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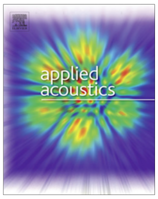

Time-frequency analysis of acoustic signals from a high-lift configuration with two wavelet functions

Ling Li, Peiqing Liu, Yu Xing, Hao Guo [*]

Institute of Fluid Mechanics, Beihang University, Beijing 100191, People's Republic of China
Key Laboratory of Fluid Mechanics (Beihang University), Ministry of Education, Beijing 100191, People's Republic of China

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ABSTRACT

This paper introduces the continuous wavelet transform method to analyze different multiple tonal phenomena of the high-lift configurations, aiming at revealing the time-frequency information of these multiple tones simultaneously. Two types of multiple tones can be respectively observed in the far-field noise spectra at landing and cruise configurations, but their inherent physical mechanisms are different. Two wavelet functions are applied in this paper. The Morlet function as a complex wavelet function returns both amplitude and phase information for capturing oscillatory behaviors, so that it can clearly distinguish the mode switching mechanism and the amplitude modulation mechanism of different multiple tonal phenomena. While the Mexihat function as a real wavelet function returns only amplitude information, so that it is usually to isolate peaks or discontinuities of signals and cannot reveal the mechanisms of different multiple tonal phenomena. In summary, the Morlet function is more appropriate to analyze the periodical oscillatory acoustic tonal signals from multiple tonal phenomena.

1. Introduction

In the last decades, people have paid more attention to the civil aircraft noise in consideration of comfort and economy, especially during the phases of takeoff and landing. In the last 40 years, the engine noise has been significantly reduced by 20–30 dB with the introduction of turbofan engines and the application of high-bypass ducts and serrated nozzles. Thus, airframe noise has become a major contributor, especially during the approach and landing phases when the engines operate at low power setting and the high-lift devices and landing gears are fully deployed. Generally, the landing gears and high-lift devices with slats and flaps are regarded as the dominant airframe noise sources. More recently, there has been considerable interest in both numerical and experimental sides to investigate the noise generated from high-lift configurations [1–4].

Generally, the far-field noise of high-lift configurations can be categorized into two parts, namely the broadband noise and the discrete tonal noise. For most high-lift configurations, the noise spectra are usually governed by several discrete tones, but the associated noise sources and the noise generation mechanisms are different. Three types of multiple tones have been observed in the noise spectra of high-lift configurations, and the corresponding noise sources are the slat cove region [5–10], the trailing edge [11] and other small cavities such as pin holes [12], respectively.

The multiple tonal phenomenon related to slat cove has been widely studied before, and the tonal noise generation mechanism is attributed to the fluid-dynamic resonance inside the slat cove region, quite similar to the cavity noise mechanism. Khorrami et al. [5] performed a detailed computational aeroacoustic analysis of a high-lift device and found several mid-frequency tones in the far-field noise spectra. Yamamoto et al. [6] also found that these multiple tones were radiated from a three-dimensional high-lift wing, but the associated mechanism was not discussed. Roger and Pérennès [7] firstly suggested that the separated shear layer in the slat cove region and the pressure wave generated from the reattachment point could form a self-sustained feedback loop and radiated tonal noise. Hein et al. [8] simulated the acoustic resonant phenomena of a cylinder with a rectangular cutout model and a high-lift configuration, and pointed out that the dominant resonance in slat cove is similar to the cavity resonance. Recently, Terracol et al. [9] modified the Rossiter's formula to predict the tonal frequencies, and the predicted values agreed well with both experimental and numerical results [9,10].

Other types of multiple tones are normally radiated from special high-lift configurations. Makiya et al. [11] experimentally investigated the slat trailing edge noise of a NACA23012 configura-

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[*] Corresponding author at: Institute of Fluid Mechanics, Beihang University, Beijing 100191, People's Republic of China.
E-mail address: guohao@buaa.edu.cn (H. Guo).

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tion and observed several spectral peaks at moderate Reynolds number. Moreover, these tonal frequencies changed with a ladder-type variation when increasing freestream velocity, which is quite similar to the features observed from single-element airfoils [13–19]. Hence, Makiya et al. [11] pointed out that the tonal noise was generated from another feedback loop phenomenon between the boundary layer instability waves (i.e., Tollmien-Schlichting waves) upstream of slat trailing edge and the acoustic waves at slat trailing edge. Pott-Pollenske et al. [12] conducted a flight test of an A319 aircraft and found that the pressure release hole in the lower wing surface would generate intense multiple tones. Recently, Li et al. [20] have measured the far-field noise of the 30P30N configuration in the cruise condition, i.e., both the slat and flap are stowed. Several mid-frequency tones are presented in the noise spectrum, and the noise source is conjectured to be located in the flap-main element gap.

However, previous studies generally used the traditional power spectral method to analyze these multiple tonal phenomena. The traditional power spectral method is based on the time-averaged Fourier transform, such that the temporal information of multiple tones has been missed, and the potential nonlinear interactions between different tones cannot be revealed. For the 30P30N high-lift configuration, previous experiments [20] show that two types of multiple tones can be observed at landing and cruise configurations, respectively. The noise spectra are similar and the frequency spacings between adjacent tones are approximately same, but the noise sources are quite different. In order to distinguish the inherent physical mechanisms of these multiple tonal phenomena, the continuous wavelet transform method is introduced and two wavelet functions are applied. The choice of the wavelet function plays an important role in identifying the properties of the analyzed signals. Two wavelet functions, namely the Morlet function and the Mexihat function are usually chosen in the signal-processing field of fluid induced problems. Pröbsting et al. [15–17] and Padois et al. [18] used the Morlet function to analyze the velocity and acoustic signals from single-element airfoil and they all found the amplitude modulation phenomenon. Kaspersen and Krogstad [21] used the Mexihat function to detect the energetic structures of a zero pressure gradient boundary layer flows. Hamdan et al. [22] analyzed the flow-induced vibration problem of a cylinder in cross flow using various basic wavelet functions and found that the Morlet function seemed to give the reasonable and adequate results. Since the multiple tonal phenomena of high-lift configurations have not been investigated with time-frequency analysis before, the appropriate wavelet function for far-field acoustic analysis will be determined in this paper.

The aims of the present paper are to reveal and distinguish the inherent physical mechanisms for two types of multiple tones using continuous wavelet transform method. Two wavelet functions are introduced and the results are compared to determine a more appropriate function for acoustic signals analysis. The organization of this paper is as follows. In Section 2, the experimental setup is described. In Section 3, the continuous wavelet transform is briefly introduced. In Section 4, the experimental results are presented and analyzed. Finally, this paper is concluded in Section 5.

2. Experimental setup

Experiments are conducted in D5 aeroacoustic wind tunnel at Beihang University. The D5 aeroacoustic wind tunnel is an open-jet, closed-circuit wind tunnel, and the test section is 2.0 m in length with a square cross section of 1.0 m by 1.0 m. An anechoic chamber with 6.0 m in length, 6.0 m in width and 7.0 m in height is built surrounding the test section to provide a non-reflecting condition, and the cut-off frequency is 200 Hz. The wind speed can be continuously controlled from 0 to 80 m/s with the turbulence intensity less than 0.08% in the core of the jet [23]. It should be mentioned that the test section is reconstructed according to the Virginia Tech Anechoic Wind Tunnel [24] with Kevlar cloth and perforated plate to ensure the test section aerodynamically closed and acoustically open. Although little noise energy loss may occur during the radiation process, the tonal frequencies and the modulation effect are not influenced. Hence, no corrections are applied to the acoustic signals.

The experimental model is 30P30N three-element supercritical high-lift configuration from BANC (Benchmark Problems for Airframe Noise Computations) Workshop [25,26]. As shown in Fig. 1, the 30P30N configuration is mounted vertically between two endplates to ensure the two-dimensional flow condition around the configuration. The stowed chord c of the experimental model is 0.457 m and the span is 1 m. The slat and flap chords are approximately equal to 15%c and 30%c, respectively. The deflection angles of slat and flap (denoted as δ_s and δ_f,respectively) are 30° when fully deployed. For the approach configuration in the present study, the slat and flap gaps are 2.95%c and 1.27%c with overlap settings of $-2.95\%c$ and 0.25%c, respectively. Both the slat and flap can vary continuously in order to measure the acoustic features of the model in different conditions.

Two cases are discussed in this paper. The first case is the landing configuration with slat and flap both fully deployed and their deflection angles $\delta_s = 30^\circ$ and $\delta_f = 30^\circ$, respectively. The second case is the cruise configuration with slat and flap both fully stowed, and this configuration is quite similar to a single-element configuration. For the two cases, the angle of attack is 7° and the freestream velocity is 35 m/s, corresponding to the Reynolds number based on the stowed chord of 10^6.

The far-field noise is measured in the anechoic chamber by a 1/2 inch free field microphone. The microphone is placed at 5c far away from the center of the model pressure side, as seen from Fig. 1. The acoustic signal is acquired at 65536 samples/s and the record time is 10 s.

3. Continuous wavelet transform method

In contrast to traditional power spectral method, the continuous wavelet transform method is a joint time-frequency analysis method which can decompose a time series into time and frequency spaces simultaneously. The continuous wavelet transform can be defined as [27,28]:

$$W_x(\tau, a) = \int_{-\infty}^{\infty} x(t)\Psi^*_{a,\tau}(t)dt \tag{1}$$

where W_x is the wavelet coefficient, $x(t)$ is the time series of experimental signal, $\Psi_{a,\tau}(t)$ is the wavelet function, and the symbol $*$ denotes the complex conjugate. The wavelet function is obtained by varying the wavelet scale a and the time delay $\tau$of the mother wavelet function $\Psi(t)$ as:

$$\Psi_{a,\tau}(t) = a^{-1/2}\Psi\left(\frac{t-\tau}{a}\right) \tag{2}$$

Two basic mother wavelet functions are introduced and compared in this paper. The first is the Morlet wavelet function and the other is the Mexihat wavelet function. The Morlet function is a complex function and is defined as:

$$\Psi(t) = e^{i\omega_0 t}e^{-t^2/2} \tag{3}$$

where the parameter ω_0 is the non-dimensional frequency and usually taken to be 6 to satisfy the admissibility condition [29]. Moreover, for the Morlet wavelet transform, the wavelet scale a and the