Mode switching and hysteresis in the edge tone

I Vaik and G Paál
Budapest University of Technology and Economics, Department of Hydrodynamic Systems, Műegyetem rkp. 1, Budapest, H-1122
E-mail: vaik@hds.bme.hu

Abstract. The edge tone flow is one of the most simple aero-acoustic flow formulation. Despite it has been researched for several decades it is not yet fully understood. The flow consists of a planar free jet and a wedge shaped object placed oppositely to the jet. Under certain circumstances the jet starts to oscillate as it impinges on the wedge. The jet can take different shapes, these are called the stages of the edge tone. As the main parameters of the configuration varies the frequency of oscillation changes continuously within each stage. At some points the jet jumps between stages making a sudden jump in the frequency of oscillation as well. Also it was found that at certain parameters the jet jumps between stages without any change in the conditions. This study throws light on some very interesting non-linear phenomena according to the stage jumps of the edge tone. Both experimental and numerical techniques were used during the research.

1. Introduction
The edge tone is a simple flow configuration producing a remarkably complex behaviour. It consists of a planar free jet and a wedge-shaped object, placed oppositely to the jet exit (figure 1). The main parameters of the configuration is the nozzle wedge distance \( h \) and the mean exit velocity of the jet \( u \), but also the exit velocity profile of the jet has a mentionable effect on the evolved flowfield.

It was observed that under certain conditions the jet oscillates around the wedge (also called edge) in a more or less periodic manner. The oscillating flow creates an oscillating force on the wedge which creates a dipole sound source, thus this flow provides the excitation mechanism for the resonator in many wind instruments. \[1, 2, 3, 4\]

Figure 1. Sketch of the edge tone.
The frequency of oscillation varies continuously as the main parameters change. The frequency of oscillation is linearly proportional with the mean exit velocity of the jet, and inversly proportional with the nozzle-wedge distance. However, at certain parameter values the evolved flow changes qualitatively, resulting in a sudden change in the frequencies as well. These qualitatively different looks of the evolved flow are called the stages of the edge tone. Higher stages can be superposed onto lower ones, thus creating a nonperiodic oscillation or can be present purely. The ordinal numbers of the stages correspond roughly to the number of half waves in the shape of the jet between the nozzle and the wedge. Figures 2, 3 and 4 present three different appearances of the edge tone. The velocity fields calculated by a commercial computational fluid dynamics (CFD) solver are presented as vector plots.

![Figure 2. Stage I. at Re = 150.](image)

![Figure 3. Stage II. at Re = 400.](image)

The authors made an extensive experimental research on the edge tone, and also investigated this flow phenomenon with the help of CFD simulations. Several attributes of the phenomenon (such as the linear frequency dependence on the mean exit velocity and the inverse proportionality between the frequency and the nozzle-wedge distance) were reproduced in both ways. Four stages of the edge tone have been reproduced experimentally and three with numerical flow simulations. [5, 6]

In the numerical simulations geometrical sizes were chosen to be identical with those found in Powell’s work [1]. During the measurements geometrical sizes were about three times larger,
because this way - according to the similarity rules - the frequency of oscillation was about 10
times lower, and so the observation of the visualised flow was possible with a high speed digital
camera taking still pictures at a maximum frame rate of 90 fps. To be able to compare the
results from the literature, from the CFD simulations and from the experiments nondimensional
numbers were introduced as the following:

- Reynolds number, \(Re = \frac{u \delta}{\nu}\), for the mean exit velocity of the jet, where \(\delta\) is the width of
  the jet and \(\nu\) is the viscosity of the air;
- \(\frac{h}{\delta}\) for the nozzle-wedge distance, where \(h\) is the nozzle-wedge distance and \(\delta\) is the width
  of the jet;
- Strouhal number, \(St = \frac{f \delta}{u}\) for the frequency of oscillation \((f)\).

2. CFD simulations
A commercially available CFD code based on a finite volume technique (ANSYS-CFX) was used
to calculate the flow field. Without going into the details of the solver ([7]) only the setup is
discussed here.

As a first step of all numerical solution of partial differential equation systems a spatial
discretisation of the domain is needed. The virtual geometry and the numerical mesh was
created in ANSYS ICEM CFD. The domain was much larger than the area of interest to avoid
the unwanted effects of the boundary conditions on the flow phenomenon. ANSYS CFX is a
3D solver, calculations of 2D flows is possible with a one cell layer mesh by defining symmetry
boundary conditions on the bottom and top surfaces. Thus a mesh with one layer of hexahedra
was created. After a careful mesh study the resulting mesh contained only 36300 volume
elements.

The second step is to define the physics of the flow and to set the numerical discretisation of
the PDE-s. Second order temporal and spatial discretisation of the Navier-Stokes equation was
used in the solver. Because of the low Reynolds number (the maximum Reynolds number used
during the simulations or the experiments was not greater than 3000) neither compressibility
nor turbulence modelling was required. With the addition of a passive scalar variable for the
”smoke” it was possible to model the flow visualisation of the experiments. A simple transport
equation was used to calculate the density of smoke in the domain.

As a transient calculation one has to define the initial state of the flow. It was also investigated
to what extent the initial conditions effects the evolved flow. It was found that the least numerical
error and instability is introduced into the computation if the initial condition is a medium is at rest, so with 0 m/s velocity values and constant pressure distribution.

Details of the CFD simulations (more about the mesh, the setup and results discussed from several aspects) can be found in [5].

3. Experimental work

The sketch of the measurement rig can be seen in figure 5. Shop air was introduced into a 57 l cylindrical reservoir through a mass flow rate sensor (Sensortecnics, Honeywell AWM700, working on a heated element principle producing voltage output). This mass flow rate sensor was used to measure the mean exit velocity of the jet. 3/4" reinforced flexible plastic tubes were used in the rig to connect the shop air system of the laboratory through the mass flow rate sensor to the reservoir. A pressure reducing valve was used to reduce the pressure to 0.5 bar, thus eliminating the effect of the exhausting main shop air reservoir of the laboratory. The mass flow rate sensor was placed between two throttle valves, as the first calibrations showed that the sensor is sensitive to the inner pressure. With the careful parallel settings of these two valves it was possible to regulate the mass flow rate (and thus the mean exit velocity of the jet) without changing the inner pressure in the sensor. A long copper pipe was inserted just before the mass flow rate sensor to ensure undisturbed inflow into the sensor. Two nozzles were used to create a top hat or a parabolic exit velocity profile for the jet (figure 6). Former was formed by two quarter cylinders ensuring quick contraction and so creating a top hat velocity profile. For the creation of parabolic velocity profile the nozzle was built up of two 150 mm long parallel plates with a 15 mm rounded entry. The dimensions of the nozzle for the top hat case were: δ = 3.31 mm with a height of 76.1 mm; and for the parabolic case: δ = 3.09 mm with a height of 63.4 mm. So the aspect ratio was high enough to get a two-dimensional flow in the middle. The steel wedge was 150 mm high, so twice as high as the nozzle to avoid the end effects. The nozzle wedge distance was adjustable between 5 mm and 54 mm, so the dimensionless nozzle-wedge distance h/δ was adjustable between 1.67 and 17.7. A pressure transducer (Sensortecnics, 113LP01D-PCB) was built into the steel wedge at a distance of 26.2 mm from the tip of the wedge. The output signal was recorded with a 16 bit National Instruments A/D converter. The measuring rage of this sensor is [-100 Pa; 100 Pa] and the amplitude of the pressure fluctuation to be measured was about ±0.05 Pa for the lower range of Reynolds number. The output of the sensor for the full range is [1 V; 6 V], so for the 0.05 Pa amplitude pressure oscillation the fluctuation of the output voltage was in the range of 0.00125 V resulting an only 4 step resolution using the 16 bit A/D converter. The highest pressure during the measurements was about 4 Pa, what results about 0.1 V difference in the output signal. In order to be able to digitalize such small analogue voltage signals with the 16 bit A/D converter a special amplifier was used, which extended the [3.3 V; 3.7 V] voltage region to the [-10 V; 10 V] region. In the top hat jet case it was possible to visualize the flow with an incense stick. The smoke filament was illuminated by floodlight and the image was recorded with a high speed digital camera (LaVision ImagerCompact) taking pictures with a maximum frequency of 90 Hz with a spatial resolution of 320x240 pixels. No visualization was made in the parabolic case. Details of the measurements can be found in [6].

4. Detection of a mode switch

As discussed in the abstract and in the introduction, this paper aims to describe the mode switching events of the edge tone. There are several kinds of mode switching in the edge tone if the main parameters are changed continuously. Some of the borders of these modes are ‘permanent’ (the mode stays stable if the parameter is changed), some of them can show hysteretic behaviour, some of them exhibit a random mode switching within a certain parameter range.
It was possible to take a picture series of the visualised flow field (only in the top hat case), but with our experimental rig it was not possible to properly trigger the camera to record the stage jump, so that it was rather fortuitous to record the jump even if the parameters were set to the proper values.

The analogue output signal of the pressure transducer was continuous and it was possible to digitalize and record this signal even long enough to record the pressure history during a mode switch. The qualitative change of this signal shows evidently the mode switch. To find the qualitative change in the recorded pressure histories a sliding window Fourier transformation technique can be used.

The process was the following: FFT was carried out from a $\Delta t$ s long piece of the full signal starting at each $n \cdot \tau$ s time (usual $\tau$ was much less than $\Delta t$, about 10-50% of $\Delta t$), thus creating a spectrum with a $1/\Delta t$ Hz frequency resolution for that period. Then all of the spectra can be visualised in one contour plot: the amplitude is plotted as colours against the frequency on the $x$ axis, and the time (the start time of the 'window') on the $y$ axis. So the colours on a horizontal cut of the figure at $t$ s on the $y$ axis represent the spectrum of the pressure signal for the $[t, t + \Delta t]$ period.

5. Observed phenomena

5.1. Stage jump in the CFD simulation

During the numerical simulations the jet was much more stable than in the experiments. This is because the CFD simulations are lack of any flow disturbances that throw the jet off its 'balance'. With the high computational cost required for a long transient simulation this made the CFD simulation of a stage jump very hard. Still a jump from a pure first stage into a first and second stage coexistence was simulated. Figure 7 shows a pressure history at a point on the surface of the wedge at a distance of 2 mm from the tip of the wedge. The qualitative change of the signal can clearly be observed. The described moving window FFT method can be used for this signal too (see figure 8), the stage jump is nicely observable.

5.2. Mode switching and hysteresis during the change of the Reynolds number in experiments

There is a qualitative difference between the top hat and the parabolic case: In the top hat case when a higher stage of the edge tone evolves the lower stage(s) never switch(es) off, so a configuration when two or more stages coexist can be found. Pure 2\textsuperscript{nd} or 3\textsuperscript{rd} stage oscillation cannot be produced. In the parabolic jet case the same coexistence can be found, but there are also pure higher stage oscillations. Since it has more modes, the parabolic case is discussed here.

With a constant geometry ($h/\delta = 10$) the following can be observed when the Reynolds number is increased from zero:

- At first there is no oscillation at all. The wedge cuts the jet in half, and the flow is steady;
• At \( Re \approx 85 \) the first stage of the edge tone evolves;
• Then increasing the Reynolds number, at around \( Re \approx 180 \) the second stage appears next to the first stage, the two of them coexisting;
• Then further increasing the Reynolds number qualitatively different behaviour can be observed: from about \( Re \approx 360 – 420 \) the first stage disappears and only the second stage exists;
• Further increasing the Reynolds number \( (Re \approx 550 – 750) \) the second stage disappears and the third stage of the edge tone evolves, but at the same time the first stage appears again both coexisting;
• At the highest Reynolds numbers a pure third stage oscillation was observed (from about \( Re \approx 650 – 1000 \)).

5.3. **Hysteresis in experiments**

When decreasing the Reynolds number the same process can be observed in the opposite direction, but with one big difference: there is no pure second stage oscillation when decreasing the Reynolds number from a third and first stage coexistent mode. So the edge tone behaves
differently in the [350; 600] Reynolds number region if the it approached from lower Reynolds number of higher Reynolds number. Figures 9 and 10 show this hysteretic behaviour.

![Figure 9. Hysteretic behaviour, increasing Reynolds number.](image)

![Figure 10. Hysteretic behaviour, decreasing Reynolds number.](image)

5.4. Stage jumps and mode switching in experiments

The following pictures show the results of the moving window FFT for some mode switches:

- Figure 11: A jump from a first and second stage coexistence into a pure first stage mode can be seen here. One can clearly observe the qualitative change in the spectrum at about $t = 6$
s. It was found that the frequency of the first stage is about 10% lower if the second stage is also present than in pure first stage oscillation. This phenomenon can also be observed in this picture. Also another typical nonlinear phenomenon can be found: in the two stage coexistence mode there is a peak at the difference of the frequencies of the two stages;

- Figure 12: The first stage switches on and off next to the second stage, without any change in the conditions;
- Figure 13: The first stage switches on next to the second stage;
- Figure 14: The first stage switches off;
- Figure 15: The jet jumps from a pure second stage oscillation into a first and third stage coexistence;
- Figure 16: The jet jumps back from a first and third stage coexistence mode into a pure second stage coexistence;
- Figure 17: The first stage switches on next to the third stage;
- Figure 18: The first stage switches off and on next to the third stage.

Figure 11. Mode switching: jump from first and second stage coexistence into pure first stage.

Figure 12. Mode switching: the first stage switches on and off next to the second stage.
Figure 13. Mode switching: the first stage switches on next to the second stage.

Figure 14. Mode switching: the first stage switches off resulting a pure second stage oscillation.

Figure 15. Mode switching: jump from the second stage into the first and third stage coexistence.
Figure 16. Mode switching: jump from the first and third stage coexistence into a pure second stage oscillation.

Figure 17. Mode switching: jump from a pure third stage oscillation into a first and third stage coexistence mode.

Figure 18. Mode switching: the first stage switches on and off next to the third stage.
6. Conclusions
The edge tone has several qualitatively different appearances, and the jut jumps between stages if the main parameters are varied. Pure stages or the coexistence of the stages are both possible. There are certain conditions where the edge tone is not stable in any of its appearances, and switches between modes without having any change in the conditions of the flow. The edge tone also displays hysteresis. Stage jumps and mode switching were reproduced both numerically and experimentally and the hysteretic behaviour of the edge tone was also observed in the measurements.

7. Acknowledgement
This work is connected to the scientific program of the 'Development of quality-oriented and harmonized R+D+I strategy and functional model at BME' project. This project is supported by the New Hungary Development Plan (Project ID: TMOP-4.2.1/B-09/1/KMR-2010-0002).

References
[1] Powell A 1961 On the edge tone Journal of the Acoustical Society of America 33, 395-409
[2] Brown G B 1937 The vortex motion causing edge tones Proc. Phys. Soc. Lond. 49 493-507
[3] Jones A T 1942 Edge tones Journal of the Acoustical Society of America 14 131-9
[4] Curle N 1953 The mechanics of edge tones Proc. Roy. Soc. A. 216 412-24
[5] Paal G and Vaik I 2007 Unsteady flow phenomena in the edge tone Int. J. Heat Fluid Flow 28 575-86
[6] Vaik I and Paal G 2009 Experiments on the edge tone Proceedings of the Conference on Modelling Fluid Flow (CMFF’09), 9-12 September 2009, Budapest, Hungary
[7] www.ansys.com