Final report

OTKA project 124939

Sensitivity of jets and shear layers

1. Introduction

The goal of the project was the better understanding of flow oscillations and instabilities and the active interaction with these. One motivation of the research was the understanding and the modelling of self-sustained flow oscillations, responsible, among others for the sound production of organ pipes. One direction of the project was the investigation of instability waves propagating on plane jets, and finding out in which point the excitation of such waves is the most efficient, i. e. where the is jet most sensitive. Oscillating jets can be found for example in wind instruments, in pipe branches, around the tongue of radial turbopumps but also in many other places where the flow impinges a sharp object. There are applications where oscillation is wanted and others where it is unwanted. In both cases it is important that we understand the mechanism of the oscillation and identify the points most sensitive to excitation. Based on the preliminary results and the developed toolkit developing a more elaborate model of the organ pipe or the recorder was also an aim.

The other main motivation for the research of flow instabilities arose from the transportation industry: from the viewpoint of the drag force and aerodynamic/hydrodynamic losses the laminar-turbulent transition has a great importance. Much energy can be saved if this transition is delayed; i. e. the boundary layer remains laminar on a higher proportion of the surface of the vehicle. The theory of the instability waves propagating and growing in laminar boundary layers developed to study this. We planned to adapt a stability analysis method to special surface coatings and actuators, which can delay the transition and reduce the drag.

2. New results

Jet, edge-tone, recorder

The steps described below, are components, which eventually led to a comprehensive feedback model of first the edge tone, then of wind instruments.

First, new methods were implemented to investigate the oscillation of a planar jet. In previous years, the Rayleigh and Orr-Sommerfeld equations [1], which describe the disturbances in parallel flows, have been implemented [2]. These were extended by the modified Orr-Sommerfeld equation [3] and the Wentzel–Kramers–Jeffreys-Brillouin (WKJB) [4]. The codes were verified and numerical convergence was achieved. The solution of parabolised stability equations (PSE) [5] was implemented, which seemed to be a promising method to model disturbances in jets. Unfortunately, the rapidly changing velocity profiles close to the orifice cannot be handled with these equations. This was one of the outcomes of András Szabó’s diploma-thesis [6], which was also presented on a conference [7].

The aim was to find the best method to describe the oscillations in jet, for every Reynolds number range. The reliable solution techniques (Rayleigh, Orr-Sommerfeld, modified Orr-Sommerfeld, WKJB) were compared to each other and a computational fluid dynamics (CFD) simulation (Fig. 1.). The results were summarised in a high quality journal paper [8]. The comparison of the various descriptions of the oscillation showed that the more sophisticated methods have no real advantage over the well-established Orr-Sommerfeld and Rayleigh equations. They describe well the jet oscillations 2 nozzle width downstream of the orifice. The Orr-Sommerfeld equation should be used below a Reynolds number 300 and the Rayleigh equation above that value.

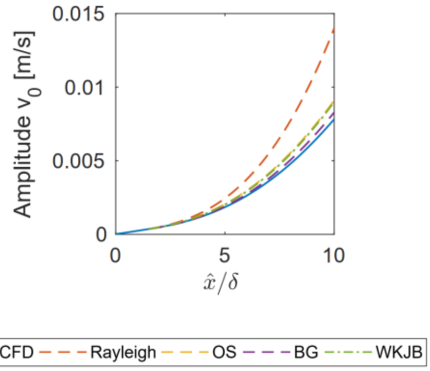
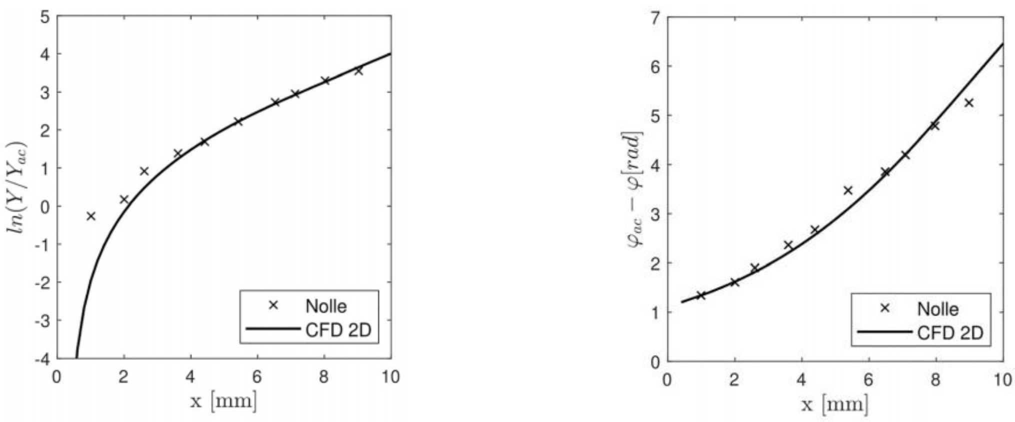


Fig. 1 The amplitude of the transversal velocity component along the centerline of the excited jet at St = 0.5 and Re = 300 [8]



(a) (b)

Fig. 2 The natural logarithm of oscillation amplitude normalized by the acoustic exciation level (a) and the phase delay (b) in an acoustically excited jet. Crosses: experiment [10], line: our CFD result [12]

A further outcome of the study was the discovery of the so-called strange mode. It was found with the Orr-Sommerfeld equation. It exists only close to the base flow and it has extremely high growth rate. Its origin is still unclear. It can explain the high phase speed found by Vaik et al. [9] previously in the simulation of edge-tone.

Furthermore, the development of a new excitation technique was necessary for the comparison because the disturbances have to be initiated in a CFD simulation. A unified treatment that includes the acoustic excitation in an incompressible simulation was developed and implemented for the jet. The idea of the procedure was similar to the Lighthill analogy, where the hydrodynamic pressure field can be reproduced in an acoustic simulation but here we did exactly the opposite. Here, the acoustic pressure and its effects were reproduced in a hydrodynamic simulation. The method was validated on two experiments ([10], [11]) and good agreement was found (Fig. 2.). The results were published in a high quality journal paper [12]. Furthermore, the results were presented on an online conference OGÉT [13].

After the jet oscillation was modelled properly, the next goal was to determine the most sensitive part of the jet and its response in the case of various excitations. This was done using the adjoint versions of the previously mentioned Orr-Sommerfeld and Rayleigh equations. With their help the amplitude of the disturbance waves can be estimated for a given excitation [14]. Since in a real world situation the excitation by vortices is more common, the implementation of the adjoint Orr-Sommerfeld equation was tested in the case of a plane jet excited with a fluctuating vortex. The non-linear interaction of the jet and the vortex initiates the disturbance and it is treated by source terms. For the well-known vortex structure, a rigid body rotation near the centre and a potential vortex far from the centre, a new formula was proposed. The results were presented on a conference [15]. An excellent agreement was found between CFD simulations and the estimation of the oscillation amplitude with the adjoint method. It was conjectured previously that the most sensitive part of the jet is the shear layer in the immediate vicinity of the nozzle exit and this was confirmed by the calculated amplitudes of the adjoint modes. The results were presented on the Conference on the Modelling Fluid Flow (CMFF'18) [16].

The last missing step in the modelling the hydrodynamic part of feedback mechanism of the edge tone is estimation of the amplitude of the generated vortex field at the tip. We suggested a new model where the strength of the generated vortex field is the opposite of the strength of the vorticity of the disturbance wave at the tip. This idea comes from the fact that the tip "destroys" disturbance waves. The model is verified with a developed new simulation technique and excellent agreement was found between our results and the experiments of Vaik [17] regarding the frequency of the edge tone (Fig. 3.). The comprehensive edge-tone model and the associated results were published in the most prestigious fluid dynamics journal, the Journal of Fluid Mechanics [18].

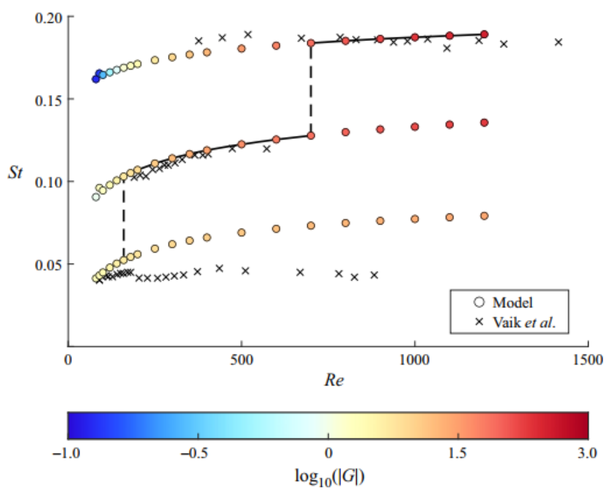


Fig. 3 The frequency of modes in an edge-tone configuration. Cross: previous measurement of our group. Circles: the predicted frequency of our model. The colours represent the logarithm of the gain, if it is larger than 0, oscillations will develop [18]

As the last step, the edge-tone model was extended with an acoustic resonator in collaboration with Dr. Péter Rucz of the Dept. of Networked Systems and Services Laboratory of Acoustics and Studio Technologies. We combined our jet model with his impedance model for the investigation of a recorder. The model was adapted for a Yamaha flute. The results were compared to Rucz's measurements, and good agreement was found between the model and the experiments (Fig. 4.). The results were published in a high-quality journal [20].

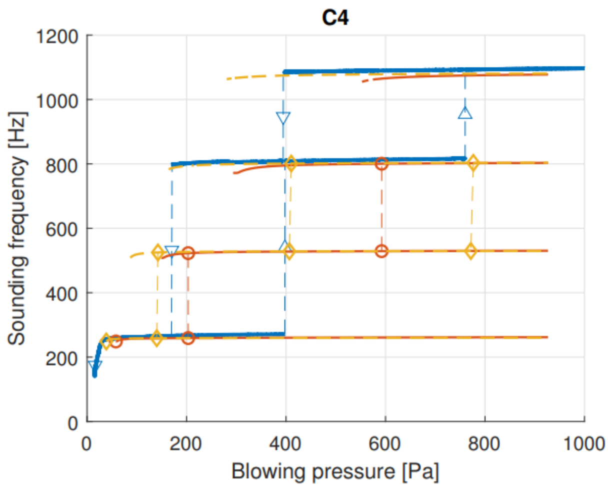


Fig. 4. The sounding frequencies of the Yamaha YRT304B-II tenor recorder as the function of the blowing pressure. Blue line: measurement, red line and orange dashed line: two different version of the proposed model. The blue dashed line indicates mode switching in the measurement. The diamond and circles indicates the mode switching according to the new models [20].

Boundary layer stabilization

The instability of the flows plays also an important role in the laminar-turbulent transition. Above a certain Reynolds number, the boundary layer becomes unstable and instability waves, the so-called Tollmien-Schlichting waves develop. They continuously grow, eventually leading to the development of a turbulent boundary layer, associated with a larger friction drag than in the laminar case. Delaying the transition can reduce the friction loss on ships and airplanes. One way to do that is to use a compliant coating over the surface and this coating damps and dissipates the energy of the disturbance waves. First, an idealised model of a compliant coating was investigated, using the Reynolds-Orr and the Orr-Sommerfeld equations. The wall consists of active controllers. They measure the fluctuating wall shear stress and they move small elements of the wall proportionally to the stress. The Reynolds-Orr equation does not model the developing disturbances; it can estimate the critical Reynolds number only, below which the flow is stable for any finite excitation. A special boundary condition was developed to model the coating. In the case of positive proportional control parameters, the critical Reynolds number can be significantly increased, and the loss can be reduced. The results were presented on conferences [20], [21], [22] and published in a high quality journal [23].

The coating was investigated also by PSE equations. It was verified that the coating can delay transition, but the calculated critical Reynolds number was lower than that in the previous calculation with Orr-Sommerfeld equation. András Szabó presented this research on the TDK [24], where he won first prize and on the OTDK, where he won third prize in his section.

Furthermore, we proposed that in the case for positive control parameter the coating can be substituted with passive elements. The geometry of that structure was developed and analysed using the Orr-Sommerfeld equation. The results showed that under the given material constraints the critical Reynolds-number can be tripled in water at a flow speed of 10 m/s. This means that roughly 8-10% friction drag reduction can be achieved. The results were presented at the 12th European Fluid Mechanics Conference, at the Conference on the Modelling Fluid Flow (CMFF'18) [25] and at BIFD [22]. In the next step, we optimized the parameters of the coating elements for two different scenarios. First, the critical Reynolds number is maximized, where the transition begins. However, the laminar-turbulent transition happens faster in these cases than in the uncoated case due to the larger growth rates and this is after all not advantageous. The second scenario focused on maximizing the transitional Reynolds number, which is more feasible from a practical point of view. The results were published in a high quality journal [26].

The above-mentioned results were calculated using linear stability analysis. Unfortunately, it does not work well if the external disturbances (turbulence level, acoustic waves, surface roughness, vibrations) are strong. Our previous result [23] with the non-linear method showed that the proposed control or coating could, under certain circumstances even accelerate the transition. However, the non-linear method predicts an extremely conservative Reynolds number. Multiple attempts were made to improve the non-linear stability analysis tool, namely the Reynolds-Orr equation. The methods minimize the Reynolds number where the kinetic energy of any disturbance does not grow. The corresponding perturbation is called the critical one here. Below that limit, the kinetic energy must decay exponentially, meaning the flow is unconditionally stable for any disturbance. First, the enstrophy (volume integral of the square of the vorticity) change of the critical perturbation was investigated, mainly in the channel flow with varying geometric parameters. In the case of the channel flow, the properties of the most critical disturbance, obtained from direct numerical simulations agree well with those obtained from stability analysis under the condition that the enstrophy change was zero. The results were published in a high quality journal [27].

Further investigation of the critical perturbation field showed that it does not fulfil the compatibility condition of the Navier-Stokes equations. If the initial velocity field violates the condition, the smooth solution of the equations does not exist, which is physically unreasonable. An analytic example was obtained, which is continuous but violates the condition. During these investigations, we cooperated with Dr. Márton Kiss of the Department of Differential Equations in the Institute of Mathematics in BME. The paper about this result appeared in a high quality journal [28].

A further idea was that if the compatibility condition is added to the original Reynolds-Orr equation, the constraint may increase the predicted critical Reynolds number, which is significantly lower than the values obtained from experiments or simulations. According to the calculations, in the case of Poiseuille and Couette flows, the critical Reynolds numbers increased significantly, by 40-50%. However, the predicted values are still one order of magnitude smaller, than the experimental ones. The paper was submitted to a high quality journal but was rejected. It will be submitted after proper correction after the end of this OTKA project.

Finally, we mention that we made the first steps towards another boundary layer stabilisation technique, the one with miniature vortex generators. This will be the topic of our next OTKA project.

3. The outcome of the research

In summary, we published **eight** high ranking journal papers [8], [12], [18], [19], [23], [26], [27], [28], one of them in the highly prestigious Journal of Fluid Mechanics [18]. The results were presented on seven conferences [7], [13], [15], [16], [20], [21], [25], where further scientific cooperations were established. We got to know Prof. Maarten Vaniershot from the KU Leuven. We started working on boundary layer stabilization within the framework of a CELSA project and we are planning to apply for a Marie-Curie grant. Furthermore, we cooperated with two different researchers at our university. Further conferences were also attended in connection with topic but since the OTKA financing ran out by that time, we do not list those here.

One PhD dissertation [29] was defended, and two master theses and one TDK paper were written during the project. Two further PhD dissertations are in progress.

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