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Aeroacoustic Characteristics of Boundary-Layer Regimes

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Introduction

Sound is one of the physical phenomena that can be perceived directly by human beings, although an observer does not necessarily need to be in close proximity to a source of sound. Usually, humans can readily distinguish between loud and quiet sounds, and between discrete high- and low-pitch tones in an emitted acoustic spectrum. Sound can be described as an acoustic wave that propagates through a medium. The acoustic wave causes a small perturbation in the local static pressure field. Such an acoustic wave can be generated, for example, by vibrating surfaces or by certain local changes in the pressure field. A solid object placed in a moving fluid (e.g., an airfoil in an air flow) produces changes in the pressure field, which can be propagated to the far field in the form of an acoustic wave.

Motivation

This thesis aims to describe the boundary layer as a source of aerodynamic noise, and to study the effects of the boundary-layer transition in the early stages on the acoustic field. This research extends the current aeroacoustic theory and experimentally validates the new theoretical findings, contributing to the field of fundamental research into the aeroacoustics of the boundary layer. The theoretical part of this thesis should bring new insight into the frequency of sound emitted by a laminar boundary layer with linear instabilities.

Objectives of The Thesis

Main hypothesis*: In a laminar boundary-layer regime, the acoustic source is created by a velocity perturbation. If the perturbation is assumed to be of a single mode, the linear Orr--Sommerfeld equation can be used to estimate the acoustic source term of Lighthill's equation for the boundary layer to obtain the peak tone emitted by the laminar boundary layer.*

- Description of the aeroacoustic footprint of a boundary layer experiencing linear instabilities in a laminar regime before the transition to a turbulent regime
  - Theoretical description of the aeroacoustic sources caused by linear instabilities in the boundary layer
  - Proposal of a frequency model for the prediction of laminar boundary-layer instability noise
- Experimental investigation of the boundary-layer instability noise
  - Design of an experiment to validate the obtained theoretical results
  - Further examination of the experimental data---using the experimental data to determine the acoustic feedback length
- Validation of the proposed model and experimental results
  - Validation of the proposed theoretical frequency model and experimental results on the NACA 0012 airfoil with the empirical model

Methods for Achieving the Objectives

The theoretical description of the acoustic footprint of the boundary layer is based on studying linear instabilities in the boundary layer, i.e., the spatial solution of the Orr-Sommerfeld equation. The solution of the Orr-Sommerfeld equation is used with the source term of Lighthill's equation for the boundary layer to obtain the point acoustic source. These acoustic sources is then evaluated to obtain the frequency footprint of the boundary layer. For the case study, the NACA 0012 airfoil is chosen, due to the availability of an empirical model of Brooks, Pope, and Marcolini (1989). The BPM empirical model of NACA 0012 is quite extensive and is used for the validation and comparison of the proposed frequency model. The experimental part includes measurement of acoustic pressure using built-in microphones on the NACA 0012 airfoil. These results are used to confirm the theoretical frequency model and analyze the instability feedback length.

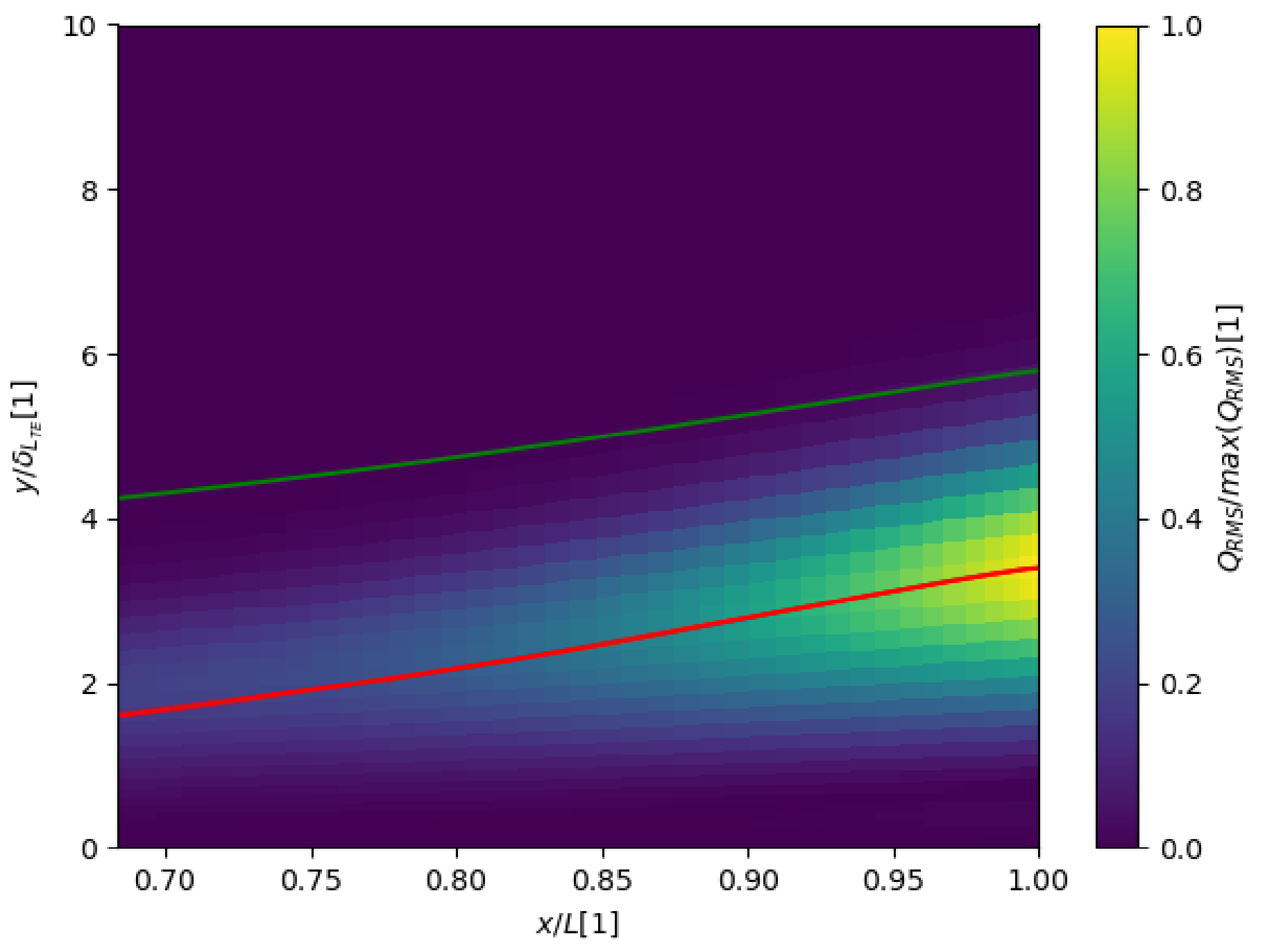

Figure 1: Field of acoustic sources in the boundary layer $Q_{\mathrm{RMS}}(x,y)$ of NACA 0012 with 6.62 m/s freestream velocity and perturbation frequency 293 Hz. The red curve is the local boundary-layer displacement thickness ($\delta^*/\delta_{L_{TE}}$) and the green curve is the local conventional boundary-layer thickness ($\delta/\delta_{L_{TE}}$).

Boundary-layer linear instability noise

The source model for the noise in the boundary layer based on the perturbation stream function are proposed (see Fig. 1). This model only describes the source of noise, without any acoustic effects caused by the presence of the solid wall. This acoustic source model is used to predict the dominant acoustic frequency of the boundary layer caused by linear instabilities. Although the aerodynamically generated noise could be connected to the Tollmien-Schlichting waves, this does not necessarily mean that the frequency of the dominant sound source is the same as the frequency of the most amplified Tollmien-Schlichting waves (see Fig. 2). The noise source depends not only on the amplification factor of the Tollmien-Schlichting waves, but also on their wave number and the magnitude of the perturbation. In the proposed model, the magnitude of the perturbation is normalized to its maximum absolute value. This magnitude of perturbation is influenced by the outer flow (i.e., by the turbulence intensity of the freestream) and cannot be expressed directly. Due to this, the proposed model cannot be used directly to evaluate the acoustic pressure in the far field (i.e., the sound pressure level) and evaluate whether the emitted sound is audible.

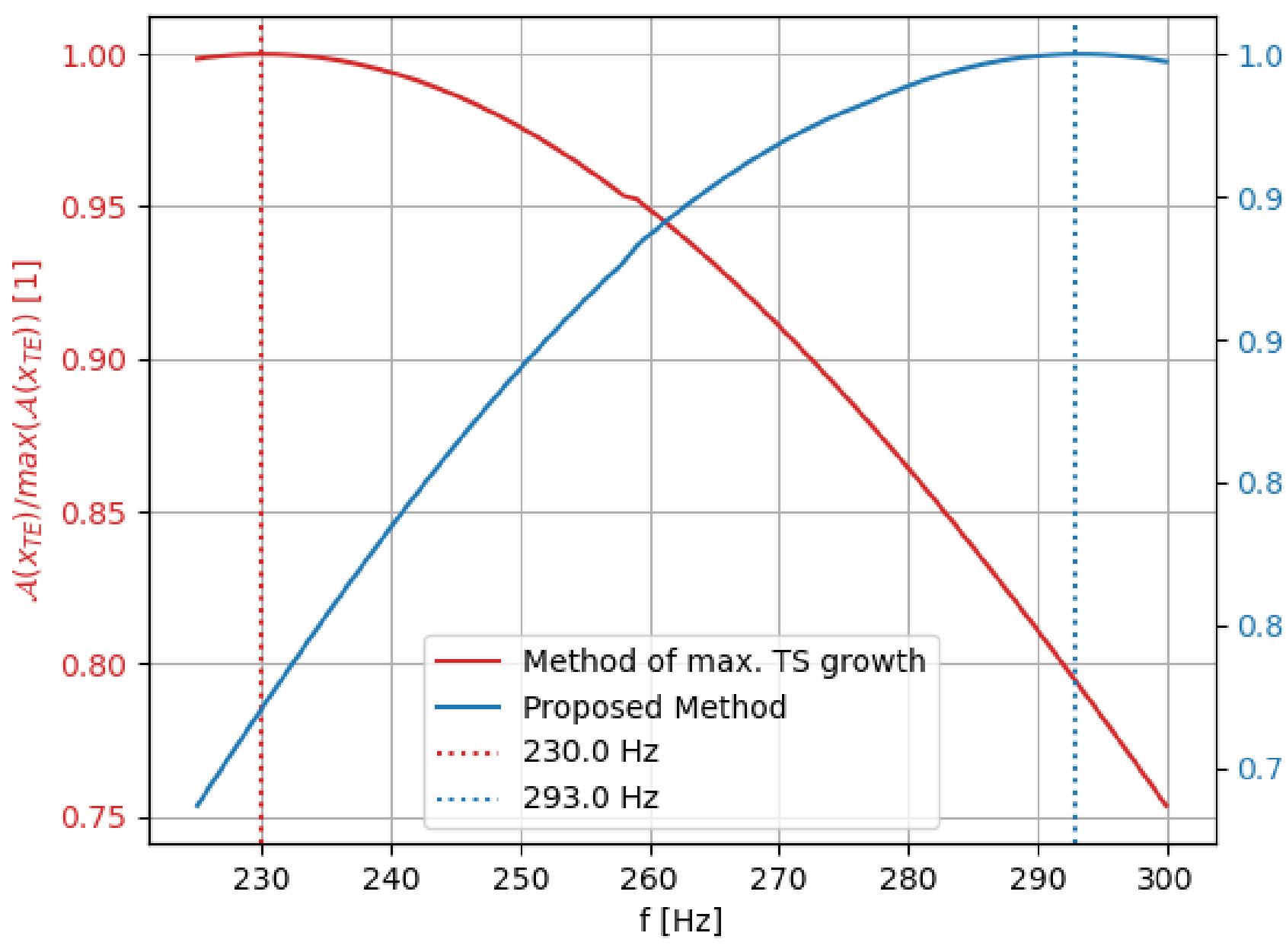

Figure 2: Comparison of the proposed tonal model with the model of the maximal growth of Tollmien–Schlichting waves for velocity $6.62\ m/s$ (Reynolds number $Re_L = 44143$).

Measurement

The experimental validation of the theoretical findings of the aeroacoustic (frequency) signature of the boundary layer is carried out on the well-known NACA 0012 airfoil. This choice of airfoil is based on the possibility of validating the simulated solution and eventually extending the set of measured data for future use. The measurement of static pressure fluctuations was performed using electret microphones. Fig. 3 shows the main frequency results of conducted experiments.

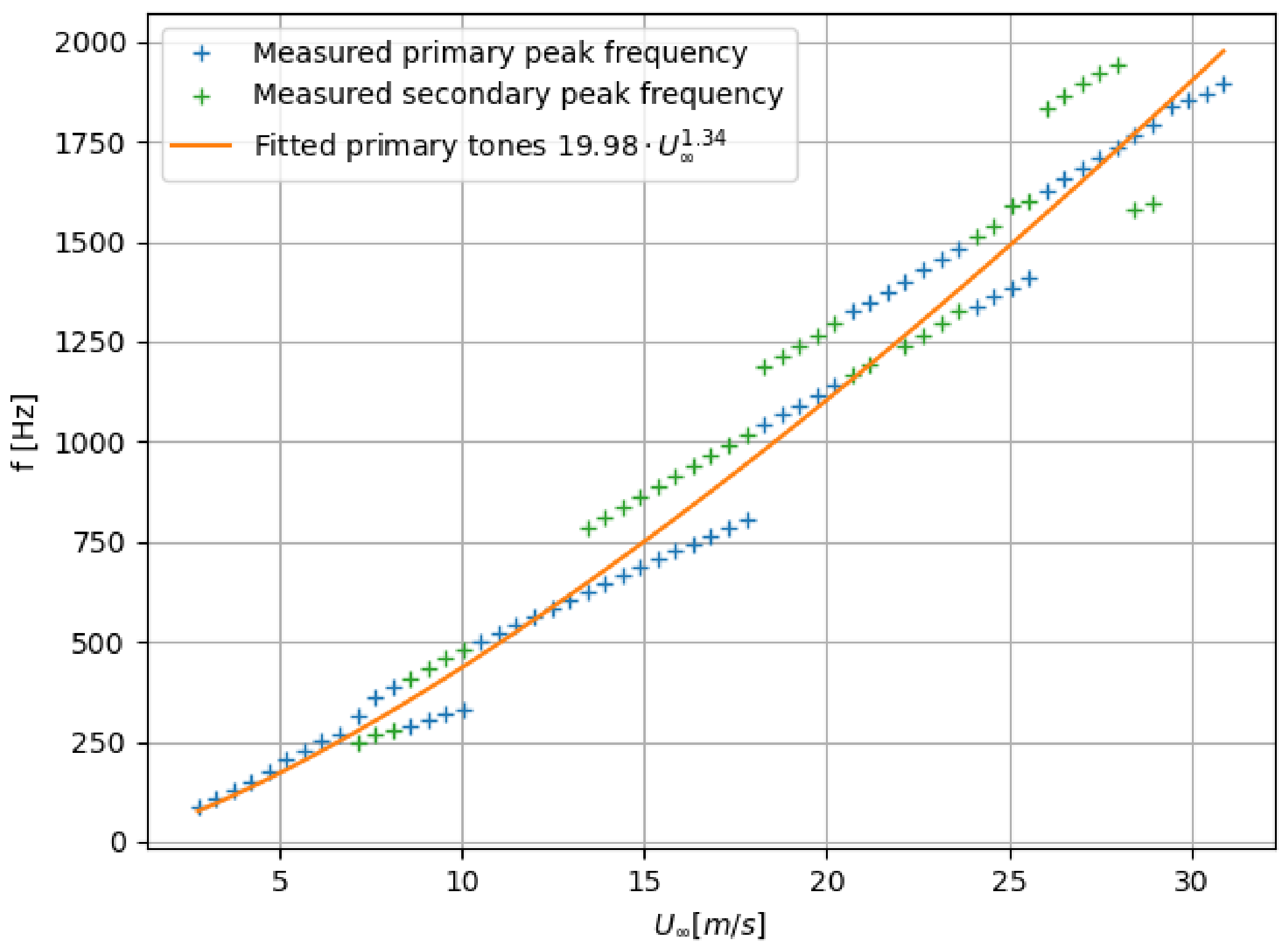

Figure 3: Primary and secondary tones in all measured points.

Results

Dominant frequencies of the laminar boundary-layer instability were obtained using a novel method of acoustic sources, the method of maximum instability amplification factor, and experimental measurements. These results are compared to the empirical model proposed by Brooks, Pope, and Marcolini (the BPM model). This comparison is shown in Fig. 4.

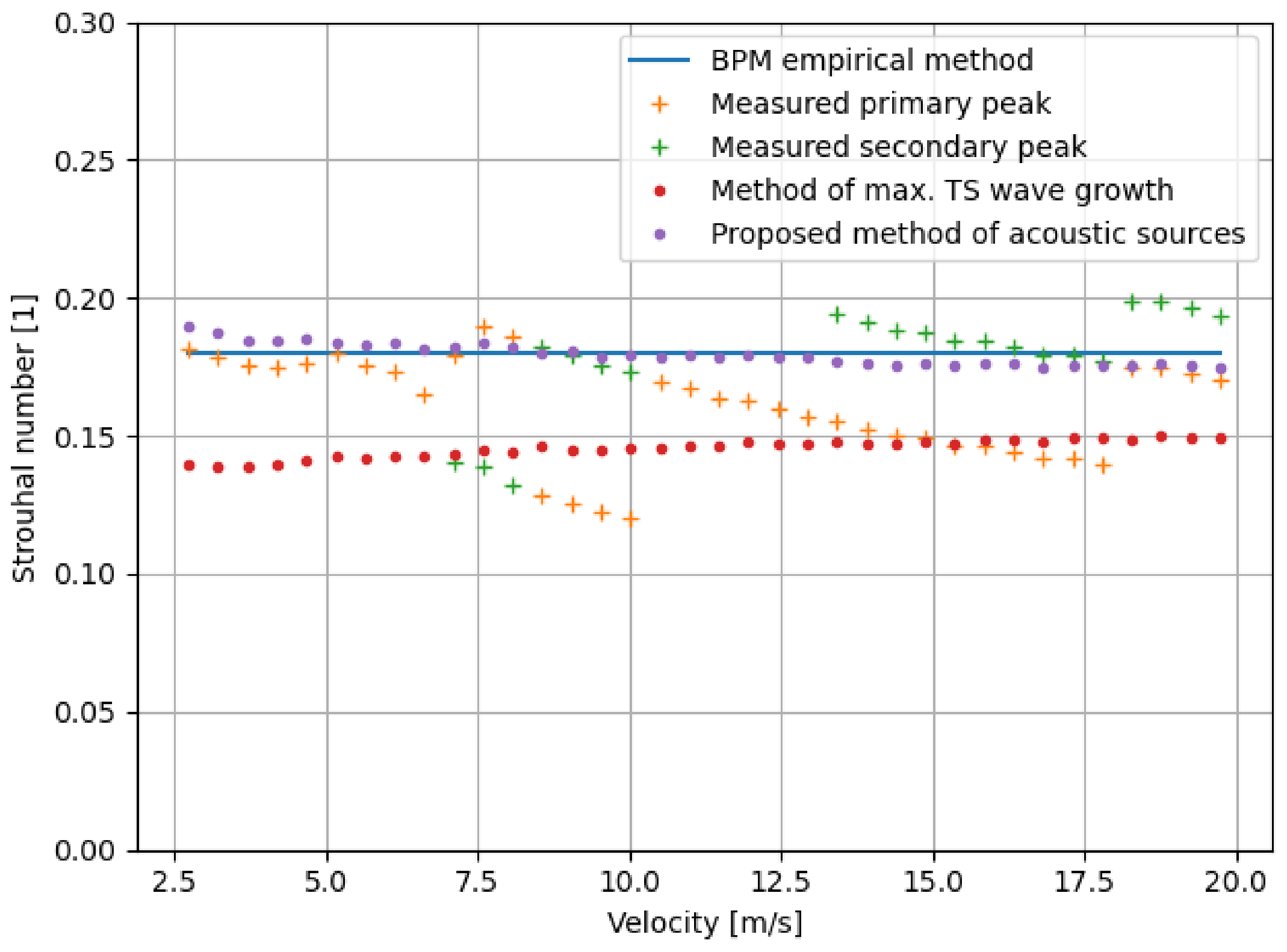

Figure 4: Measured, empirical, and simulation peak Strouhal number for velocities below the predicted transition in the laminar separation bubble.

Acoustic Feedback

In Fig. 5, empirical values of the acoustic feedback length are presented based on the method proposed in the thesis. For comparison, the distance from the first occurrence of an instability in the boundary layer to the trailing edge is shown with blue dots. Although used computational model predicts the transition to the turbulent boundary layer for velocities above $20\ \mathrm{m}\cdot\mathrm{s}^{-1}$, it should be assumed that the transition in the experiment occurs at a lower velocity. It can be theorized that the change in feedback length around $18\ \mathrm{m}\cdot\mathrm{s}^{-1}$ could be a footprint of the boundary-layer transition.

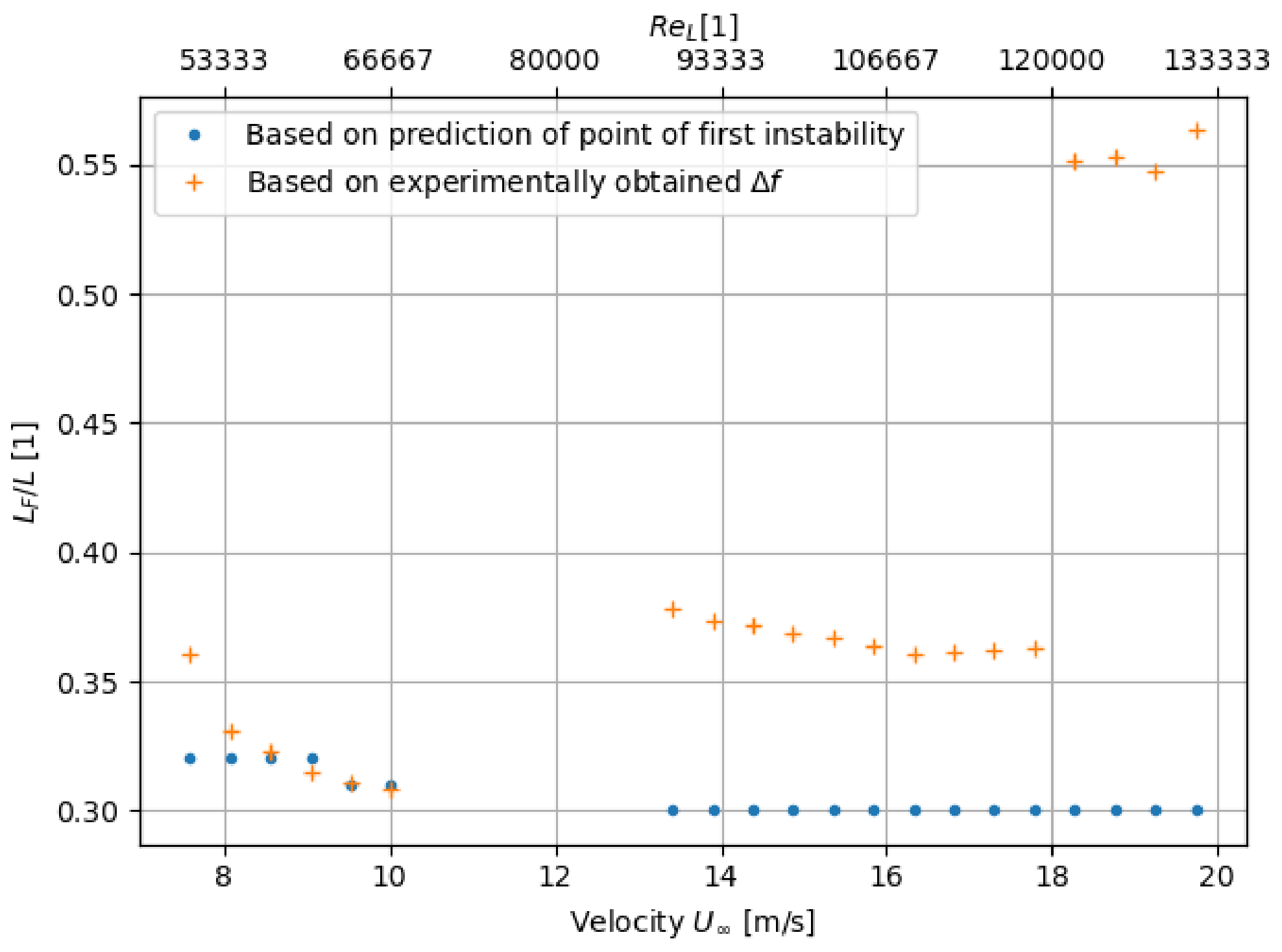

Figure 5: Feedback length based on experimentally obtained Δf and the theoretical feedback length, which is equal to the distance from the first occurrence of instability to the trailing edge.

Conclusions and Future Work

The novel theoretical model is based on the linear instability theory. The solution of the Orr-Sommerfeld equation is used to determine the acoustic source field of one mode within the boundary layer. Then, a method of comparison of acoustic fields for different frequencies is developed. The proposed model is compared with the solution of the method of maximal amplification of Tollmien-Schlichting waves. The experimental results were also used to analyze the acoustic feedback length. It was possible to obtain this quantity; however, it is rather difficult to compare these results. The feedback length (and the acoustic feedback overall) could be investigated in more detail in some future work using a different experimental approach in an aeroacoustic facility. For example, with a higher sampling rate, the phase delay between measurement points could be investigated; however, effort must be taken to prevent the results from being contaminated with the background noise and echoes.

The proposed model could also be extended with a (perhaps empirical) model of the behavior of the linear instabilities when they reach the part of the boundary layer in the turbulent state. The impact of the linear instability noise on the overall noise in the presence of turbulent boundary-layer noise could be investigated. Another extension of the proposed model of acoustic sources could be based on estimating the magnitude of the initial velocity perturbation. With this estimation and by taking into account the presence of the solid surface, it should be possible to evaluate the emitted sound in the far field and determine whether it is audible.

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