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Flow and acoustics of the edge tone configuration

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June 8, 2013

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Booklet of the Ph.D. dissertation

Contents

Table 1: Symbols

Notation	Meaning	SI unit
$\beta/2$	number of element layers in the source region of the acoustic mesh (half space only because of the symmetry condition)	-
δ	width of the jet	m
ϵ	phase lag in the feedback loop eq. (2)	-
λ	wavelength of jet disturbance	m
Λ	acoustical wavelength	m
ν	kinematic viscosity	m^2/s
ϕ	Phase delay relative to the reference point	rad
c_1, c_2, c_3	coefficients of $St\,(Re, h/\delta)$ in eq. (1)	-
f	frequency of oscillation	Hz
h	nozzle-to-wedge distance	m
h/δ	dimensionless nozzle-to-wedge distance	-
k	exponent of h/δ in the h/δ dependence of St eq. (1)	-
n	ordinal number of the stage	-
Re	Reynolds number, $Re = \frac{u\delta}{\nu}$	-
St	Strouhal number, $St = \frac{f\delta}{u}$	-
T	period time	s
u	mean exit velocity of the jet	$\mathrm{m/s}$
u_{conv}	convection velocity of jet disturbance	$\mathrm{m/s}$
w_{CFD}	thickness of the element layer in the 2D CFD simulation	m
w_{acou}	height of an element in the source region of the acoustic mesh	m
W	depth of the jet / height of the flow	m
x, y, z	Cartesian coordinate directions	

Table 2: Abbreviations

Notation	Meaning
2D	Two-dimensional
3D	Three-dimensional
CFD	Computational Fluid Dynamics
CAA	Computational AeroAcoustics

Introduction

What is the edge tone?

The edge tone is one of the simplest aero-acoustic flow configurations. It consists of a planar free jet that impinges on a wedge-shaped object (traditionally called the edge). The main parameters of an edge tone configuration are the mean exit velocity of the jet (u), the width of the jet (δ) and the nozzle-to-wedge distance (h) (Figure 1). Secondary parameters may also influence the flow, such as the velocity profile of the jet (top hat and parabolic profiles are the most common ones), the offset of the wedge from the jet center line, the shape of the nozzle or the angle of the wedge. Despite its geometric simplicity the edge tone displays a remarkably complex behaviour. Under certain circumstances a self-sustained oscillation evolves with a stable oscillation frequency. The oscillating jet creates an oscillating force on the wedge, that generates a dipole sound source, that under certain circumstances creates an audible tone.

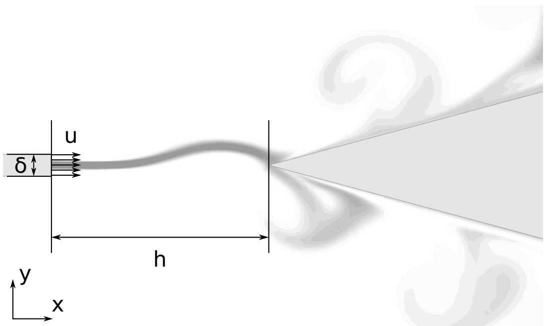
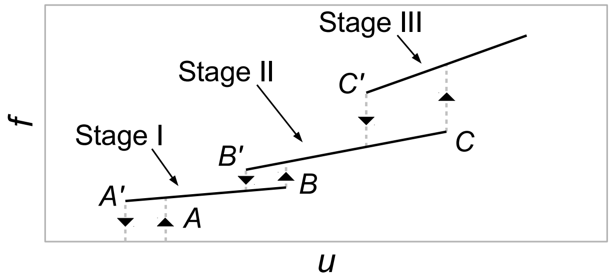


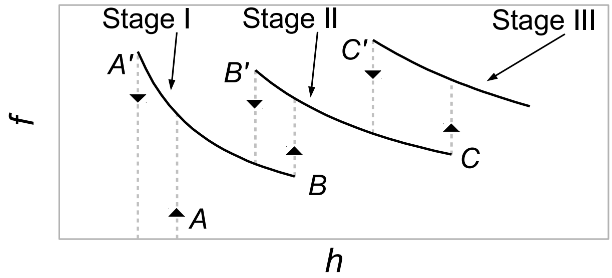
Figure 1: Snapshot from a CFD simulation of a first stage edge tone flow with the main parameters of the edge tone configuration (δ – width of the slit on the nozzle; h – nozzle-to-wedge distance; u – mean exit velocity of the jet)

The oscillating jet can take different shapes, these are called the stages of the edge tone. Their ordinal number corresponds roughly to the number of half waves between the nozzle and the wedge. Figure 1 shows a snapshot from the result of a computational fluid dynamics (CFD) simulation of a first stage edge tone flow. The flow is visualised by “virtual smoke” introduced in the central part of the nozzle.

Figure 2(a) shows what happens with the oscillation frequency when the mean exit velocity of the jet is varied in a fixed geometrical configuration (at constant δ and h values). At low velocities the wedge cuts the jet in half and a steady flow is formed. Increasing the velocity above a certain threshold velocity – that value is of course dependent on the geometric configuration – the first stage of the edge tone sets in (position A). Further increasing the jet velocity the second stage comes into being with a sudden jump in the frequency to a higher value (position B). Usually the first stage still coexists with the new, second stage, thus a multi-stage operation mode can



(a) mean exit velocity of the jet



(b) nozzle-to-wedge distance

Figure 2: Characteristics of frequency variation as a function of the

be observed, but the second stage can be present purely as well. At higher velocities the third stage of the edge tone is formed (position C) – again with a sudden jump in the frequency to a higher value – either with some of the lower stages coexisting, or purely. Further increasing the velocity, even higher stages may evolve, with a jump in the frequency to a higher value at the onset of each new stage. Similar behaviour can be observed when the velocity of the jet is decreased. The frequency of the oscillation decreases, and at a point the highest stage disappears (at positions *C'* and *B'* the third and the second stage disappears, respectively) with a sudden drop in the frequency and at last at low jet speeds the first stage of the edge tone disappears and a steady flow is formed (position *A'*). It can be that the velocity value at the point where a stage disappears during the decrease of the jet velocity (position *C'*, *B'* or *A'*) may differ from the velocity value at the point where this stage first appeared when the velocity was increased (position C, B or A), so hysteresis may occur.

On the other hand, when the nozzle-to-wedge distance is varied while the velocity of the jet is kept constant (Figure 2(b)), the following can be observed. At low distances no oscillation occurs. Increasing the distance, at a certain lower limiting value the first stage of the edge tone forms (position A). Further increasing the distance, the frequency of the oscillation decreases. At a point the second stage sets in with a sudden jump in the frequency to a higher value (position B). Further increasing the distance, the frequency again decreases until the next stage forms with the sudden jump in the frequency again to a higher value (position C). Now, if the nozzle-to-wedge distance is decreased from a higher value, then the frequency of oscillation increases until a certain position where the jet jumps back to a lower stage where the frequency is also lower (position *C'* and *B'*) and at last the oscillation disappears completely (position *A')*. Just as in the case when the velocity is varied hysteresis may occur, it can be that the jump between the stages forth and back are at different positions ($A \neq A'$ or $B \neq B'$ or $C \neq C'$).

The following dimensionless numbers will be used:

- **Reynolds number** based on the mean exit velocity of the jet and the width of the jet will be used as the dimensionless jet velocity: $Re = \frac{u\delta}{\nu}$
- **Strouhal number** based on the frequency of oscillation (f), the width of the jet and the mean exit velocity of the jet will be used as the dimensionless oscillation frequency: $St = \frac{f\delta}{u}$
- $\boldsymbol{h/\delta}$ will be used as the dimensionless nozzle-to-wedge distance

Because of scaling laws, two edge tone configurations with different jet velocities and geometric sizes, but at the same Reynolds number and h/δ dimensionless nozzle-to-wedge distances produce oscillations with different frequencies but with the same Strouhal numbers, therefore when comparing results from different sources (theoretical and/or experimental and/or numerical) comparison of the Strouhal numbers at same Reynolds numbers and at same h/δ values will be carried out.

Frequency and phase characteristics of the edge tone

The literature is consequent in the proposition that the oscillation frequency is roughly proportional to the mean exit velocity of the jet and inversely proportional to the k^{th} power of the nozzle-to-wedge distance:

$$f \propto \frac{u}{h^k}.$$

Sometimes an additive constant in one or both of the relationships is also present (such as $f \propto \frac{u+c_u}{h^k+c_h}$).

About the value of the exponent k there has been a long debate. In the early phase of the research rather $k = 1$ was favoured (Brown and other researchers before him [15], Curle [16]) later it became generally accepted that $k = 3/2$ (Curle using Savic's results [16], Holger et al. [17], Crighton [18]). In 1942 Jones [19] found a variety of exponents, all between 1 and $3/2$, depending on the stage number. Recent research (Bamberger et al. [20]) and also the results of my experimental and numerical studies indicate that $k = 1$ is more correct.

Several formulae can be found in the literature for the dependence of the oscillation frequency on the mean exit velocity of the jet and on the nozzle-to-wedge distance. In order to ensure comparability, these formulae were transformed to Strouhal numbers. Although they all has a similar form:

$$St\left(Re, \frac{h}{\delta}\right) \approx \left(c_1 - \frac{c_2}{Re}\right)\left(\frac{1}{\left(h/\delta\right)^k} - c_3\right), \tag{1}$$

but they can produce big differences at the same Reynolds number and h/δ values. Table 3 shows the value of the coefficients for the first three stages for the most important results in the literature, while Figures 3 and 4 show the Strouhal number of the first stage plotted as a function of the Reynolds number at $h/\delta = 10$ and as a function of h/δ at $Re = 200$, respectively. To avoid the overloading of the figures with curves only three theoretical (Curle's two formulae [16] and Holger's [17] formula) and three experimental (Brown's [15], Jones' [19] and Brackenridge's [21] formulae) results are plotted. The experiments of Brown and Jones fit acceptably well (for $h/\delta = 10$ above $Re \approx 150$), the experiments of Brackenridge has a mentionable but still not too high deviance from their results (above $Re = 200$). The formulae from the theoretical considerations tend to over-estimate the results of the measurements. It can be seen that for low Reynolds numbers and/or low nozzle-to-wedge distances the curves separate and the difference can easily be more than 100 %. For higher Reynolds numbers or nozzle-to-wedge distances the differences between the formulae are somewhat more bounded, but still can reach 25 %.

All of the theoretical models in the literature can be summarised as the disturbances on the jet that born somewhere near the nozzle have to travel to the wedge, where they somehow interact with it. As a result of their interaction a "signal" is sent to the place where disturbances of the jet are born.

As Powell suggests: the oscillating jet creates an oscillating force on the wedge, that creates a dipole sound source. The generated sound then excites the jet – at low Mach numbers with no time delay – and a new disturbance is born that grows as it travels downstream to the wedge.

The phase relation of this loop can be summarised in the following equation:

$$h = \lambda\left(n + \epsilon\right) \tag{2}$$

Table 3: Parameters of the $St\,(Re, h/\delta)$ relationships (equation (1)) by different authors

Stage	Author	c_1	c_2	c_3	k
Stage I	Brown [15]	0.4659	12.06	0.007	1
	Jones [19]	0.39	0	0	1
	Curle [16]	0.625	0	0.0267	1
	Curle-Savic [16]	1.43	0	0	$3/2$
	Brackenridge [21]	0.6298	38.4	0.0235	1
	Holger [17]	1.532	0	0	$3/2$
	Crighton [18]	2.477	0	0	$3/2$
	Kwon [22]	0.45	0	0	1
	Bamberger et al. [20] (exp.)	0.513	0	0	1
	Bamberger et al. [20] (CFD)	0.443	0	0	1
Stage II	Brown	1.072	27.74	0.007	1
	Jones	1.217	0	0	1.14
	Curle	1.125	0	0.0148	1
	Curle-Savic	3.46	0	0	$3/2$
	Brackenridge	1.512	92.2	0.0235	1
	Holger	3.332	0	0	$3/2$
	Crighton	10.385	0	0	$3/2$
	Kwon	1.05	0	0	1
Stage III	Brown	1.77	45.83	0.007	1
	Jones	2.52	0	0	1.22
	Curle	1.625	0	0.0103	1
	Curle-Savic	6	0	0	$3/2$
	Holger	6.057	0	0	$3/2$
	Crighton	21.32	0	0	$3/2$
	Brackenridge	2.645	161.3	0.0235	1
	Kwon	1.65	0	0	1

where λ is the wavelength of the disturbance, n is a whole number corresponding to the stage number, and ϵ is a small number indicating that the effective resonance length of the edge tone system somewhat differs from h.

There is no agreement in the literature about the value of ϵ, it may also depend on the details of the configuration and on the stage number. The most often occurring value is 0.25 (Curle [16], Powell [23]), Holger et al. [17] found values between 0.35 and 0.5 depending on the stage, but negative values are also suggested -0.2 (Nonomura et al. [24,25]), -0.25 (Kwon [22,26]) or $-3/8$ (Crighton [18]). One reason for the uncertainty in the dependence of the frequency of oscillation on h is the uncertainty of ϵ. The exact positions where the dipole source is located (i.e. at the tip of the wedge or at a certain distance away downstream from the tip) and where the sound generated by the acoustic dipole source excites the jet (directly at the nozzle, or somewhat further downstream) are still not explored.

Also the theories presented usually assumes that the wavelength and convection velocity of the disturbance do not change between the nozzle and the wedge, and thus the phase of the disturbance decreases linearly in proportion to the distance, but this was found to not to be true (Stegen and Karamcheti [27], Section 1).

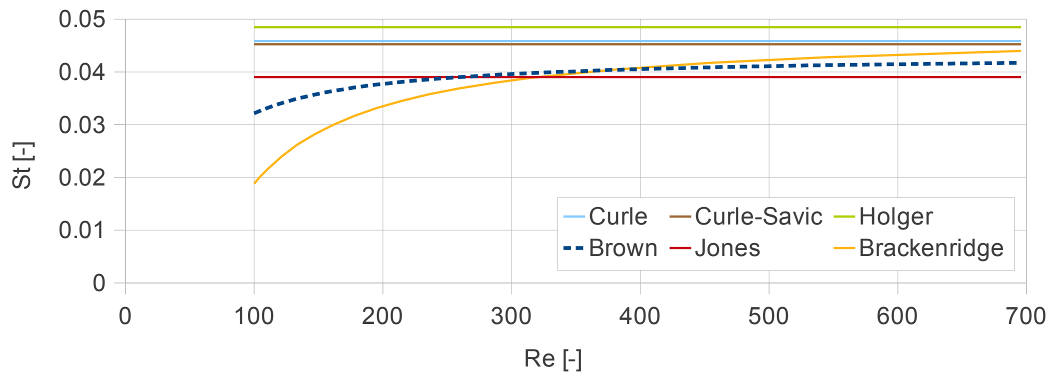


Figure 3: Dependence of the Strouhal number of the first stage edge tone oscillation on the Reynolds number at $h/\delta = 10$ in various results reported in the literature [15–17, 19, 21]

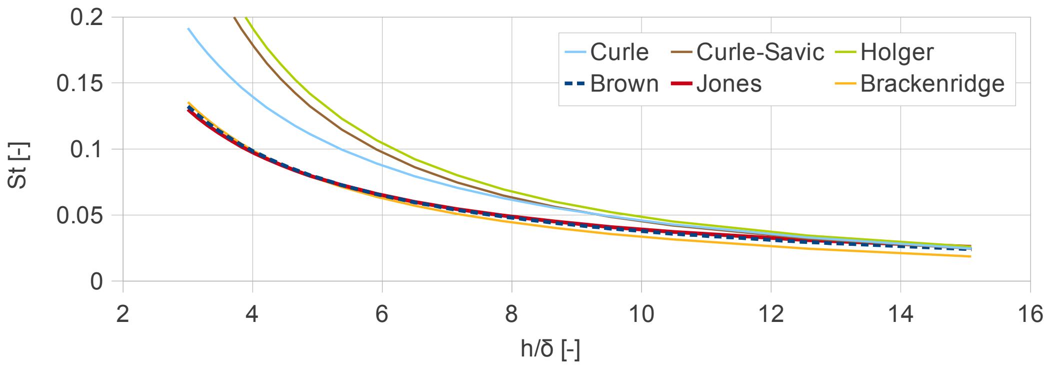


Figure 4: Dependence of the Strouhal number of the first stage edge tone oscillation on the dimensionless nozzle-to-wedge distance at $Re = 200$ in various results reported in the literature [15–17, 19, 21]

Neglecting these "minor" problems, assuming that the disturbance has to travel the nozzle-wedge distance (Stage I with $\epsilon = 0$, thus $\lambda = h$) with the mean speed of disturbance propagation that is about 40 % of the mean exit velocity of jet, the period of one feedback loop is about $T \approx \frac{h}{0.4 \cdot u}$ and so the frequency of the first stage oscillation would be about $f \approx \frac{0.4 \cdot u}{h}$, which is very close to the above formula of Jones for the first stage. For the higher stages this heuristic model does not work.

Why the edge tone? – Aims of the work

The edge tone is a very interesting aeroacoustic flow phenomenon. On the flow side, it is a planar flow (as long as the depth (W) of the jet is much larger than its width (δ)) while on the acoustic side, under certain circumstances it generates an audible, tonal sound that has a true three-dimensional dipole directivity – at least in the far field and as long as the depth of the jet is not comparable to the acoustic wavelength (Λ). Usually these conditions ($\delta \ll W$, and $W \ll \Lambda$) are fulfilled. Therefore the edge tone is a perfect subject of testing a newly developed method of coupling a 2D flow simulation with a 3D acoustic simulation (Section 2). At the same time, in spite of its geometric simplicity, the edge tone produces flow phenomena that are interesting in themselves (Section 1) and not yet fully understood. Despite its intensive research in the previous more than one hundred years the literature is still not concordant even about its most basic attribute, its frequency characteristics.

The aims of my dissertation can be divided to three groups, that also makes the structure of the dissertation:

1. The aim of Chapter 2 of my dissertation is to investigate the flow of the edge tone phenomena with experimental and numerical tools, verify one of the formulae for the Reynolds number and dimensionless nozzle-to-wedge distance dependence of the Strouhal number published already and to point out a weak point, an incorrect assumption of all the models that were published, namely that the convection velocity of the disturbance on the jet is not constant.
2. The aim of Chapter 3 of my dissertation is to create a method of coupling a 2D flow simulation with a 3D acoustic simulation, and to investigate the acoustic attributes of the edge tone with this newly developed method.
3. At last, the aim of Chapter 4 of my dissertation is to investigate a real-world appearance of the edge tone phenomenon, namely the flow inside the foot model of an organ pipe.

1 The flow of the edge tone

The flow of the edge tone have been investigated both by numerical and experimental means. In the experiments four methods were used to determine the oscillation frequency. It is shown that in spite of its inaccuracy the so-called "wavelength method" is quite unique as it is capable to measure the oscillation frequency of the edge tone from only two subsequent photographs. The other three methods (the "vortex counting method", the Fourier analysis of the output signal of the pressure transducer and the stroboscopic principle) gave the same results within their accuracy. For the CFD simulations criteria to the value of the time step were deduced analytically to keep the absolute or the relative numerical error at the constant value of a reference case.
(Thesis 1)

The planar nature of the flow was verified by comparing the results of the 2D and the 3D CFD simulations and also experimentally by flow visualization. Parametric studies were carried out to determine how the Strouhal number of the oscillation depends on the Reynolds number and on the dimensionless nozzle-to-wedge distance. The results of the CFD simulations agree well with that of the experiments and they verifies Brown's experimental results [15]. This can be seen in Figure 5, which shows the experimental and numerical results of the Reynolds number dependence study of the top hat edge tone together with the semi-empirical formula of Brown. Also the formulae describing the $St\,(Re, h/\delta)$ relationships in case of top hat and parabolic edge tones were determined. Figures 6 and 7 show the experimental and numerical results for the top hat and parabolic cases, respectively.
(Thesis #2)

Several modes of the edge tone have been observed in that stages of the edge tone are present purely or several stages coexist at the same time. In the case of top hat edge tones with the advent of the higher stages the lower stages do not disappear, the lower stages coexist with the new, higher stage, while in the case of parabolic edge tones the higher stages can be present purely as well. Figure 8(a) shows the Strouhal numbers of the parabolic edge tones when the Reynolds number is increased. It can be seen that at the onset of the second and third stages (at $Re \approx 200$ and $Re \approx 650$, respectively) it first coexists with the first stage, then later the first stage disappears and the second and third stage is present purely (from $Re \approx 350$ and $Re \approx 900$, respectively). In case of parabolic edge tones hysteresis was found at the boundary of the stages, meaning that the jump from the third stage back to the second stage when the Reynolds number

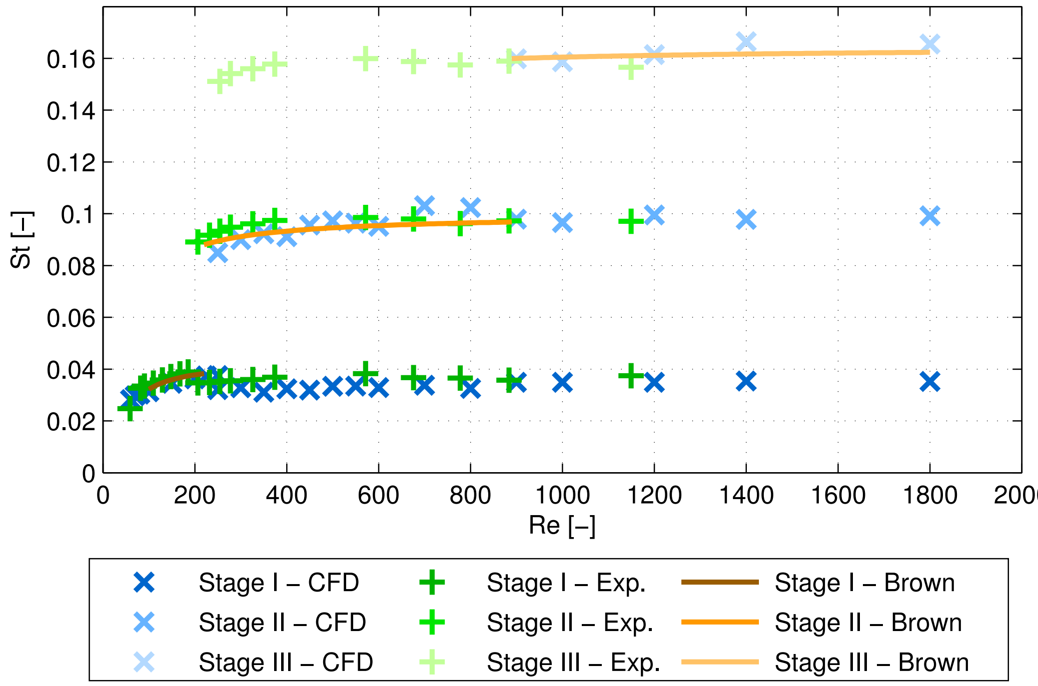


Figure 5: Reynolds number dependence of the Strouhal number; top hat profile, $h/\delta \approx 10$

was decreased (Figure 8(b)) is at a different position than the jump from the second stage to the third stage while increasing the Reynolds number (Figure 8(a)). Actually when the Reynolds number is decreased the coexistence of the third and the first stages lasts longer, and there is no pure second stage oscillation at all.

(Thesis #3)

The phase and the convection velocity of the jet disturbance was also investigated. The phase of the jet disturbance relative to a reference point was determined with a cross-correlation technique. It was found that the phase varies nonlinearly with the distance from the nozzle, thus the convection velocity is not constant as it is assumed in all of the theoretical considerations. The phase change (ϕ) can be characterised with the following formula in case of pure first stage edge tone oscillations independently from the velocity profile and from the Reynolds number:

$$\phi_* \left(\frac{x}{h}\right) = \frac{\phi\left(\frac{x}{h}\right)}{2\pi} \approx 0.6036 \cdot \left(\frac{x}{h}\right)^2 + 0.2781 \cdot \frac{x}{h} \tag{3}$$

This agrees almost perfectly with the power function $\frac{\phi}{2\pi} = 0.9 \cdot \left(\frac{x}{h}\right)^{1.63}$ suggested by Stegen and Karamcheti [27] after measuring the phase at a $Re \approx 950$ and $h/\delta \approx 5.58$. Figure 9 shows the two curves together with the result of the CFD simulations at $Re = 200$, $h/\delta = 10$ with a top hat jet. From equation (3) the convection velocity of the disturbance (u_{conv}) follows as:

$$\frac{u_{conv}\left(\frac{x}{h}\right)}{u} = \frac{h}{T \cdot u} \cdot \frac{1}{\phi'_*\left(\frac{x}{h}\right)} = St \cdot \frac{h}{\delta} \cdot \frac{1}{\phi'_*\left(\frac{x}{h}\right)}$$

The Strouhal number of a first stage edge tone is between $0.028 - 0.044$, from that – at $h/\delta = 10$ – the convection velocity of the disturbance relative to the mean exit velocity of the jet near the nozzle is $1 - 1.58$, which decreases to a value of $0.2 - 0.3$ as it reaches the wedge. The mean value of the disturbance convection velocity relative to the mean exit velocity of the jet is between $0.32 - 0.5$.

(Thesis #4)

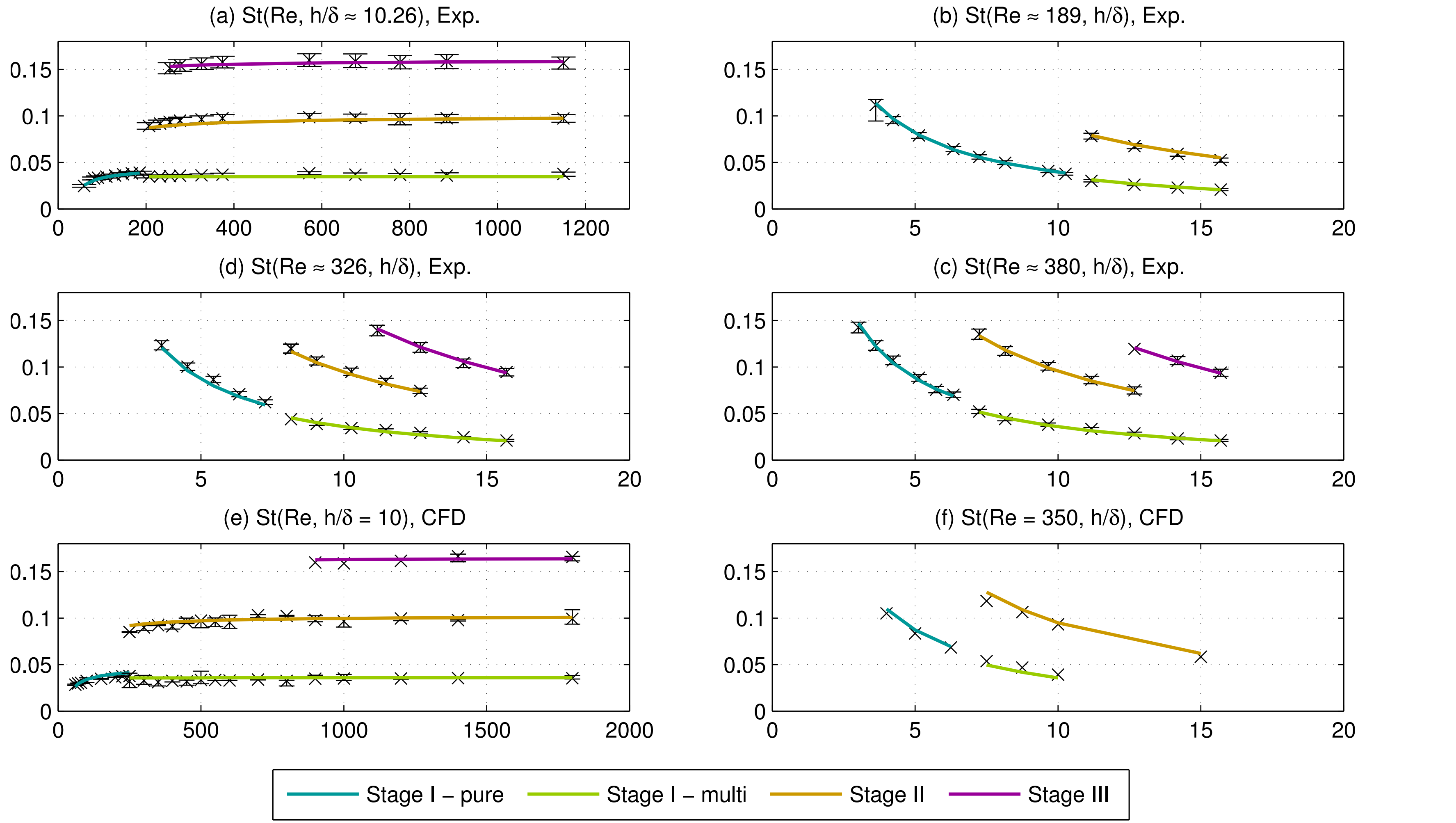


Figure 6: Strouhal numbers of the top hat edge tone. Crosses with error bars denote the numerical (CFD) or experimental (Exp.) results. Solid lines are the best fit curves described in Thesis #2

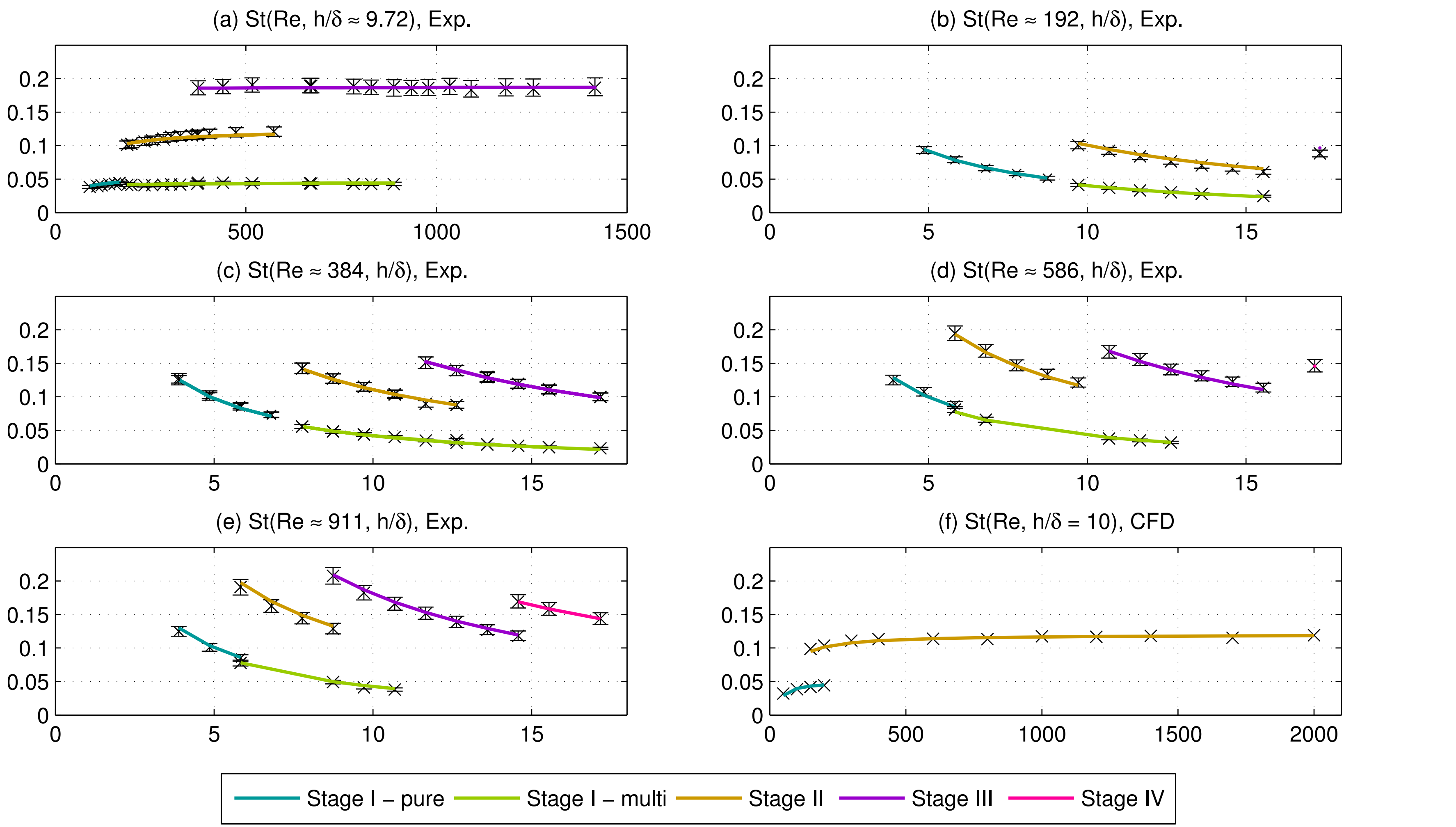


Figure 7: Strouhal numbers of the parabolic edge tone. Crosses with error bars denote the numerical (CFD) or experimental (Exp.) results. Solid lines are the best fit curves described in Thesis #2

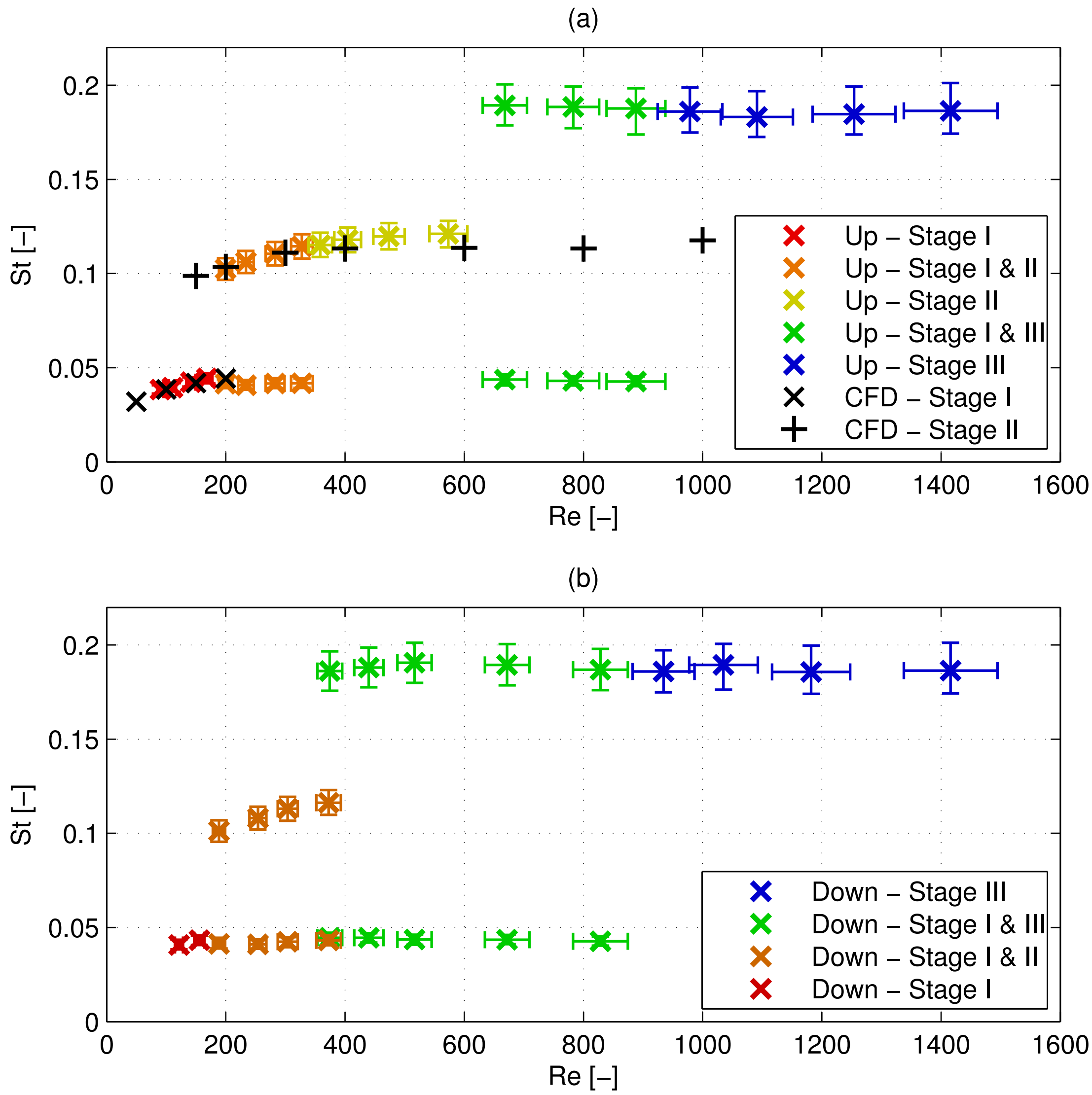


Figure 8: Hysteresis in the stages of the edge tone; parabolic profile, $h/\delta = 10$; (a) increasing Reynolds number, (b) decreasing Reynolds number

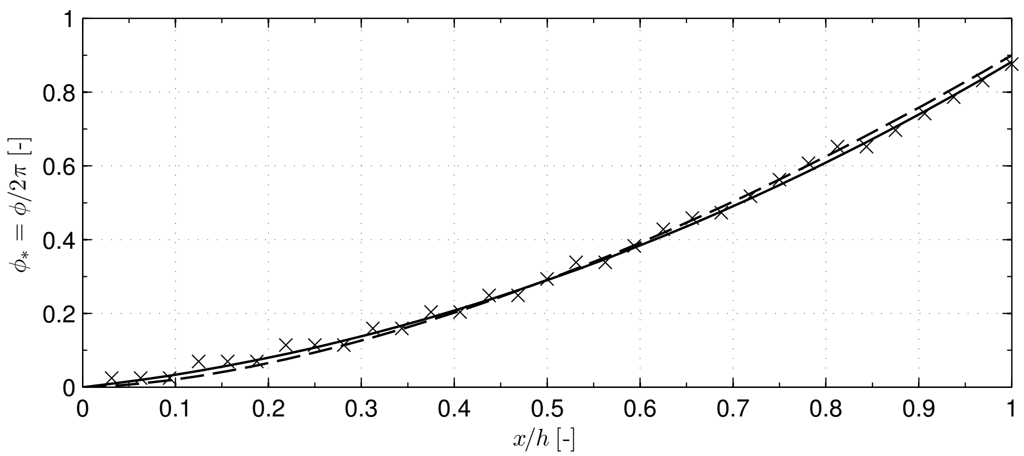


Figure 9: Phase drop of a first stage edge tone oscillation; Results from CFD simulation at $Re = 200$, $h/\delta = 10$, top hat profile (X); Fitted parabola (equation (3), solid line) and power function suggested by Stegen and Karamcheti [27] (dashed line)

2 Acoustics of the edge tone

Resource requirements for the calculation of sound production in a planar flow are often unnecessarily high due to a full, three-dimensional CFD simulation. However, planar flows can be simulated in two dimensions thus reducing the time and memory requirement of the CFD part of the coupled aeroacoustic computation. This section will present a newly developed hybrid Computational AeroAcoustic (CAA) method to calculate the sound generation of a planar flow by coupling a 2D CFD simulation with a 3D acoustic simulation. The basic idea of this method is to calculate the acoustic source terms from the 2D CFD simulation with Lighthill's analogy [28] and perform a 3D acoustic simulation after interpolating the sources onto the acoustic mesh and extruding and them in the third direction. It is also shown to be sufficient to properly scale the sources after interpolating them onto the acoustic mesh and carry out the 3D acoustic simulation with only a surface source distribution without extrusion.

If a 2D CFD simulation is to be carried out with one layer of w_{CFD} high elements to model a W high planar flow and the acoustic source region mesh has $\beta/2$ layers of elements, each having a height of $w_{\mathrm{acou}} = (W/2)/(\beta/2)$, then the steps of the final computational algorithm to compute the 3D acoustic field of the whole W high planar flow is as follows:

Step 1: 2D CFD simulation

Step 2: Calculation of the acoustic nodal sources on the CFD mesh

Step 3: Conservative interpolation of the acoustic nodal sources onto the bottom layer of the acoustic mesh.

Step 4: Copying and scaling the nodal sources by a factor of $\gamma = w_{\mathrm{acou}}/w_{\mathrm{CFD}}$ for the bottom and the top layers and $2 \cdot \gamma$ for each intermediate layer.
Alternatively: concentrating all the sources onto the bottom layer by scaling the sources on the bottom layers with a factor of $\gamma = W/w_{\mathrm{CFD}}$ without copying it to further layers.

Step 5: If harmonic analysis is sufficient, then the acoustic nodal sources are Fourier transformed and a harmonic acoustic simulation is performed.
Alternatively: if necessary, a full time domain transient acoustic simulation is carried out.

At the price of an acceptable error in the final results, which was in our case below 1 %, the calculation time can be reduced by a factor of 8. It has also been shown that the acoustic sources can be concentrated in one layer without committing a significant error.
(Thesis #5)

The proposed method is applied to the edge tone to investigate its acoustic field numerically. It is shown that the numerical results compare well with the analytical formula of an acoustic dipole generated by a periodic force acting on the fluid. It is also shown that only the first $0.72h$ long part of the wedge is important for the sound production, and the amplitude of the force acting on this part of the wedge is lower than the strength of the dipole. This can be explained in the following way: The two should agree if the edge tone were a perfect dipole source. However it is a dipole only if observed from the far field. Near the wedge wall it is rather like two unconnected monopoles of opposite phase, separated by the wedge. If we go to the far field, this separation becomes unimportant but in the proximal and near field it is important and it increases the amplitude relative to the perfect dipole because of the lack of connection. The fact that in the lower frequency cases the two values differ less, can be explained by the larger diffraction effects around the wedge, so that the separation effect and thus the distortion of the perfect dipole behaviour is less. Furthermore, the scaling of the acoustic pressure with the third power of the Reynolds number could be well demonstrated.
(Thesis #6)

3 CFD simulations of an organ pipe foot model

A well-known realization of the edge tone phenomenon is the flow in a flue organ pipe. The air leaves the foot of the organ pipe through the flue forming a planar free jet. This jet interacts with the upper lip and initially starts to oscillate with a frequency determined by the edge tone characteristics. During the attack transient this oscillation frequency very quickly transforms into the resonator fundamental frequency. Since the attack transient is crucial for the subjective perception of the sound, and the acoustic features of the attack transient are determined by the exact way of transition (sometimes through a higher harmonic), it is very important for the understanding of the acoustics of the organ pipe to study the behaviour of the flue-upper lip area that is in fact a specialised edge tone system.

Außerlechner et al. [29, 30] built an experimental pipe foot model (i.e. an organ pipe without a resonator) to investigate how the jet leaves the foot of the organ pipe, and how it interacts with the upper lip. First they made free jet experiments without the upper lip. They found that near the flue the jet has a Nolle profile [31] and at larger distances ($> 5\,\mathrm{mm}$) the velocity profile becomes approximately Gaussian. They determined the centreline and the width of the jet as parameters of the Gaussian probability density function describing the velocity profile and found that the jet contracts asymmetrically to about $78 - 87\%$ of the width of the slit as it leaves the foot and that the centreline of the jet is almost a straight line. After the free jet measurements they made edge tone measurements. They found a mixed mode of the edge tone with the first, second and third stages coexisting. By changing the spatial position of the upper lip placed at 10 mm above the flue they found that the maximum edge tone amplitude and thus the strongest produced sound can be achieved when the upper lip is placed in the centreline of the jet.

It is shown that the flow in the model of the foot of an organ pipe can be effectively simulated with a commercial CFD code. Experimental results of Außerlechner et al. [29] were reproduced in many respects. Good agreement was found in the: direction of the jet, the velocity profiles, the jet centreline, the optimum position of the upper lip (at the mean centreline position of the jet), and the frequencies of the first, second and third stages of the edge tone. In addition, the Strouhal numbers have been compared to that of the edge tone (Thesis #2, Brown's or Jones' results [15, 19]) and the agreement is excellent.

The work presented here opens the possibility to investigate the influence of other parameters in organ pipe foot models, such as the ratio of cutup and flue width, the jet direction (by changing the position of the languid), the sharpness of the upper lip, etc. Some numerical experiments with slight changes of the relative position of the languid and the lower lip exerted a large influence on the jet angle and contraction (i.e. loss). If the upper lip was adjusted again in its optimum position, the frequency remained the same. This indicates that the organ builder has to find an optimum combination for the languid, lower lip and upper lip position, matched with the pipe supply pressure. Modelling the full organ pipe would require more work since the interaction of flow and acoustics is still not fully understood but having a reliable tool in hand that can reproduce the edge tone flow accurately is of great value in organ pipe research.
(Thesis #7)

4 Theses

Thesis #1

The edge tone phenomenon was produced both experimentally in the laboratory and by a commercial Computational Fluid Dynamics (CFD) software (ANSYS-CFX) numerically.

1.1 The following four different methods for the measurement of the oscillation frequency of the edge tone were compared:
- the "vortex counting" method;
- the "wavelength method";
- stroboscope principle;
- the Fourier analysis of the signal of the pressure transducer;

I showed that except for the "wavelength method" the other three yields the same result within their accuracy. In spite of its inaccuracy, the "wavelength method" is woth mentioning, because it is able to measure the frequency of the edge tone oscillation from only two subsequent photographs.

1.2 I have carried out a detailed mesh- and time step-dependence study in the $Re = 200$, $h/\delta = 10$ case. I have deduced a formula with which the necessary time step to keep the absolute error of the simulation on the reference level can be determined for other Reynolds numbers. As a result I showed that in order to keep the absolute error at a constant value, the time step (τ) has to be changed in proportion to $u^{-3/2}$. Furthermore I showed that if the relative error is to be kept constant then it is sufficient if $\tau \propto u^{-1}$, which – taking into consideration that the f is nearly proportional to u – results in a constant period resolution.

Related publications: WoS journal: [1]; Non-WoS publications: [5–8]

Thesis #2

Several formulae can be found in the literature describing the relationship between the dimensionless parameters (Strouhal number (St), Reynolds number (Re) and dimensionless nozzle-to-wedge distance (h/δ value)) of the edge tone. The different formulae results in different Strouhal numbers at the same Reynolds number and h/δ values; at certain parameter values the relative difference between the Strouhal numbers can be up to 100 %.

The experimentally measured and numerically calculated Strouhal numbers (dimensionless oscillation frequencies) at the same Reynolds number and dimensionless nozzle-to-wedge distance agree within accuracy. My results verify Brown's experimental results. The dependence of the Strouhal number of the edge tone on the Reynolds number and the h/δ value can be described by the following formula, similar to that of Brown [15]:

$$St\left(Re, \frac{h}{\delta}\right) = \left(c_1 - \frac{c_2}{Re}\right)\left(\frac{1}{h/\delta} - c_3\right),$$

where the values of c_1, c_2 and c_3 constants are:

		c_1 [-]	c_2 [-]	c_3 [-]	R^2
Top hat velocity profile	Stage I pure	0.4837	12.31	0.005461	0.9941
	Stage I multi	0.4167	0.2292	0.01426	0.9015
	Stage II	1.066	27.11	0.004157	0.9614
	Stage III	1.884	19.96	0.01261	0.9934
Brown's [15] experimental results top hat velocity profile	Stage I	0.4659	12.06	0.007	
	Stage II	1.072	27.74	0.007	
	Stage III	1.77	45.83	0.007	
Parabolic velocity profile	Stage I pure	0.5230	11.08	0.004836	0.9953
	Stage I multi	0.5029	6.6451	0.01417	0.9832
	Stage II	1.177	37.15	−0.002273	0.9786
	Stage III	1.972	6.954	0.007792	0.9916
	Stage IV	2.365	−55.21	−0.000999	0.9982

I showed that if the Reynolds number is based on the cubic mean value of the velocity profile (that guarantees energy-flux equivalence) instead of the mean velocity (that guarantees mass flow rate equivalence) then the difference between the Strouhal numbers of the top hat and parabolic edge tones diminishes. From this it can be concluded that the attributes of the edge tone are determined by the energy-flux.

Related publications: WoS journal: [1]; Non-WoS publications: [5–10]

Thesis #3
It is known from the literature that the appearance of the edge tone flow at some – not well defined – parameter value changes qualitatively, the jet switches to another stage. Pure and coexisting stages are both reported in the literature and sometimes also hysteretic behaviour in the stage jumps can be found. I completed the observations of the literature with the following remarks:

3.1 I showed by experimental and numerical means that with top hat jets at the appearance of the higher stages of the edge tone the lower stages do not disappear, the stages are coexisting superposed on each other, while in the case of parabolic jets the second stage can be present purely as well.
I showed by experiments in detail that in the case of parabolic jet profile the second stage first coexists with the first stage then the first stage disappears and the second stage is present purely. Then at the advent of the third stage the first stage again appears but the second stage disappears, while at last the first stage again disappears and the third stage is present purely.

3.2 I showed by experimental and numerical means that at certain parameter settings (at the stage boundaries) the edge tone jumps from one stage to another without any external excitation. This stage jump can be permanent (one-way) or it can be temporary meaning that the jet jumps back and forth randomly between the two stages ("mode switching").

3.3 I showed by experiments that in case of parabolic jets increasing and then decreasing the Reynolds number the position of the stage jumps changes, hysteretic behaviour can be observed. No hysteresis can be observed with top hat jets.

Related publications: WoS journal: [1, 2]; Non-WoS publications: [5, 6, 8, 11]

Thesis #4
Each existing theoretical model of the edge tone assumes that the disturbance of the jet travels with a constant convection velocity. The value of this velocity is different in different models, typically $0.3-0.6$, in most cases $0.4-0.5$ times of the mean exit velocity of the jet is used.

I showed by numerical simulations that the phase of the jet disturbance (ϕ) changes nonlinearly with the distance measured from the nozzle, thus the convection velocity of the jet disturbance is not constant between the nozzle and the wedge. I found that in the case of a first stage edge tone the phase changes independently of the Reynolds number and can be described as:

$$\phi_*\left(\frac{x}{h}\right)=\frac{\phi\left(\frac{x}{h}\right)}{2\pi}\approx 0{,}6036\cdot\left(\frac{x}{h}\right)^2+0{,}2781\cdot\frac{x}{h}$$

From that the convection velocity of the disturbance follows as:

$$\frac{u_{conv}\left(\frac{x}{h}\right)}{u}=\frac{h}{T\cdot u}\cdot\frac{1}{\phi_*'\left(\frac{x}{h}\right)}=St\cdot\frac{h}{\delta}\cdot\frac{1}{\phi_*'\left(\frac{x}{h}\right)}$$

The Strouhal number of a first stage edge tone is between $0.028-0.044$, from that – at $h/\delta=10$ – the convection velocity of the disturbance relative to the mean exit velocity of the jet near the nozzle is $1-1.58$, which decreases to a value of $0.2-0.3$ as it reaches the wedge. The mean value of the disturbance convection velocity relative to the mean exit velocity of the jet is between $0.32-0.5$.

Related publications: WoS journal: [1]; Non-WoS publications: [5, 6]

Thesis #5
Several flow phenomena can be well approximated as planar flow although the sound generated by them is three-dimensional. Until now for a three-dimensional Computational AeroAcoustic (CAA) simulation a three-dimensional CFD simulation was needed (3D-3D coupling).

I have developed a method with that the three-dimensional acoustic field generated by a (finite W thick) planar flow can be determined without the need of the three-dimensional CFD simulation of the full W thick flow domain by modelling only a thin (w thick) slice of the planar flow (2D-3D coupling). The basic idea is that the acoustic sources are computed from the two-dimensional ANSYS-CFX simulation, then they are interpolated onto the acoustic mesh where they are extruded in the third direction and there a proper scaling (given in the dissertation) is applied. Further simplification can be achieved if the acoustic sources are not extruded, only a W/w scaling is applied, thus the acoustical sources are concentrated onto a plane.

I showed that if the thickness of the planar flow is much smaller than the acoustical wavelength i.e. the sound source is acoustically compact, then the acoustical far field resulting from a 2D-3D coupling negligibly depends on the resolution of the extrusion (including the case when the sources are concentrated on a plane without extrusion). Furthermore I showed that the acoustic far fields resulting from a 3D-3D or 2D-3D coupling differ negligibly.

Related publications: WoS journal: [3]; Non-WoS publications: [12–14]

Thesis #6
I investigated the acoustic field of the edge tone by the method described in Thesis #5.

I showed that from the sound generation point of view only a short, $0.72h$ long part of the wedge plays a role. I investigated the amplitude of the fluid force acting on this part of the wedge $\left(\widehat{F}\right)$ and the strength of the sound source generated by the flow $\left(\widehat{G}\right)$. I found that contrary to the theoretical dipole in the edge tone configuration the generated acoustic sources at the two sides of the wedge are separated by the wedge, thus reducing the interaction between the two theoretical monopoles of the dipole, therefore $\widehat{G} > \widehat{F}$. The ratio of the two force $\left(\widehat{G}/\widehat{F}\right)$ depends on the frequency of the generated sound. At lower frequencies – because the diffraction effects at the edges of the wedge is greater – the ratio of the forces is lower.

Related publications: WoS journal: [3]

Thesis #7
A real-world appearance of the edge tone is the flow in an organ pipe. As the air exits the foot of the organ pipe a jet is formed an it impinges on the upper lip.

I modelled the self-sustained oscillation in the foot of an organ pipe with the help of a commercial CFD code (ANSYS-CFX). I investigated how the position of the upper lip (that plays the role of the wedge in this specialized edge tone configuration) affects the evolved edge tone phenomenon. I showed that the strongest and most stable edge tone flow – and thus the strongest and most stable sound production – is achieved when the upper lip is placed in the centreline of the jet blowing from the foot of the organ pipe. My numerical results and the experimental results of Außerlechner et al. [29] in a similar configuration agree well.

Related publication: WoS journal: [4]

WoS journal publications

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Non-WoS publications

[5] I. Vaik and G. Paál, "Numerical simulations of the edge tone," in *Forum Acusticum Budapest 2005: 4th European Congress on Acustics*, (Budapest, Hungary), pp. 635–639, 2005.

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