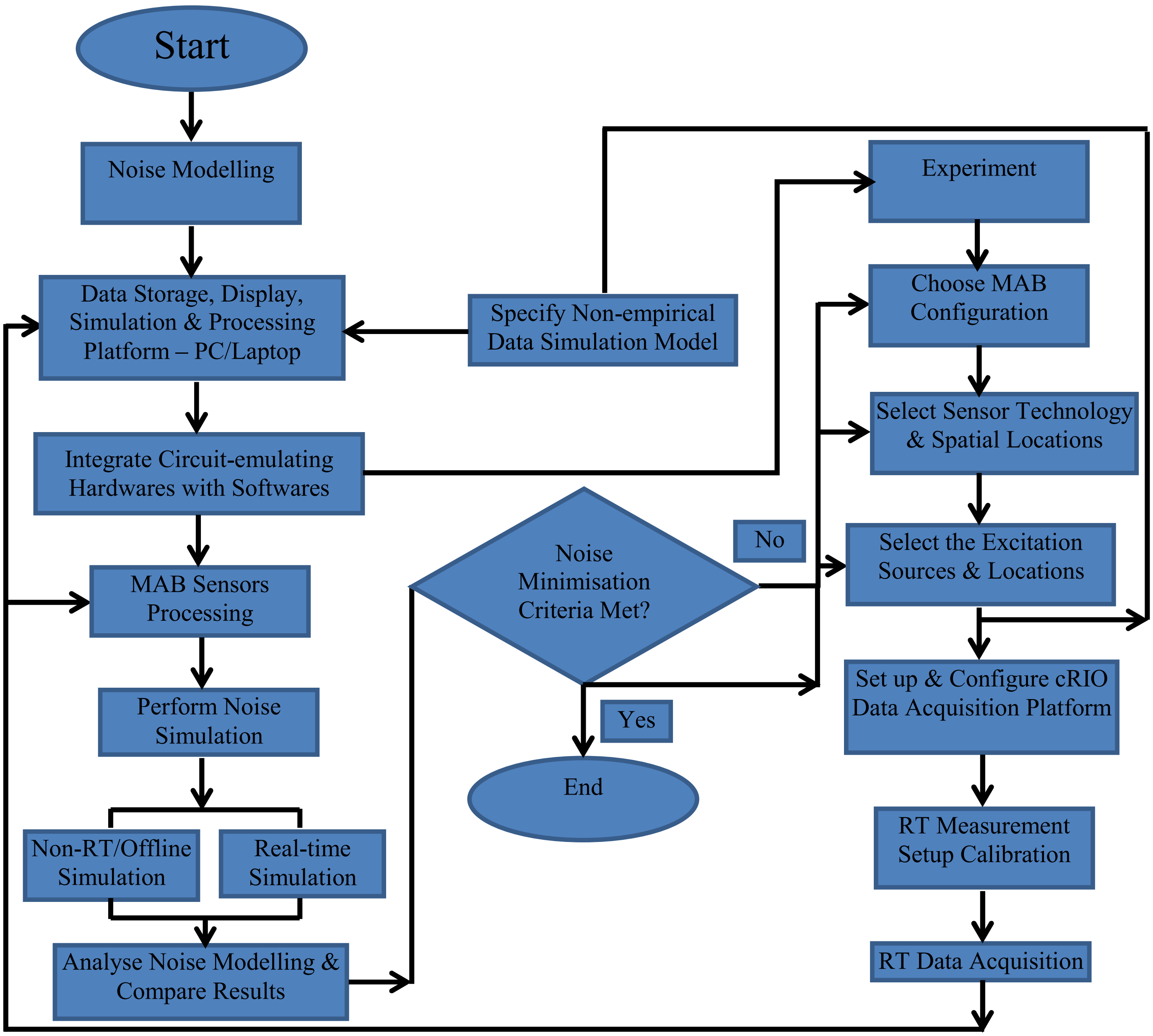

Fig. 1. An Adaptive Embedded Measurement Flowchart for Acoustic Noise Modelling

The adaptive embedded measurement flowchart is given in Fig. 1. The compact RT input/output (cRIO) data acquisition platform is an integrated embedded system development, prototyping and characterisation environment that bears a RT adaptive target device called field programmable gate arrays (FPGAs). This enables deterministic measurements and in situ test scenarios to be accomplished with recourse to integrated multi-software-hardware development platforms. The adaptive embedded experimental procedure for the acoustic noise characterisation of a dynamic system includes the following:

- Choose the number of sensors for the noise modelling and identify the spatial location points for the sensors;

- Choose a microphone array beamforming (MAB) mapping configuration for the array elements; select arbitrary excitation or sound source(s); develop a mapping of the array combinations and beamform-steering strategies;
- Identify the generic static and dynamic noise sources and locations and their neighbouring sensors; surface-mount the omnidirectional sensors (such as microelectromechanical system (MEMS)-based microphones) at the specified spatial locations for the sensors; connect the sensors to their respective channels on the cRIO data acquisition module(s); the output of the cRIO-based RT data acquisition platform is connected to a PC/laptop running a RT operating system and data extraction softwares;
- Calibrate the measurement set up and obtain the noise conditions of the channels and connected devices; trigger the set up for a zero-excitation noise data acquisition and a known excitation noise data acquisition;
- Repeat the procedure for directional conventional MEMS, digital CMOS-based MEMS – in each case, investigate the various MAB mapping configurations and spatially distributed excitation sources; link the acquired data with the noise model simulation environment for a RT (and an offline) modelling and analyses; and
- Calibrate the system at appropriate intervals of time for time-variant noise parameters of resident noise sources while keeping the time-invariant noise parameters constant.

5. Results and Discussion

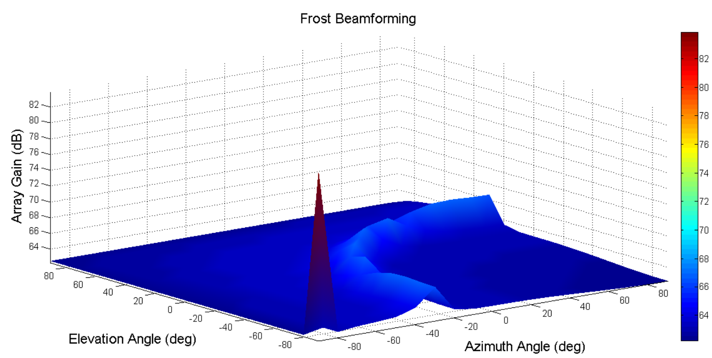

Fig. 2. SNR-based System Selectivity Gain of the Frost Beamformer

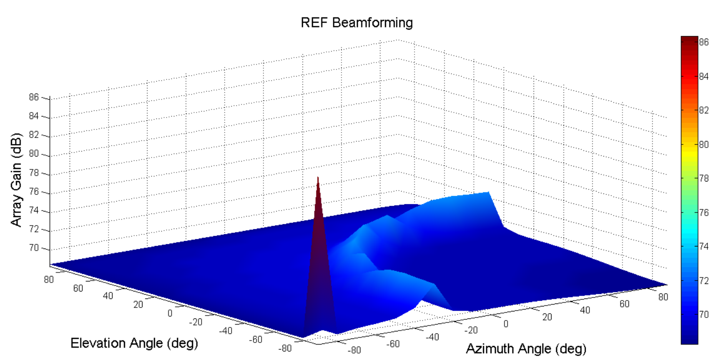

Fig. 3. SNR-based System Selectivity Gain of the REF Beamformer

Figures 2 and 3 show the SNR-based dynamic system selectivity gains of the ULA based on the residual noise extraction technique; the REF outperforms the conventional Frost beamformer by 3 dB. The broadside gain (Fig. 4) for the ULA reveals over 10-dB gain enhancement by the REF compared with the CFB. At the incident azimuth and elevation angles of -30° and 0° respectively, the REF yields a SNR-based steering gain of approximately 6 dB over the CFB.

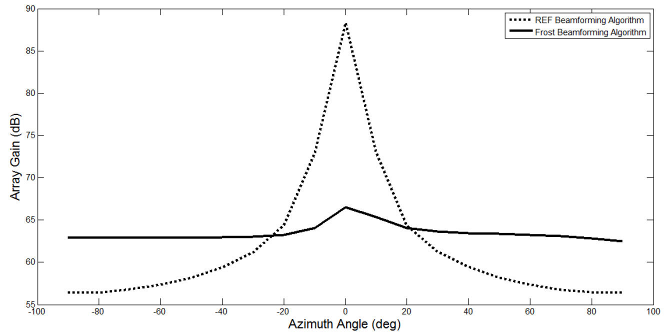

Fig. 4. SNR-based Broadside Gain for the ULA ($N = 4$; $d = 10$ cm; Filter Length = 4)

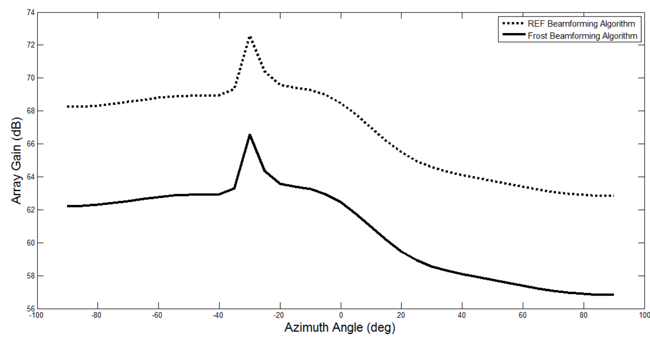

Fig. 5. SNR-based Steering Gain for the ULA at (-30,0) ($N = 2$; $d = 12$ cm; Filter Length = 2)

6. Conclusions

An adaptive embedded system-based measurement platform has been presented in this paper for the noise characterisation of dynamic systems including automobile applications. The regulated-element algorithm yields better residual noise extraction capabilities than the conventional Frost beamformer resulting in a better gain enhancement and deployment of less sensors and filter elements.

References

[1] McCowan, I., "Microphone Arrays: A Tutorial," *PhD Thesis*, pp. 8, 21–23, 26, April 2001.

[2] Lewis, J., "Microphone Array Beamforming: Application Note," *Analog Devices publication,* pp. 7, 2012

[3] M. Štrupl, and P. Sovka, "Analysis and Simulation of Frost's Beamformer," *Radioengineering*, vol. 12, no. 2, pp. 1–9, 2003.

[4] S. Chern, and C. Sung, "The Hybrid Beamforming Algorithm for Multiple Jammers Suppression," *Signal Processing*, vol. 43, pp. 113–127, 1995.

[5] H. Hung, S. Chang, S. Chen, and C. Chang, "Real-time Implementation of Frost Beamformer for Underwater Communications," *Journal of Marine Science and Technology*, vol. 7, no. 1, pp. 1–7, 1999.

[6] B. Veen, and K. Buckley, *Beamforming Techniques for Spatial Filtering,* CRC Press, 1999.

[7] Frost's Beamforming. http://www.labbookpages.co.uk/audio/beamforming/frost.html.