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Identification of the formation of resonant tones in compressible cavity flows

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ABSTRACT

Identification of the fluid dynamic mechanisms responsible for the formation of resonant tones in a cavity flow is challenging. Time-frequency non-linear analysis techniques were applied to the post-processing of pressure signals recorded on the floor of a rectangular cavity at a transonic Mach number. The results obtained, confirmed that the resonant peaks in the spectrum were produced by the interaction of a carrier frequency (and its harmonics) and a modulating frequency. High-order spectral analysis, based on the instantaneous wavelet bi-coherence method, was able to identify, at individual samples in the pressure–time signal, that the interaction between the fundamental frequency and the amplitude modulation frequency was responsible for the creation of the Rossier–Heller tones. The same technique was also capable to correlate the mode switching phenomenon, as well as the deactivation of the resonant tones during the temporal evolution of the signal.

1. Introduction

The requirement for modern aircraft to have a reduced radar-cross-section (RCS), as well as improved aerodynamic performance, has introduced the need to incorporate weapon bays in the designs of the next generation of military aircraft. When the bay doors open, the flow in the weapon bay becomes highly turbulent and unsteady, posing a hazard to any desired weapon release. Moreover, airframe and weapon can be damaged by the intense acoustic field that is developed by the flows, which can produce unsteady pressure levels of up to 170 dB at particular resonant modes. As shown by Rockwell and Naudasher [1], these phenomena are strongly dependant on the geometry as well as on the free-stream conditions. The frequencies, at which the resonance occurs, called Rossiter modes (from the pioneering work of Rossiter [2]), can be estimated, in compressible flow, using Heller and Bliss's semi-empirical method [3]. Both the Rossiter and Heller methods were developed for rectangular cavities; however, these equations cannot predict the distribution of the modal amplitudes, which vary greatly depending on the flow condition and cavity geometry. Previous experiments relating to rectangular cavities of various depths have been conducted to study the unsteady fluctuations and to understand the physics behind the phenomenon. Tracy and Plentovich [4] correlated the effect of geometrical parameters and Mach number to the sound pressure level (SPL) and overall sound pressure level (OASPL) distributions inside the cavity, while Ahuja and Mendoza [5] studied the effect of other parameters such as the boundary layer thickness at the cavity's leading edge.

Whilst the basic assumption of the Rossier–Heller theory on resonating cavities is that the phenomenon is statistically stationary and composed of non-harmonic tones, more recent studies have revealed a more complex nature underlying the oscillating mechanism. Kegerise et al. [6] demonstrated that cavity flow is subject to non-statistically-stationary behaviour, in particular to what is called 'mode switching', i.e. a process whereby the dominant energy shifts from one resonant tone to another as the signal evolves in time. Such behaviour was demonstrated by analysing the pressure histories using the time-frequency analysis capabilities of the wavelet transform. Additionally, it was discovered that the flow is also affected by non-linearities, such as quadratic frequency and phase coupling. These features appear in the frequency spectrum as additional peaks, accompanying the main Rossier–Heller tones. Utilising high-order spectral analysis (HOSA), Kegerise et al. [6] classified such additional tones as the result of quadratic coupling between the principal tones. A subsequent study by Delprat [7] introduced a new model for the resonating mechanism, which explained the additional peaks as well as the main ones. It was observed that the Rossier–Heller tones could be interpreted as the result of a frequency shift (i.e. an amplitude modulation) of

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Nomenclature

C_p	pressure coefficient	
D	cavity depth	m
f	frequency	Hz
f_n	Nyquist frequency ($f_s/2$)	Hz
f_r	frequency resolution	Hz
f_s	sampling frequency	Hz
i	imaginary unit	
L	cavity length	m
M	Mach number, characteristic modes of the signal in the Strouhal number domain	
m_n	nth Rossiter–Heller mode	
p	static pressure	Pa
q	dynamic pressure	Pa
St	Strouhal number ($f \cdot L/U_\infty$)	
T	temperature	K
U	flow speed	$\mathrm{m\,s^{-1}}$
W	cavity width	m
γ	modulation parameter	
δ	boundary layer thickness	mm
μ	mean value	
σ	root mean square	
ω	angular velocity ($2\pi \cdot f$)	$\mathrm{rad\,s^{-1}}$
$\bar{x}$	time averaged value of the discrete time series $x_n \left(\sum_{j=1}^{N} x_j/N\right)$	
$\hat{X}$	discrete Fourier transform of the variable x	
X^*	complex conjugate of the variable X	
$\langle x_n \rangle$	expected value of the discrete time series $x_n \left(\sum_{j=1}^{N} x_j/N\right)$	

Abbreviations

BC	bi-coherence	
BP	bi-phase	rad
DFT	discrete Fourier transform	
FFT	fast Fourier transform	
FPL	fluctuating pressure level	dB
GWSP	global wavelet spectral power	dB
HOSA	high order spectral analysis	
IWBC	instantaneous wavelet bi-coherence	
OAFPL	overall fluctuating pressure level	dB
OASPL	overall sound pressure level	dB
PSD	power spectral density	
RCS	radar cross section	
SPL	sound pressure level	dB
STFT	short-time Fourier transform	
WAVT	wavelet average variance trend	dB
WSP	wavelet spectral power	dB

Subscript

∞	freestream conditions

a frequency-modulated wave. Delprat [7] proposed the following equation for a generic Rossiter tone of nth order (f_n).

$$f_n = (n-\gamma)\cdot[f_a \pm k\Delta f] \quad n = 1, 2, 3, \ldots \tag{1}$$

In Equation (1), f_a is the fundamental frequency loop of the cavity (also called the 'carrier frequency'), γ is the modulation parameter, or the ratio of the amplitude modulation frequency f_b to f_a, Δf is the modulating frequency (which usually coincides with the lowest frequency peak in the spectrum), and k is an integer. From this supposition, Delprat [7] derived the pseudo-harmonic approximation. Hence, the Rossiter tones can be deduced from a knowledge of the carrier frequency, the modulating frequency, and the amplitude-modulation frequency.

One significant outcome of this model was the evidence of an amplitude-modulation mechanism of the fundamental frequency that acted as a frequency shifter and generated the non-harmonic Rossiter tones. It was also responsible for the mode switching phenomena with temporal variation of the parameter γ [7]. Additionally, a very low frequency component, which in the past was considered the result of background noise, was identified as a true physical phenomenon. Kegerise et al. [6], using bi-spectral analysis observed that the fundamental frequency, f_a, experienced amplitude modulation at the Δf frequency, whilst frequency-modulation behaviour was observed in the time-frequency analysis. Nevertheless, no significant coupling between the Rossiter modes and the Δf frequency could be established; the same was true for the frequency shift operated by the amplitude modulator. As pointed out by Delprat [7], that was an expected outcome because frequency-based bi-spectral analysis cannot resolve FM/AM phenomena since no information is given regarding the temporal evolution of the coupling. The spectrogram itself has difficulties in analysing such complex phenomena since it cannot increase the resolution in time without losing resolution in frequency.

In this study, pressure histories were obtained from wind tunnel experiments on a simple rectangular cavity with a length-to-depth ratio of five and at a Mach number of 0.81. Then, using wavelet analysis as the base transform for HOSA methodologies, the non-linear mechanisms proposed by Delprat's model were explored.

Fig. 1. Transonic wind tunnel with side door removed; flow direction right to left.

2. Experimental setup

Experiments were performed in the closed-circuit, ejector-driven, transonic wind tunnel, located at the Defence Academy of the UK at Shrivenham (Fig. 1). The tunnel has a working section 500 mm long, 206 mm high and 228 mm wide. The air supply is provided by a Compair L110-10 compressor, dried, and stored in a 34 m^3 reservoir. The wind tunnel is designed to operate in the Mach number range from 0.5 to 1.4, and is controlled, via a feedback mechanism, by the air inlet main control valve. At a working section Mach number of 0.81, and with a reservoir

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