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The influence of side hole undercutting on vorticity

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Vortices in musical instruments form in a non-uniform flow, where air currents of different velocities or directions mix. Non-uniform flow, in the case of flutes or recorders, occurs at the labium, at the open end and at the side holes. Side hole undercutting has been shown to minimise vortex formation. Previous numerical simulations have visualised airflow velocity influence on vorticity. In experimental studies, where a tube with a side hole was excited by a loudspeaker, it was observed that speaker loudness and hole geometry influenced the vorticity. Recent simulations explore the effect of undercutting on the transient and show detailed results on the vortex formation. In this study, we aim to compare vortex formation between 6 different side hole geometries with a significant undercut and another 6 without undercutting, under realistic input conditions. Using the same geometry as in the simulations mentioned above, we employ time-resolved Particle Image Velocimetry to measure flow velocity at a sampling rate of 10 kHz. The recorder is excited utilising a commercial recorder mouthpiece with constant input conditions maintained at 100 Pa.

1. INTRODUCTION

One way to adjust the pitch of the instrument without using a different bore or playing techniques, is to use tone holes otherwise known as side holes.¹ The player can cover and open the holes using their fingers or keys, effectively changing the pitch that the instrument is playing. The pitch change depends on the open hole's position and geometry. Over time, experienced instrument makers realized that making an additional cut around the inner edge of the tone hole by either chamfering the edge with a knife or smoothing with some sort of abrasive material does affect the sound in a sometimes preferable way. This alteration of the tone hole is what is now called undercutting.

Wind instruments that employ tone holes to adjust the pitch oftentimes have their tone holes undercut, especially if they are handmade.² Undercutting tone holes may serve multiple purposes. One of these purposes is pitch correction. The other reason is the reduction of higher harmonics, focusing more energy on the fundamental.³ These undercuts are most often cut with a chisel which would leave a straight undercut. Additionally, undercutting may be done asymmetrically around the tone hole, most often to adjust pitch. While tone hole undercutting for pitch adjustment remains a very interesting and complex topic, we would like to explore another objective that undercutting achieves. The reduction of higher harmonics simultaneously comes with a reduction of vorticity. As it was already shown, sharp edges in T-junctions of straight pipes can create vortexes whose size varies at the frequency of the internal pipe oscillations.⁴ These vortexes also shed possibly reducing the energy that the pipe oscillations carry. We want to explore how does undercutting affect the vorticity and what are the implications of it on the spectrum of the internal flow of the instrument.

Flow can be observed using advanced optical visualization techniques, such as Schlieren or Transmission Electronic Speckle Pattern Interferometry (TESPI). These methods rely on the density or temperature difference of the gas in order to observe the air movement and work very well when we are observing shock waves at the bell of the trumpet⁵ or to visualize exhaled breath of the human singing voice.⁶ The small variations at a steady state in a closed bore might not be visible using these techniques. Another method is to inject the flow with tracing particles and illuminate them with a strong light source. The tracing particle position can then be captured using a high speed camera. This measurement method is called Particle Image Velocimetry (PIV)⁷ and we have chosen to use it to measure the flow inside a transparent bass recorder bore. This method has shown to enable measurements such as organ nicking influence⁸ and loudness influence on the tone hole acoustic streaming velocities.⁹ Measurements of a tone hole diameter influence on a soprano recorder validate the approach even further, displaying the capabilities of PIV to measure tone hole influence on a mouthpiece excited recorder.¹⁰

Complex numerical simulations have been performed on the same exact geometry as our experimental setup.¹¹ These simulations focus on one tone hole geometry and show 3 dimensional vortex observations inside and around the tone hole for varying input velocity values.

The primary objective of this paper is to observe the vorticity inside a wind instrument with a tone hole, comparing cases where the hole is simply drilled to those which are also undercut. To assess the influence of undercutting, we employ high-speed time-resolved PIV at the inner wall of the instrument, right underneath the tone hole. By varying the tone hole geometry while keeping the undercut radius constant, we gain insight into how the diameter and height of the tone hole influence vorticity. We begin by describing the setup, the measurement procedure and the data processing steps, after which we show some results that we have obtained by computing a mathematical operator (*curl*) to quantify the strength of the generated vortices.

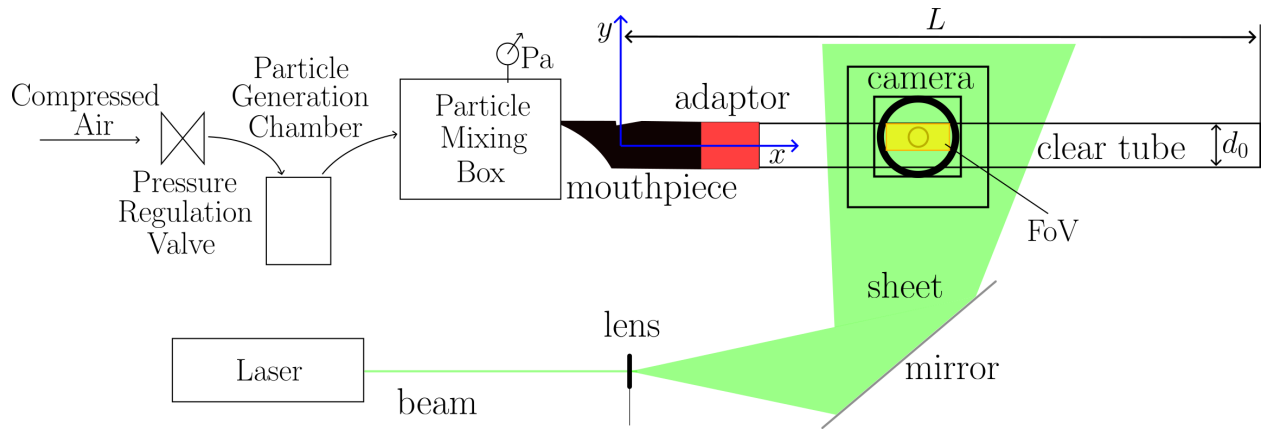


Figure 1: Simplified diagram of the PIV experiment assembly. The high speed camera is set perpendicular to the plane of the laser sheet. Depiction of pressure transducers is omitted, but they are present during all the experiments.

2. SETUP

The measurements are conducted at the laboratory of the Institute of Fluid Mechanics and Heat transfer at the Vienna University of Technology. Flow measurements are performed on a transparent acrylic recorder with a square cross section that is manufactured by the authors. A custom made recorder was necessary to facilitate the Particle Image Velocimetry (PIV) experiments. PIV requires tracing particles, a high power illumination sheet and a high speed camera. The transparent bore allows for a measurement inside an instrument, while the square geometry expands the available cross-section height to allow for wall-to-wall measurement due to the elimination of optical distortion of otherwise round cross section. Wall-to-wall field of view is crucial when studying vortex generation at the edges of the tone hole. Pressure measurements were simultaneously performed allowing us to validate the frequency peaks that we observe with PIV measurement. Additionally, pressure measurements inside the particle mixing box were crucial during the acquisition of data as it will be explained in section 2.C.

A. RECORDER GEOMETRY

A custom made recorder is assembled from a Thomann baroque bass recorder (TRB-31B) mouthpiece, a custom adapter and a transparent bore with square cross section. The adapter creates a smooth transition from a round cross section bass recorder mouthpiece to a transparent square cross section bore. This recorder is a simplified version of a traditional recorder. It contains only one tone hole and the bore has a non-varying cross-section, whereas in the traditional recorder, the bore would taper and have a smaller diameter at the open end than at the mouthpiece.¹² The distance from the labium to the open end of the recorder is 706.8 mm, while the side length of the square cross-section is $d_0 = 26$ mm. The playing frequency of this recorder with no open tone holes is $f_0 = 220 - 221$ Hz (depending on atmospheric conditions). A tone hole is placed at the acoustic center of the instrument – 333 mm from the labium. This location was found using PIV, where the lowest flow velocity oscillation amplitude indicated the acoustic center.

B. MEASUREMENT EQUIPMENT

In order to observe the influence of undercutting on tone holes with different geometries, we have used two-dimensional time-resolved high-speed PIV with the Field of View (FoV) focused right under the tone hole. This was achieved using a high-speed pulsed dual cavity laser (527 nm, 25 mJ per pulse, Litron

LD60-532) and a high speed camera (Phantom VEO 340 L). The flow for 2D PIV measurements should be illuminated by a sheet of light, which in our case was done using laser beam expanding optics, achieving a 1 mm thickness laser sheet at the FoV. $2\text{ }\mu\text{m}$ diameter tracing particles were generated using SAFEX fog fluid which allowed for reliable PIV measurements, given our digital imaging resolution (19.475 px/mm). Additionally, pressure data was recorded inside the bore, outside the labium and at the particle mixing box, which represents the mouth of a player, giving us the mouth pressure. Mouth and bore pressures were recorded using pressure transducers (Endevco 8507C-2) capable of measuring static and dynamic pressure.

C. MEASUREMENT PROCEDURE

Measurements are taken at steady state under a mouth pressure of 100 Pa. This pressure level corresponds to the typical pressure level range for playing bass and tenor recorders.¹³ The geometry of the tone hole is varied. The variations include 3 diameters of tone holes; all of them have short and tall chimney versions, with all of these cases also having a case with undercut (rounded 3 mm radius undercut) and without. All cases are summarized in Table 1 and tone hole geometrical variations are visualized in Fig. 2. The tone hole geometry change was accomplished by using interchangeable tone hole elements that fit inside a large hole placed at the acoustic center. During the measurements, mouth pressure was live monitored to assure constant mouth pressure throughout the experiments during the acquisition of the PIV data.

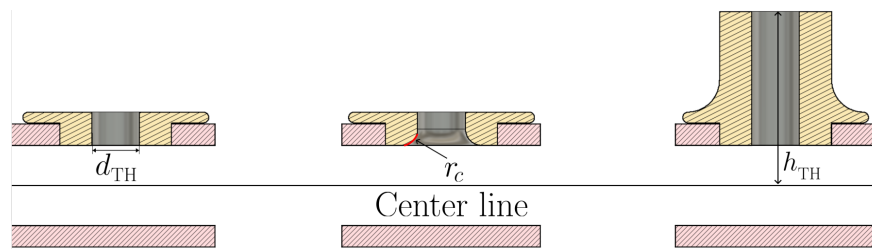


Figure 2: Cross-section of the tone holes with geometrical identities, marking tone hole diameter d_{TH} , undercut curvature radius r_c (highlighted in red) and the tone hole height h_{TH} .

	Short ($h_{TH} = 19\text{ mm}$)		Tall ($h_{TH} = 38\text{ mm}$)	
Diameter [mm]	Non-Undercut [Hz]	Undercut [Hz]	Non-Undercut [Hz]	Undercut [Hz]
9	299.76	304.20	261.50	262.57
12	320.23	323.87	280.50	281.97
15	336.73	339.47	298.80	299.87

Table 1: Playing frequencies at a single tone hole location with different geometries.

D. DATA PROCESSING

The Field of View (FoV) was chosen to be $46 \times 16\text{ mm}$, which allowed us to capture particle motion at a sample rate of 10 kHz. Captured images were mirrored and pre-processed in the acquisition software LaVision DaVis 10.2.1. Pre-processing includes sliding minimum subtraction with a kernel of 6 time-steps, which is followed by spatial normalization using a local average over 50×50 pixels. These processing steps remove static background such as reflections and micro scratches from the images as well as normalize the intensity of brightness throughout the image in case the FoV was not illuminated uniformly.⁷ Afterwards, exported images were processed by an open source PIV software PaIRS UniNa¹⁴ to extract the velocity

vectors. A final integration window of 18×18 pixels was chosen which corresponds to a square window with a side length of 0.924 mm and an overlap of 50%, yielding a vector grid dimension of 98×32 vectors. In order to quantify vorticity we have chosen to calculate the time averaged two dimensional mathematical operator curl. Vorticity of the velocity is calculated using following operation:

$$\text{curl}_z = \frac{\delta V}{\delta x} - \frac{\delta U}{\delta y}, \quad (1)$$

where V is the vertical and U the horizontal velocity component of the flow field and δx and δy the grid spacing in x and y directions, which in our case are equal. That is, at each grid point the algorithm looks at how much the vertical component changes as you move in x , and how much the horizontal component changes as you move in y , and subtract the two. These values are then saved and time average is computed, giving time averaged 2D vorticity matrices.

3. RESULTS

The high sampling rate of PIV implies a small FoV. An illustration of the FoV is given in Fig. 3, where walls are overlaid on the $2D \text{ curl}$ plot spanning the whole FoV. In the figure, wall thickness and distance between the walls is to scale. Even though the FoV did not extend the whole bore height, positioning it just below the tone hole edge at the top of the bore (as shown in the figure 3) provides a sufficiently large FoV to observe local undercutting influence on vorticity.

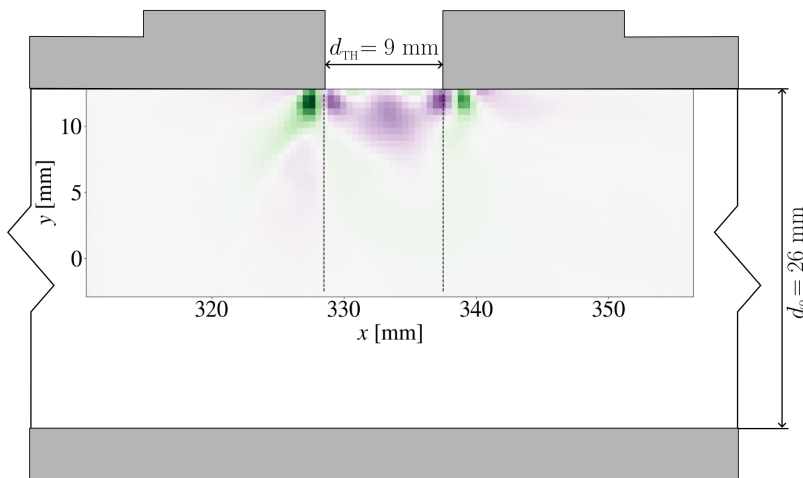


Figure 3: FoV of the camera during measurements. Grey areas mark the top and bottom walls. Wall thickness and the distance between walls is to scale.

To compare undercutting effect on vorticity we have evaluated 12 cases as described in section 2.C. Our sole interest lies in observing vortex formation when we have a sharp (non-undercut tone holes) and smooth (undercut tone holes) airflow transition to the tone hole. The vorticity can simply be evaluated using the time averaged curl function as described in section 2.D.

The two dimensional time average vorticity for the 9 mm diameter tone hole with all of its variations is shown in Figure 4. Positive curl values signify anti-clock-wise rotation of the flow, while negative values signify clock-wise rotation, and the amplitude signifies the strength of the vortex. Here we can see highest absolute curl values with the sharp edges of the tone hole. The height of the tone hole increases the vertical streaming of the vortices, spreading the vortex flow further downwards than the short tone holes. Undercutting shows a significant decrease of vortex formation, which we can see through the low magnitude of curl values.

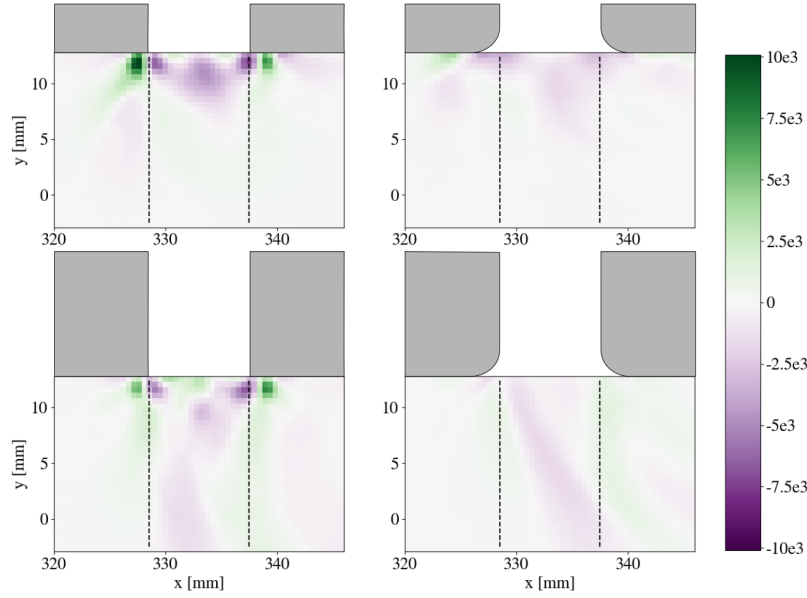


Figure 4: Time averaged 2D vorticity for tone hole geometries with the $d_{TH} = 9$ mm. Vertical dashed lines mark the edges of the tone holes. Grey areas indicate the walls surrounding different types of tone hole geometries, these show d_{TH} to scale, but r_c and h_{TH} are for illustrational purposes only.

Another trend we can observe is that clock-wise vortices (negative curl values) form on the inner edges of the tone holes, while anti-clock-wise vortices form on the outer edges. This is evident due to positive values dominating areas outside the dashed lines and negative values dominant in the area between them. We can clearly see these trends in the cases where the vorticity is high (non-undercut cases).

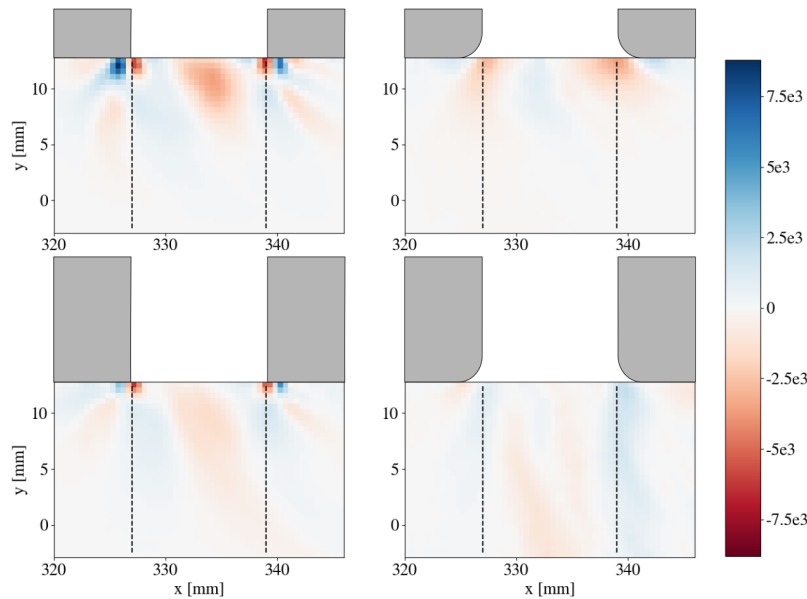


Figure 5: Time averaged 2D vorticity for tone hole geometries with the $d_{TH} = 12$ mm. Vertical dashed lines mark the edges of the tone holes. Grey areas indicate the walls surrounding different types of tone hole geometries, these show d_{TH} to scale, but r_c and h_{TH} are for illustrational purposes only.

When looking at larger diameter cases, similar trends are observed (see Fig. 5 and 6), which show time

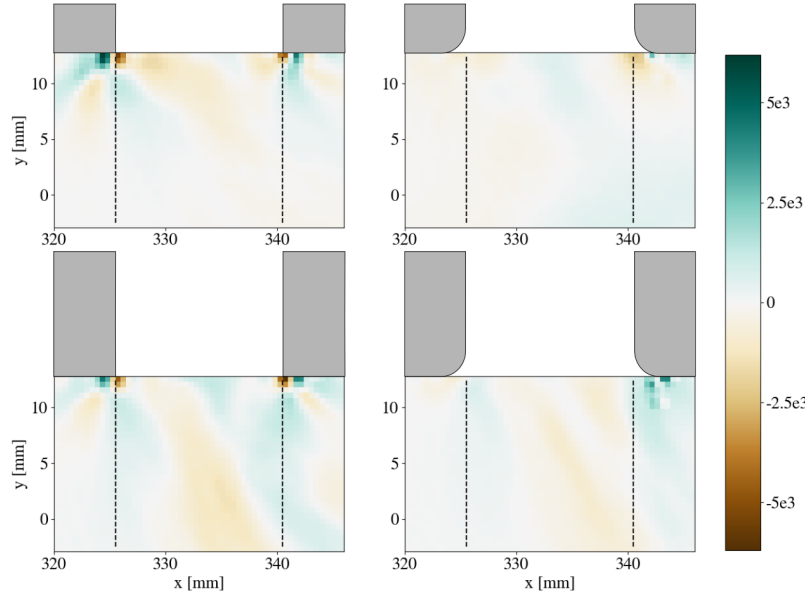


Figure 6: Time averaged 2D vorticity for tone hole geometries with the d_{TH} 15 mm. Vertical dashed lines mark the edges of the tone holes. Grey areas indicate the walls surrounding different types of tone hole geometries, these show d_{TH} to scale, but r_c and h_{TH} are for illustrational purposes only.

averaged curl values for tone holes with $d_{TH} = 12$ mm and $d_{TH} = 15$ mm respectively. It is otherwise noticeable that increasing the diameter lowers the vorticity as indicated by the magnitude of the color bars in Figures 4, 5 and 6.

4. CONCLUSIONS

Our results demonstrate that high-speed, time-resolved Particle Image Velocimetry (PIV) is an effective tool for resolving the vorticity within the flow field inside wind instruments near the tone hole. By capturing velocity data near the inner wall underneath the tone hole, PIV allows us to visualize and measure the rotational flow structures that arise due to different tone hole geometries and undercutting conditions. While more extensive studies are needed to quantify and draw more definitive conclusions about the undercutting influence, we provide a proof of concept that this method can become a valuable tool to study non-linear flow inside wind instruments. Experimental measurements such as these are crucial for understanding the acoustic performance and design of wind instruments.

5. ACKNOWLEDGMENTS

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6. AUTHOR DECLARATIONS

T.L. was in charge of conceptualization, data curation, formal analysis, investigation, methodology, visualization and writing the original draft. G.C. helped out during the steps of the experimental campaign

and preparation for it, as well as instructing T.L. how to use the resources, including the software and hardware of PIV. A.S. provided the team with resources critical for the experimental campaign. V.C. took a supervisory role, assisting in the conceptualization and formal analysis, as well as helping during the draft writing and providing with review and editing of the final submission, V.C. acquired the financial support for the project leading to this publication. The authors have no conflicts to disclose.

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