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Obtaining phase velocity of turbulent boundary layer pressure fluctuations at high subsonic Mach number from wind tunnel data affected by strong background noise

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ABSTRACT

Boundary layer measurements at high subsonic Mach number are evaluated in order to obtain the dominant phase velocities of boundary layer pressure fluctuations. The measurements were performed in a transonic wind tunnel which had a very strong background noise. The phase velocity was taken from phase inclination and from the convective peak in one- and two-dimensional wavenumber spectra. An approach was introduced to remove the acoustic noise from the data by applying a method based on CLEAN-SC on the two-dimensional spectra, thereby increasing the frequency range where information about the boundary layer was retrievable. A comparison with prediction models showed some discrepancies in the low-frequency range. Therefore, pressure data from a DNS calculation was used to substantiate the results of the analysis in this frequency range. Using the measured data, the DNS results and a review of the models used for comparison it was found that the phase velocity decreases at low frequencies.

1. Introduction

Phase velocity of pressure fluctuations beneath a turbulent boundary layer provides important information when predicting the excitation of a surface exposed to the flow. In the process of prediction, a wavenumber spectrum is modeled which - for the turbulent boundary layer flow - consists of a convective ridge. The position of the convective ridge is important to find the modes of the structure which are most likely excited by the flow. The position of the convective ridge is representative of the phase velocity of turbulent structures in the boundary layer acting upon the surface. Modeling the phase velocity is therefore an important part of predicting excitation behavior. Such modeling has been used for instance by Graham [1], by Liu [2], Rocha [3] and by Berkefeld [4] who each used a constant phase velocity with frequency. However, findings by Bull [5], Farabee and Casarella [6], Panton [7], and Abraham and Keith [8] have presented frequency dependent behavior. Determining phase velocity from a wavenumber spectrum is especially suitable for the prediction of excitation as the wavenumber spectrum itself can be used well to describe the excitation potential of a turbulent boundary layer.

Several models have been set up in the past in order to predict the phase velocity of the pressure fluctuations as a function of frequency [9–12] and as a function of transducer separation [13]. It will become apparent that the existing frequency-dependent models deviate strongly in the region of low frequencies. The models were set up at lower speeds

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Nomenclature

$[.]_{est}$	estimated value
$[\ldots]^*$	Hermitian conjugate
Δf	frequency bin width
δ	boundary layer thickness
δ^*	displacement thickness
η	transducer spacing in cross-direction
γ	coherence between two signals
$[\hat{\ldots}]$	normalized values from numerical calculation
κ	von Kàrmàn constant
ω	angular frequency
Φ	cross-spectral density
ϕ	discrete Fourier transform
ρ	density of air
τ_w	wall shear stress
Imag	imaginary part
Ma	Mach number
Real	real part
Re	Reynolds number
θ	polar angle in the wavenumber domain
φ	phase between signals
ξ	transducer separation
a, b	parameters for the Keith/Abraham model
a_{ST}, b_{ST}, c_{ST}, d_{ST}	parameters for the Smol'Yakov Model
f	frequency
f_s	sample rate
i	frequency bin index
j	imaginary unit
K	signal subset index
k	sample index
k_0	acoustic wavenumber
k_c	convective wavenumber
k_x	wavenumber in x-direction
k_x, k_y	wavenumbers in 2D focus grid
N	number of transducers
n, m	transducer indices
N_{avg}	number of averages
N_W	window size
P	wavenumber spectrum
p_0	total pressure
p_∞	static pressure
q	dynamic pressure
R	cross-spectral matrix
T	static temperature
t	measurement duration
T_D	signal delay time
T_W	window time length
u_0	flow velocity
u_τ	friction velocity
u_φ	phase velocity
x	x-position
y	y-position
z	wall distance
z^+	dimensionless wall distance

than in the present investigation which was performed at Ma = 0.8. The highest Mach number used in the experiments for the setup of the models was found to be Ma = 0.5 by Bull [5]. Whether or not the existing models predict the behavior correctly in a condition at even higher subsonic Mach number and low ambient pressures yet has to be determined.

In the present paper, pressure fluctuation data from a measurement in a closed test section wind tunnel is used to determine the characteristics of the phase velocity underneath the turbulent boundary layer. Several analysis methods are used in order to progressively increase the evaluation complexity applied to the experimental data. This approach was chosen in order to compare the results to different past measurements and to conclusively introduce the signal processing method used to remove the background noise in the wind tunnel from the data via signal processing. The validity of this will be shown by applying the wavenumber analysis method to obtain the phase velocity on a numerical dataset.

The measurement conditions under consideration approximate the conditions present during a cruise flight scenario of an airplane. This was done specifically, as the experimental data can then be used in order to check the applicability of the prediction models at flight conditions. This yields the possibility to use them in the prediction of interior cabin noise of an airplane.

The paper is structured in the following way: firstly, the experimental setup and the environmental conditions are described in Section 2. Afterwards, the signal processing methods are introduced in Section 3. A brief overview of several existing models for the prediction of phase velocities is given afterwards in Section 4. The analysis of the experimental data using the signal processing methods presented before is given in Section 5. These methods are ordered to start with simple phase inclinations of several two-transducer combinations (Section 5.2). The complexity of the analyses is then increased to a 1D-wavenumber analysis (Section 5.3) and finally a 2D-wavenumber evaluation in Section 5.4.

The resulting experimental data are compared to the phase velocity prediction models in Section 5.5 and the low-frequency results are verified using the surface pressure data from a DNS calculation in Section 5.6. The current work is then concluded by a discussion in Section 6 and the findings are summarized afterwards.

2. Experimental data

Experiments were carried out in the Transonic Wind Tunnel in Göttingen [14] using a closed test section with adaptive upper and lower walls. A plenum capable of pressurization enclosed the test section which allows variation of both Mach number and stagnation pressure independently of each other. A sketch of the test section is shown in Fig. 1. The experiment