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Reverberation cancellation in a closed test section of a wind tunnel using a multi-microphone cesptral method

D. Blacodon*, J. Bulté

Acoustic Unit Computational Fluid Dynamics and Aeroacoustics Department, ONERA, BP 72 – avenue de la, Division Leclerc, FR-92322, Chatillon Cedex, France

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ABSTRACT

Nowadays, although aerodynamic data are still primarily sought after during wind tunnel tests, reliable acoustic measurements also become a priority for aircraft designers. In order to gather both kinds of data, aerodynamic and acoustic tests are carried out simultaneously under the same closed test section. This solution has two major drawbacks: the acoustic signals delivered by microphones may be corrupted by the boundary layer expanding on the wind tunnel walls and by the reverberant noise originating from reflective surfaces. Technological solutions can be deployed to reduce the corruption of the signals by the wind tunnel background noise. Methods based on the power cepstrum can be used to reduce reverberation effects by removing the quefrencies due to the echoes in the cepstral domain.

The difficulty of the cleaning operation is to separate the quefrencies of the echoes from those of the echo-free signal. The proposed solution overcomes this difficulty with a multiple microphone power cepstrum method. It allows us to estimate, in a blind way, the quefrencies responsible for the corruption by echoes to carry out the reverberation cancellation operation. This method was successfully applied on numerical simulations and experiments conducted in the closed test section of a wind tunnel without and with flow noise.

1. Introduction

Wind tunnel testing constitutes a crucial step in the aircraft design cycle, and there is a need to continuously develop the technologies employed, and the advanced signal processing methods to facilitate the delivery of final validated data. In the testing of aircraft models, the aerodynamic measurements remain the main objective for the experiments carried out in a wind tunnel. However, acoustic measurements become more and more necessary today due to environmental considerations. An accurate procedure to carry out these two kinds of measurements is first to perform the aerodynamics in a closed jet wind tunnel and then the acoustics in an open jet wind tunnel. Another procedure consists in performing the aerodynamics in conjunction with the acoustics measurements in the same closed wind tunnel. During this activity, the aim is to measure the pressure field radiated from a representative scale model with a flush mounted array of microphones, without any absorbent panel installed on the walls of the test section. This kind of configuration allows us to reduce test cost and duration, but two major issues arise if one wants to characterize the acoustic sources radiated by the aircraft models: (i) the corruption of the

* Corresponding author. Tel.: +33 146 734 805.
E-mail address: Daniel.Blacodon@onera.fr (D. Blacodon).

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Nomenclature

A	arbitrary constant
$C_S(\tau)$	power cepstrum of $s(t)$
$\hat{C}_S(\tau)$	cleansed power cepstrum
$C_Y^m(\tau)$	power cepstrum of $y_m(t)$
$C_H^m(\tau)$	power cepstrum of $h_m(t)$
f	frequency in Hertz
f_s	sampling frequency in Hertz
$h_m(t)$	acoustic impulse response between the source S and the mth microphone
$h_m^{-1}(t)$	inverse of $h_m(t)$
$H_m(f)$	power spectral density of $h_m(t)$
$n_m(t)$	additive wind tunnel noise background noise measured by the mth microphone
$N_m(t)$	power spectral density of $n_m(t)$
M	number of microphones in the array
S	acoustic source
$s(t)$	echo-free signal
$\tilde{s}(f)$	Fourier transform of $s(t)$
$S(f)$	power spectral density of $s(t)$
t	time in seconds
$x_m^d(t)$	de-noised signal
$X_m^d(f)$	de-noised power spectrum
$y_m(t)$	noisy signal measured by the mth microphone
$\tilde{y}_m(f)$	Fourier transform of $y_m(t)$
$Y_m(f)$	power spectral density of $y_m(t)$
$\otimes$	convolution operator
δ_{ij}	Kronecker symbol
Δt	sampling interval $(1/f_s)$
τ	quefrency

microphone signals by the boundary layer expanding on the walls of the wind tunnel, and (ii) the reverberant noise originating from reflective surfaces within the test section.

Solutions were investigated for reducing the spurious effects of these two unwanted phenomena. A technological approach such as microphones behind Kevlar membranes [1] was examined, to reduce corruption by the boundary layer. Other noise reduction algorithms belonging to a class of multi-microphone solutions were investigated such as spectral estimation using a noise reference [2], signal subspace [3], and diagonal removal [4]. Another popular solution uses the spectral subtraction method to reduce noise contamination [5]. It is based on the subtraction of the short-term spectral magnitude of noise from that of the noisy spectrum. A generalized form of the basic spectral subtraction is given in [6] where power spectral subtraction uses power spectrum estimates instead of a magnitude spectrum.

Techniques were also proposed to reduce the spurious effects of reverberant noise in the measured signals. Some of them, like the inverse filtering, assume that the acoustic impulse responses between the sources and the microphones are known (e.g., from measurements, or by an estimation procedure), which allows us to construct an operator to cancel the reverberation effects. In the single-microphone case, the inverse filtering is imprecise and, thus, cannot completely eliminate the spurious effects of the echoes in the signal [7]. In contrast, multi-microphones inverse filtering offers the advantage of performing an ideal cancellation of reverberation [8]. However, numerical problems may occur to evaluate the inverse of the acoustic impulse responses. The solutions are quite sensitive to the accuracy of either the measured or the estimated acoustic impulse responses that are needed in the methods. In particular, this is the case when a large amount of background noise is present in the measured signals [9]. Some methods of reverberation cancellation do not require any prior knowledge of the acoustic impulse response, like the beamforming technique [10]. These very popular techniques are based on a spatial focusing to capture the sound coming from the direction of the source of interest, whereas acoustic waves coming from other directions are attenuated, thus reducing reverberation. However, beamforming techniques take into account only the direct path of the acoustic impulse responses. The performance of reverberation cancellation by beamforming is thus limited, especially in highly reverberant acoustic environments. Another class of methods is based on single microphone power cepstrum [11,12]. Such methods rely on the idea that the power cepstrum of the acoustic impulse response signal is generally concentrated around the origin of the quefrencies (corresponding to the frequencies for the spectrum), whereas that of the echo is composed of pulses (or delta functions) located away from the origin.

A very simple way to perform reverberation cancellation consists in achieving low-quefrency liftering (corresponding to filtering), or peak-picking with a comb filter. There are also methods to remove reverberation based on the complex cepstrum [13]. In contrast to the power cepstrum, the complex cepstrum retains the phase information of the signal corrupted by echoes. Thus, it can be used not only for echo cancellation but also for the recovery of the original temporal signals with homomorphic deconvolution techniques [14]. However, problems are encountered in the processing of complex cepstrum linked to discontinuities present in its phase. This drawback can be removed by the use of unwrapping techniques [15].

The power cepstrum is considered in the present paper because it is quite suitable for determining the directivity of acoustic sources radiating in the non-anechoic test section of a wind tunnel, measured in the far field by a microphone array. However, reverberation cancellation based on single microphone power cepstrum implies first selecting those quefrencies due to the echoes in the power cepstrum that must be removed. This process must be done with caution since not all the delta functions in the cepstrum are due necessarily to the echoes. For example, the power cepstrum of an echo-free coherent signal resembles a coherent signal with echoes. A second difficulty may occur, because of the overlapping of the power cepstra coming from both the clean signal and the acoustic impulse response. These problems make it difficult to use the single microphone power cepstrum for performing reverberation cancellation in practice. In order to mitigate these two