EXPERIMENTAL DETERMINATION OF FREQUENCY OF LAMINAR-BOUNDARY LAYER INSTABILITY NOISE OF NACA 0012

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Abstract

This paper presents simple method and new results of experimental investigation of laminar boundary-layer instability noise of an airfoil. The experimental method is based on small electret microphones, which are built in to the surface of the measured airfoil segment in pinholes. The paper discusses evaluation of the experimentally obtained data and presents new results for laminar boundary-layer vortex-shedding tonal sound frequency of NACA 0012. The main attribute of the proposed experimental method is the possibility of its usage in a non-aeroacoustic facility.

Keywords: laminar boundary-layer noise, aeroacoustic measurements, NACA 0012.

1 Introduction

Laminar boundary-layer instability noise of an airfoil is one of the five noise-generation mechanisms of an airfoil, as described by Brooks et al. [1]. This phenomenon was first explored by Paterson et al. in 1973 [2]. Later, this laminar boundary-layer instability noise, which is referred to as laminar vortex-shedding noise [3], was studied numerically [4, 5] and experimentally [3, 6]. The experimental studies were carried out in aeroacoustic wind tunnels, i.e., the background noise was suppressed and the wind tunnel test section was inside the anechoic chamber. The laminar vortex-shedding noise (or laminar boundary-layer instability noise) is connected to the Tollmien–Schlichting waves [7, 3]. These hydrodynamic instabilities cause the excitation of the wake behind the airfoil, and therefore the generation of lateral vibration of the wake flow which acts as a major sound source. [7] However, the existence of Tollmien–Schlichting waves itself is not a sufficient condition for emission of the perceivable tonal sound [3, 8].

This paper aims to describe a measurement that was specifically designed for a general wind tunnel without special acoustic treatment. The measurement settings consists of three electret microphones inside the surface of the tested NACA 0012 airfoil, and of two microphones outside the airflow. A part of the measurement setup was initially tested for obtaining the pressure spectra for turbulent boundary layer [9]. The built-in microphone technique was chosen due to its ability to capture weaker sound source than the microphones outside the airflow.

2 Measurement Setup

The measurement setup consists of three small built-in microphones CMC-4015-25L100 by CUI Devices, which were chosen based on their price and sensitivity. It was shown in [9], it is not necessary to use an amplifier for the signal from these microphones. Data acquisition of the voltage signal from these electret microphones was carried out using a NI cDAQ device with NI 9250 and NI 9230 modules. The microphone capsule was placed inside the airfoil below the surface, the diameter of the pinhole in surface matches the diameter of the hole (which is 0.9 mm) in the microphone casing. The only cavity in this setup is inside the microphone casing.

The pinhole diameter 0.9 mm should yield a lower frequency resolution for low-wavelength waves; therefore, the microphone should primarily correctly capture the acoustic noise rather than direct pressure change caused by Tollmien–Schlichting waves. The hydrodynamic wavelength (i.e., wavelength of Tollmien–Schlichting waves) is smaller than the acoustic wavelength [10]. According to Roger [10], the acoustically compact sensor is defined as

\[ k \cdot r_0 \rightarrow 0 \]  

(1)
where \( k \, [m^{-1}] \) is the wavenumber, and \( r_0 \, [m] \) is the radius of the circular active area of the sensor. This means that the microphone should be infinitesimally small compared to the wavelength. The active area of microphone spatially averages the measured pressure, therefore for low Mach numbers (for which the wavenumber is of higher order) the microphone significantly underestimates the pressure levels caused by aerodynamic structures due to the spatial averaging. This assumption is also confirmed by the study of Devenport et al. [11], in which they studied frequency resolution for different pinhole dimensions. The measurement presented in this paper is assumed to be conducted under low freestream Mach numbers (in range 0.01 - 0.1); therefore, the convective velocity of instability waves is assumed to be approximately in the range 0.005 - 0.05 of Mach number (based on the estimation of convective velocity provided by Yakhina et al. [12]). The metric defined in Eq. (1) is approximately 20-200 times lower for the waves of acoustic origin than for the waves of aerodynamic origin. Based on this brief analysis, the pinhole diameter of 0.9 mm is suitable for the expected purpose in the frequency range approximately 100 Hz - 1500 Hz and freestream velocity up to 34 m \( \cdot \) s\(^{-1} \) under standard atmospheric conditions.

The placement of the microphone inside the airfoil section is shown in Fig. 1a, an overview photo of the airfoil section with built-in microphone probes is shown in Fig. 1b. The three microphones were placed along the chord length as follows: Mic A at 55 \%, Mic B 68 \%, and Mic C at 80 \% of the chord length. The microphones were calibrated using the Microtech Gefell Kalibrator 4011 before they were placed inside the airfoil section, the sensitivity of the microphones was in the range from 32 mV/Pa to 35 mV/Pa. This built-in microphone setup is similar to the setup in [9].

For the reference acoustic measurement two free-field microphones Microtech Gefell M370 was mounted outside the open test section of the wind tunnel. These microphones are referred to in the results as Ref A - microphone above the leading edge of the airfoil, Ref B - microphone in the plane of the airfoil. These two free-field microphones have mean sensitivity approximately 12.5 mV/Pa.

The airfoil section of NACA 0012 was printed using Prusa SLA 3D Printer, and the surface was perfectly smoothed out to avoid the force transition to turbulence in the boundary layer. The chord length of the airfoil section is 0.1 m, and the span is 0.39 m. The airfoil section is placed between two endplates to eliminate the influence of the tips. At zero angle of attack this setting has wind tunnel blockage ratio around 2.7 \%.

For the measurement, the low-speed wind tunnel of the Department of Fluid Dynamics and Thermodynamics, FME CTU in Prague is used. The possibility of aeroacoustic measurement of this wind tunnel was previously tried out in [13]. This analysis showed suitable properties for the measurement of sound below 4 kHz (the switching frequency of the variable-frequency drive). It is expected that for the investigated type of aerodynamics noise, the peak frequencies are in this suitable range. For the calibration of the airspeed in the wind tunnel, the Pitot-static probe is used. This velocity calibration is done separately of the acoustic measurement, so the acoustic footprint is not contaminated by the sound generated by the Pitot-static probe. This is based on the assumption that every probe in the airflow generates sound. This is also the reason why the hot-wire measurement is not suitable for deeper investigation of the sound-generation mechanism.
in the boundary layer. The method of built-in microphones inside the airfoil surface is more convenient with respect to the generation of unwanted sound by the measurement probes.

The measurement was conducted under steady condition in wind tunnel in the range of velocity from $2.74 \, \text{m} \cdot \text{s}^{-1}$ to $30.89 \, \text{m} \cdot \text{s}^{-1}$ for zero angle of attack. The relevant turbulence intensity is up to 1.03% in velocity range from $2.74 \, \text{m} \cdot \text{s}^{-1}$ to $16.33 \, \text{m} \cdot \text{s}^{-1}$, and in the velocity range from $16.33 \, \text{m} \cdot \text{s}^{-1}$ to $30.89 \, \text{m} \cdot \text{s}^{-1}$ the turbulence intensity is approximately 0.25%. The main sampling frequency was 100 kHz/ch and the derived sampling frequency was 10 kHz/ch. This setup was chosen because of two different NI modules with different maximum sampling frequencies. The timebase for these sampling frequencies was the same, so the obtained signals were synchronized in time. For the processing of the obtained signal, the Welch’s method [14] was used. This method was chosen because of its ability to reject non-periodic noise - i.e., non-periodic background noise of the wind tunnel. This method is based on splitting measured data into overlapping segments and then averaging periodograms of these segments. The key parameters of this method are the length of each time segment, which affects the frequency resolution of the output spectrum, and the number of overlapping points between segments. The frequency resolution of the processed data was chosen to be 1 Hz, this parameter was then used to set the length of the segments.

A brief study of the measurement interval was conducted. Four different intervals of measurement length were chosen and compared. This comparison is shown in Fig. 2. This comparison shows that the time interval of 90 s is enough to suppress unwanted noise in the frequency spectrum and to obtain the correct frequency peaks. A longer time interval would produce cleaner results; however, there would be no additional information in the obtained results. With a longer time interval, the measurement costs more electrical power, and also requires more storage capacity, so the longer measurement is not justified.

The background noise is acquired separately, the spectral subtraction method can be used to further evaluate the measured data [15] with suppressing the background noise of the laboratory. The pressure amplitudes are still only estimations with high measurement error; however, this method is suitable to find peak tonal frequencies, which are usually easily distinguished.

The signals were processed from all of the built-in microphones (Mic A-C) and both of the reference microphones outside the airflow (Ref A-B). In Fig. 3 one selected obtained spectrum is shown. In this selected spectrum, it is possible to clearly identify the primary peak, which is the highest amplitude in the spectrum, at 686 Hz and the secondary peak, which is the second highest amplitude in the spectrum, at 863 Hz. At least one peak is present in all of the acquired signals, and...
such a tonal sound is also usually perceivable by the experimenter during the measurement. For most of the measured points, it was possible to find the secondary peak frequency. In Fig. 3 there are presented measurements of background noise of wind tunnel (i.e., measurement without the airfoil segment) from the reference microphones outside the airflow (Ref A BG and Ref B BG). This presented comparison shows that this experimental method is appropriate for the determination of tonal frequency. The overall evaluated results are presented in the following Section of this paper.

3 Results

The measurement was carried out for 59 velocity settings between $2.74 \text{ m} \cdot \text{s}^{-1}$ to $30.89 \text{ m} \cdot \text{s}^{-1}$, which corresponds with Reynolds numbers range from approximately 19000 to 213000. From each measurement, a peak frequency (or two peak frequencies) was obtained. In Fig. 4 results from all obtained measurement points are presented. This result shows a similar ladder-type structure as originally described by Arbey and Bataille [16] in 1983. The obtained primary frequencies were fitted with the function $a \cdot U_{\infty}^b$, where $U_{\infty}$ is freestream velocity, while the constants $a$ and $b$ must be found using the least-squares method. This fitting function is based on the scaling law proposed by Paterson et al. [2], which is in a slightly modified form as follows:

$$f = \frac{K}{\sqrt{\nu c}} U_{\infty}^b$$

where $f$ [Hz] is primary peak frequency, $c$ [m] is chord length, $\nu$ [m$^2$ \cdot s$^{-1}$] is kinematic viscosity, $b$ is the fitted constant (Paterson et al. [2] originally proposed $b = 1.5$), and $K$ is empirically obtained constant.

Using the fitted function with constants $a = 19.98$ and $b = 1.34$, the constant $K$ is 0.024. Paterson et al. [2] expected theoretical results with $K = 0.02$ and $b = 1.5$, while their experimental work showed results $K = 0.011$ and $b = 1.5$. In Fig. 4 there is shown comparison of the experimentally obtained peaks presented in this paper with results obtained by Paterson et al. The measured frequency peaks in this paper are in between the two results suggested by Paterson et al. This indicates an agreement between the original observation of Paterson et al. and presented new results obtained in non-aeroacoustic facility. The results are presented in form of dimensional frequency.
Figure 4: Primary and secondary tones in all measured points. The Reynolds number characteristic length is chord length of the airfoil.

rather than Strouhal number. The appropriate length scale for Strouhal number is boundary layer thickness at the trailing edge [1], however, the measurement of the boundary layer thickness for this set of data is not available. In Fig. 4 there are obtained primary and secondary peaks, the mechanism of selection of primary tones (i.e. how the primary tone is established) could be subject of further research. Also some other discrete tones present in the spectrum could be consistent with the ladder structure of the presented tonal frequencies.

4 Conclusion

This paper presents a simple method for obtaining the frequency peaks using an experimental approach in a non-aeroacoustic wind tunnel. The designed method is inexpensive and efficient, and the obtained results are possible to evaluate using relatively simple approach. The main attribute of this method is the possibility of determining peak frequencies in the general wind tunnel with background noise.

The new results for the primary peak frequency of the laminar boundary-layer instability noise are presented. The experimentally obtained data were fitted with the function $f = 19.98 \cdot U_{\infty}^{1.34}$. It is also possible to use this method to obtain secondary peak frequencies. The obtained secondary peak frequencies can be used for further evaluation of the aerodynamically generated noise of the NACA 0012 airfoil at low Mach numbers flows.

References


