

Investigating the impact of tone hole geometry on the flow in wind instruments via particle image velocimetry

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ABSTRACT:

An experimental study is conducted to investigate the effects of both the diameter and shape of wind instrument tone holes on the flow behaviour in an artificial, simplified scenario. Time-resolved particle image velocimetry is used to measure flow velocity over the entire length of a square recorder bore. Flow velocity measurements enable various approaches to analyse the flow under different tone hole configurations. Simultaneous to the flow measurements, the air pressure at the input (blowing pressure) and in the interior of the tube (at five locations along the bore) is measured. Realistic excitation conditions are emulated, incorporating a commercial bass recorder mouthpiece. The flow for three different tone hole diameters is examined, with two of the tone holes also varying in height and undercutting. The amplitude of the flow oscillations is examined and compared for all tone hole configurations. The effect of tone hole undercutting is further analysed in the frequency domain, where it is observed that undercutting concentrates more energy at the fundamental frequency. Finally, it is experimentally shown that undercutting lowers the vorticity of the flow.

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I. INTRODUCTION

The study of wind instruments, particularly their acoustic properties, is a complex field that intertwines principles of fluid dynamics and music acoustics. Understanding how sound is generated and modulated within these instruments requires a detailed analysis of airflow and pressure fluctuations. One of the critical factors affecting the acoustics of wind instruments is the presence and configuration of tone holes, also known as finger holes, which alter the path and behaviour of the airflow.¹

It already has been shown that flute-like instrument sound generation relies on the acoustical interaction of an oscillating air-jet at the labium and the vibrations of the air contained within the open-ended pipe.^{2,3} The geometrical properties of the bore and the tone holes define the natural frequencies, which correspond to the resonant modes. These are the frequencies that are sustained by the instruments' geometry. The lowest pitch a wind instrument can produce depends on the oscillating regime induced by the entire air column.⁴

Since flute-like instruments have two open ends (where the pressure amplitude is minimum and the amplitude of the fluctuating flow velocity is maximum as illustrated in Fig. 1), the imposed lowest pitch of the instrument has a wavelength λ that is double the length of the air column of the

instrument.⁵ The air column asymmetrically extends outside the instruments' geometry, which is why end corrections (Δ_L and Δ_E) are used and the geometric and acoustic centres do not match.^{1,6} The half-wavelength of the played note in flute-like instruments is referred to as the effective length. Higher notes are produced by opening tone holes along the tube. This successive opening of holes shortens the effective length of the air column, which raises the frequencies of the corresponding modes.⁴

Tuning is done by the manufacturer, who adapts the position and geometry of tone holes to produce musically relevant resonant modes. Although pitch modulation via embouchure modifications or overblowing is also common,⁷ it is not considered in this work. The tone hole height is typically constrained by the wall thickness, while the diameter varies depending on the tuning.^{1,5} Additionally, some tone holes are undercut, minimising the instabilities at the tone hole location such as boundary layer separation and vortex generation at the sharp edges.^{8,9} It has been discussed that such vortex behaviour induces energy loss,¹⁰ but further investigation into the energy balance is required. Additionally, the frequency of shedding vortices in some cases was theorised to reside in the region of higher harmonics,¹¹ which might influence the harmonic content of the sound.

Methods for studying acoustic phenomena of tone holes have relied heavily on theoretical models and numerical simulations. Techniques such as the transfer matrix method

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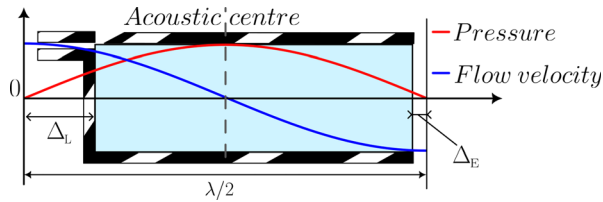


FIG. 1. Diagram of simplified pressure and flow velocity standing waves in a recorder, corresponding to the fundamental mode. The theoretical acoustic centre is marked with a dashed line. λ is the wavelength, Δ_L is the labium end correction, and Δ_E is the open end correction (Ref. 1).

allow researchers to deduce frequencies, magnitudes, and harmonicity from the input impedance or reflectance of the instrument.^{12–14} Modal decomposition,^{15,16} finite difference methods,^{1,17} and finite element methods^{18–20} can help to resolve wave propagation in the acoustic field in the case of tubes with tone holes. Direct numerical simulations help to analyse the effect of the tone hole configuration on the standing waves inside the instrument, and non-time-resolved particle image velocimetry (PIV) measurements can be used to observe flow in a small area near the labium.²¹ PIV determines the flow velocity by calculating the displacement of tracer particles that are introduced into the flow volume over a known time interval. The location of these particles is recorded with a high-speed camera.²²

Research on fluid-acoustic interactions in wind instruments has also been limited. Existing studies primarily focus on the location where airflow instabilities occur, such as on the reed of a saxophone,²³ on the labium in a recorder,²⁴ or on a flute.²⁵

Acoustic measurements in bores with a single tone hole have been used to characterise the effect of the tone hole.^{8,26,27} Experimental studies have focused on local effects, such as non-linear losses in proximity to and within the tone hole, such as boundary layer separation, vortex shedding, and jet streaming.^{8,28} These studies have employed pipes connected to loudspeakers to simulate the behaviour of wind instruments and measured the flow fields using PIV. Although this is a valuable approach, it lacks realistic excitation of the instrument because of the absence of mean flow. Mean flow can affect the air movement at the tone hole by generating vortices that shed and vary in size over time.²⁹ In addition, high amplitude pulsations in closed side-branch systems were observed in industrial applications, where the pulsations were generated by mean flow.³⁰ Therefore, incorporating mean flow during experiments becomes essential to account for these effects. Furthermore, the precise influence of the tone hole dimensions on the air-flow field remains an unexplored aspect within the existing body of literature.

This work aims to demonstrate the usefulness of PIV measurements in analysing the flow behaviour in a wind-instrument-like resonator, as well as to characterise the effect of the geometrical details of a tone hole on the resonator's response. A wide spectrum of analysis methods is presented to explore the wealth of information contained within the PIV measurement data.

While we are not attempting to investigate any wind instrument in particular, a resonator with a single tone hole at the acoustic centre serves as a simplified test case to study fundamental acoustic principles governing the tone hole's effect on the flow. Even though this is not necessarily a realistic musical setting, the proposed methodology for extracting and analysing data could eventually be used for musically relevant scenarios. This artificial scenario is chosen to emphasise the influence of the tone hole.

The experiments focus on varying the acoustic mass of the tone hole and observe the tone hole geometry influence in the time domain. Frequency domain analysis further explores tone hole effects on the flow, with particular emphasis on the effect of tone hole undercutting. Additionally, undercutting is studied in terms of vorticity.

The experiments are conducted using a real recorder mouthpiece, where airflow conditions are configured to replicate conditions of human performance. Time-resolved PIV measurements are used to detect and quantify the variations in velocity fluctuation for three different tone hole diameters; two of them are also varied in height and undercut.

II. SETUP

The experimental setup consists of two co-operating systems facilitating PIV measurements as shown in Fig. 2: an aeroacoustic system and an optics system. The former consists of an air generator, a particle generator, a particle mixing box, the recorder-like apparatus (referred to as recorder from here onwards), and pressure transducers. The latter consists of a laser, optical elements, and a high-speed camera. These systems are described in detail in the following sections.

A. Aeroacoustic system

Following the flow diagram in Fig. 2, the particle generation and instrument excitation can be traced through the aeroacoustic system. The air is supplied from a large 500 liter compressed air tank, which is connected to a particle generation chamber through a pressure regulation valve, producing $2\ \mu\text{m}$ seeding tracers made of SAFEX fog fluid. The particles are then mixed with air at the particle mixing box with inner dimensions of $19 \times 19 \times 40\ \text{mm}^3$. The recorder is attached to the particle mixing box with the help of an airtight connection. The recorder consists of a Thomann baroque bass recorder (TRB-31B) mouthpiece (Thomann GmbH, Burgebrach, Germany), an adaptor that smoothly transitions from a round to a square cross section over 50 mm, a square transparent tube made out of acrylic, and interchangeable three-dimensional (3D) printed tone hole elements. These elements are described in more detail in Sec. II D. The particle mixing box and the recorder are placed on a slider with the recorder labium window and the tone hole facing up. The slider helps to translate the recorder along the x axis. The movement in the x axis is employed to obtain the full-length measurement of the flow inside the transparent tube, as is further described in Sec. II B.

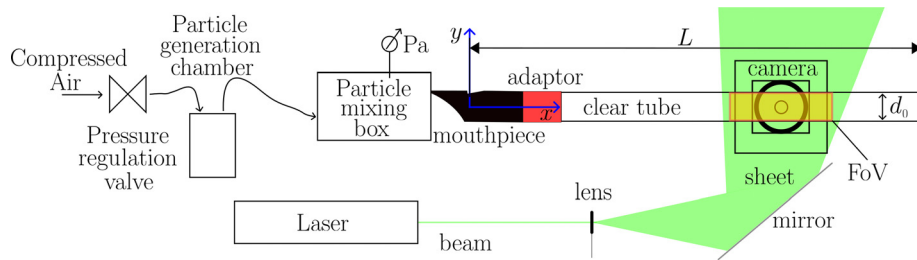


FIG. 2. Simplified diagram of the PIV experiment assembly. The high-speed camera is set perpendicular to the plane of the laser sheet. Depiction of pressure transducers is omitted, but they are present during all the experiments.

1. Bore geometry

As visualised in Fig. 2 for the purpose of PIV measurements, the bore is a transparent acrylic tube with a square, non-varying cross section. It is a simplified version of a traditional recorder bore, to guarantee wall-to-wall field of view (FoV) in optical measurements and to nullify the influence of a varying cross section. Recorders traditionally have a tapered cross section, which gets narrower towards the open end. Additionally, the majority of recorders have a round cross section, which prevents wall-to-wall FoV, due to the optical refraction of curved transparent surfaces.

The total length of the bore (from the labium edge to the open end) is 706.8 mm, and the inside diameter of the transparent tube is $d_0 = 26$ mm. The mouth pressure P_m for a typical recorder varies from 10 Pa to 3 kPa.³¹ Our setup uses a bass recorder mouthpiece; thus, we selected a mouth pressure, $P_m = 100$ Pa, which without a tone hole produces a fundamental at 220–221 Hz (depending on the atmospheric conditions).

2. Pressure measurements

Simultaneously with the PIV measurements, the radiated sound outside the instrument was recorded using an electret condenser microphone (Primo EMU-4535). The microphone was positioned off-axis near the mouthpiece, aimed at the labium. The internal pressure within the bore was captured using five pressure transducers (Endevco 8507C-2; Endevco, Halifax, NC) installed at the following locations along the bore: [298.1, 413.5, 522.4, 614.4, 681.0] mm. The advantage of these pressure transducers lies in their capability to provide accurate measurements of both dynamic and static pressure levels even at the high pressures typical inside wind instruments.¹ The input pressure was measured inside the particle mixing box, with an additional transducer, under the assumption that the pressure within the box is homogeneous. This assumption holds due to the large volume of the box, which minimises wall effects and pressure fluctuations. To ensure a consistent 100 Pa input condition, the mouth pressure measurement was live-monitored and adjusted during data acquisition. Prior to PIV measurements, an inlet pressure repeatability test was conducted on a tube without a tone hole. The pressure was turned on and stabilised at a selected level and then turned off. This process was repeated 12 times for five different pressure levels, starting at 85 Pa and increasing in 5 Pa increments. Table I shows pressure level, maximum deviation over the repetitions, and frequency. Small deviations of

the frequency when changing the inlet pressure show that we are in a stable region of operation, and a small (~ 2 %) maximum deviation of the inlet pressure allows repeatable measurements.

B. Optical system

Figure 2 also contains the diagram for the optical system that, together with particles from the aeroacoustic system, enables PIV measurements. The optics system includes a high-speed laser (Litron LD60-532, 527 nm wavelength, double cavity, 25 mJ per pulse; Litron Lasers, Warwickshire, UK), an expansion lens, a mirror, and a high-speed camera (Phantom VEO 340 L; Vision Research, Inc., Wayne, NJ). The laser beam is expanded into a two-dimensional (2D) sheet and directed into the test section, as shown in Fig. 2, illuminating tracing particles within the FoV.

The FoV of the camera spans the full height of the tube interior. The horizontal dimension of the FoV was chosen as a compromise between it being small enough to ensure a sufficient sampling rate, yet large enough to minimise the number of windows required to cover the entire length of the transparent tube. Thus, the size of a single FoV was selected to be around 87×26 mm with a camera sampling rate of 3.5 kHz. The magnification of the lens and the position of the camera result in a digital imaging resolution of 19.13 pixels/mm.

The laser is set up to avoid damaging the experimental setup. By illuminating the particles from below, the full setup achieves a shadow-free 1 mm thick laser sheet at the FoV, minimises reflections, and reduces the risk of experimental setup damage. To obtain PIV measurements along the whole length of the transparent tube, the high-speed camera and the laser sheet are held static in their positions,

TABLE I. Results of the repeatability test of the inlet pressure P_m inside particle mixing box. The table shows mean pressure (mean P_m), maximum deviation (ΔP_m), and the fundamental frequency (f_0) of the radiated sound. Each target pressure was tested 12 times and averaged.

Target P_m (Pa)	Mean P_m (Pa)	ΔP_m (Pa)	f_0 (Hz)
85	85.48	± 1.61	220.07
90	90.8	± 1.92	220.48
95	95.63	± 1.46	221.08
100	100.42	± 1.62	221.38
105	105.31	± 2.16	221.68

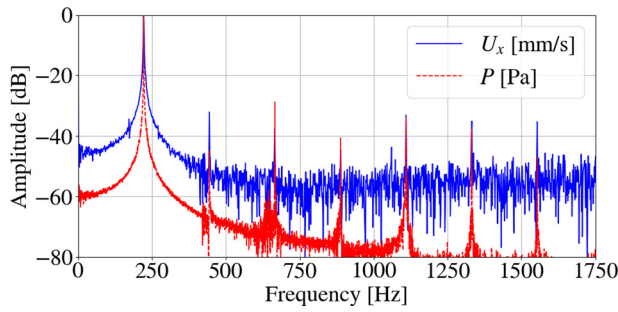


FIG. 3. Power spectrum of flow velocity U_x and pressure P at the location of the fourth microphone (614.4 mm from the labium), normalised to a maximum of 0 dB.

while the recorder with microphones and the particle mixing box are transcribed along the x axis with the help of a slider.

C. PIV reliability test

The reliability of PIV measurements for measuring flow in wind instruments was verified as follows. The frequency power spectrum of the flow velocity measured via PIV was compared to that of the acoustic pressure obtained by a pressure transducer. Figure 3 shows the spectrum of the horizontal flow velocity U_x and of the interior pressure P at the location of the fourth microphone. The peak locations in the frequency axis overlap in both measurements. This validates that PIV is capable of capturing harmonics of the flow spectrum. This approach was previously shown to be valid for a sampling rate of 15.6 kHz with a much smaller FoV.³²

D. Tone hole location and geometry

To analyse the effect of tone hole geometry on the flow velocity inside the recorder, the flow was measured for tone holes with a variable acoustic mass (varying diameter and height). These changes were achieved by several interchangeable tone hole elements (see Fig. 4). These tone hole elements are made using photopolymer resin, and they are the sole opaque components in the setup that are in the path of the laser sheet. Photopolymer is not susceptible to heat, making it an appropriate choice for laser applications.³³

The reference point $x = 0$ mm for our experiments was chosen at the sharp edge of the labium, with the open end at $x = 706.8$ mm (reference frame shown in Fig. 2). We chose to place the centre of the tone hole at the acoustic centre of the tube. This is the point where the pressure amplitude is at its maximum and the flow velocity amplitude is at its minimum (see Fig. 1). To identify this point, the flow fluctuation measured via PIV was used, since it had a higher spatial resolution in comparison to the measured pressure inside the instrument. The resulting acoustic centre, where the tone hole was eventually placed, was identified at $x = 333$ mm. The tone hole was placed at the acoustic centre, independent of its location in any particular recorder design, allowing us

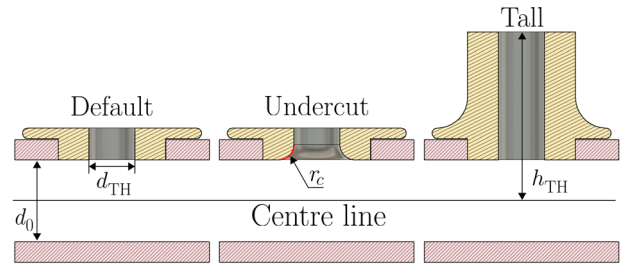


FIG. 4. Cross-section of the tone holes with geometrical parameters, marking tone hole diameter d_{TH} , undercut curvature radius r_c (highlighted in red), and the tone hole height h_{TH} .

to focus solely on the fundamental acoustic effects of tone hole geometry on the flow.

Given the time-intensive nature of data acquisition and processing, as well as the substantial volume of data produced in each experiment, we tested three different tone hole diameters $d_{TH} = 9, 12$, and 15 mm, as well as variations of undercut radius r_c and chimney height h_{TH} for the smallest and the largest d_{TH} . Figure 4 illustrates the geometric alterations on the tone hole geometry. The experimental matrix consists of eight cases, as seen in Table II. Additionally, we established a base case without a tone hole (case 00), using a plug, which is flush with the tube's inner wall. The default tone hole elements have a height h_{TH} of 19 mm (measured from the centre line), which is the minimum required height for the structural integrity of the 3D printed tone hole element. Undercut tone holes have the same height as the default but feature a rounded undercut with a 3 mm radius (labelled with a capital "R" onwards). The h_{TH} of the tall tone hole cases were twice as high as the default (labelled with a capital "T" onwards).

III. DATA PROCESSING

A. Pre-processing

Flow measurements were conducted at the bore mid-span plane, utilizing the planar PIV setup with the camera and light source described in Sec. II A. For each configuration listed in Table II, a set of 5000 frames was recorded at an acquisition frequency of 3.5 kHz using LaVision DaVis 10.2.1 software. The FoV measured 87×26 mm²,

TABLE II. Experimental matrix indicating diameter d_{TH} , undercut radius r_c , height h_{TH} , and playing frequency. The case 00 refers to a plug (case without a tone hole). R stands for rounded tone hole undercut and T stands for tall tone hole. Geometrical parameters are marked in Fig. 4.

Case	d_{TH} (mm)	r_c (mm)	h_{TH} (mm)	f_0 (Hz)
00	0	—	—	221
09	9	0	19	299
09R	9	3	19	305
09T	9	0	38	262
12	12	0	19	319
15	15	0	19	336
15R	15	3	19	340
15T	15	0	38	299

discretized into 1664×501 pixels, resulting in a magnification factor of 0.38.

The raw images were pre-processed by: 1. cropping, 2. mirroring, 3. sliding minimum subtraction with a kernel of six time-steps, and 4. spatial normalization using a local average over 50×50 pixels. The FoV was cropped, keeping only the data of the flow field. Data are mirrored to have flow moving from left to right. Sliding minimum subtraction was applied to remove the static background such as micro scratches, reflections, and microphones that might appear in the view. Sliding minimum subtraction sets the pixels that did not change over a set number of frames to zero, allowing the particle movement to be captured, while the background that might interfere with the velocity vector calculation is cleaned up.²² This procedure effectively reduced wall reflections and background noise.³⁴ Spatial intensity normalisation with local average corrects for light sheet non-uniformities. This step is useful when the laser sheet has varying brightness over the FoV, which can happen when the sheet comes at an angle to the FoV.²² Velocity fields were obtained using the PaIRS UniNa software.³⁵ A final interrogation window of 18×18 pixels, corresponding to a square window with a side length of 0.941 mm and an overlap of 50%, yielded a vector grid dimension of 183×53 with a vector pitch of 0.29 mm. This window size ensured the presence of six to eight seeding particles per window. For time-frequency analysis, a fourth-order high-pass Butterworth filter with a cut-off frequency of 100 Hz was applied to reduce low-frequency noise from the limited acquisition time (1.43 s). The high pass filter also removes any velocity offset, due to mean flow, aligning the fluctuations around 0 mm/s. Filtered data are labelled with an additional “F” in the case name (e.g., 00F) in the results presented in subsequent sections.

Pressure data were recorded using pressure transducers and amplified through two Endevco model 136 amplifiers (Endevco, Halifax, NC). The signal was then digitized and transferred to a computer via a National Instruments I/O board. A custom LabView program saved the data as 8-channel wave files at a sampling rate of 50 kHz.

B. Stitching

The full length of the transparent tube cannot fit in a single FoV. Overlapping windows and stitching them together allows us to investigate the full length of the tube. For stitching to work, precise coordinates of each window are required. This is achieved by using a calibration sheet, which has a millimetre grid with labels at every 50 mm. The full, stitched FoV is approximately $516 \times 26 \text{ mm}^2$, depending on the details of the acquisition, yielding a digital imaging resolution of 17.82 pixels/mm. A single window had a FoV of $87 \times 26 \text{ mm}^2$. Allowing for a 10 mm overlap between the FoVs, we can obtain the full-length FoV with seven measurements.

C. Phase alignment

Time-resolved flow velocity data are available over the entire centre plane of the transparent tube. The flow velocity can be extracted at any time instant. Each of the seven windows for every case was measured at a different time, where the acquisition of a single measurement took approximately 1.43 s. For each experimental case, 314–485 periods were captured, depending on the fundamental frequency due to different tone hole types. Using this data, instants are aligned in a two-stage process to simulate a single snapshot of flow velocity as if the entire length FoV was captured simultaneously. The first stage of the alignment process involved identifying a common point shared by the left and right acquisition windows, which were overlapping as mentioned above. The second stage required matching the phase of a time-snapshot of the above points. Before matching the phase, the data were first high-pass filtered as described in Sec. III A and then low-pass filtered with a fourth-order Butterworth filter with a 500 Hz cut-off. These processed data are referred to as band-passed in the range from 100–500 Hz.

IV. RESULTS

A. Flow velocity

The first stage of analysis involves looking at the flow velocity at two points in space over time. Figure 5 plots horizontal flow velocity U_x right before the tone hole (a) and at the end of the tube (b) for two different cases. The flow velocity for a case without a tone hole (00) is drawn with a black line, while the case with a 9 mm default tone hole (09) is drawn with a light blue line. In the former case, U_x has lower amplitude oscillations near the acoustic centre and larger amplitude oscillations at the open end of the tube. In the case of a 9 mm default tone hole, U_x fluctuations were, in comparison, higher at the tone hole position and lower at the open end of the tube. Although the mean values do not differ significantly between the two cases, the main effect of the tone hole on the velocity field is related to the fluctuating component magnitude. Squares and dots mark the time

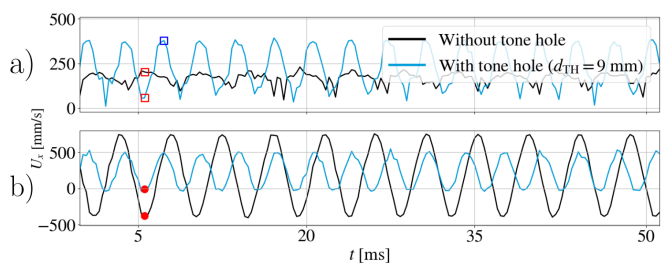


FIG. 5. The horizontal velocity component U_x over time is shown for two cases: one without a tone hole and one with a default tone hole of diameter $d_{TH} = 9$ mm. Velocity over time is presented at two locations: (a) $x = 313$ mm, $y = 0$ mm (tone hole position); and (b) $x = 692$ mm, $y = 0$ mm (open end). Red squares in (a) and red circles in (b) indicate the temporal instants of the velocity corresponding to the same markers in Fig. 6. Red and blue squares on the data with a tone hole indicate instants in Fig. 7.

instant of flow velocity, which was used in the generation of Fig. 6.

A stitched velocity profile was obtained using the methodology described in Sec. III C for a time instant where the flow at the open end is at its minimum. Figure 6 shows the corresponding horizontal flow velocity U_x . Squares and dots, in this figure, mark the x location from which Figs. 5(a) and 5(b) are generated, respectively. Additionally, the theoretical flow velocity for the case without a tone hole was obtained by plotting a fitting sum of sinusoidal waves with the measured magnitudes of the five first harmonics acquired from the horizontal flow velocity component U_x at a single location (square in Fig. 6). This theoretical line overlaps with the measurement data, which validates that PIV is capable of resolving the expected standing flow velocity wave.

The flow velocity at a single time instant with a tone hole shows a different velocity profile than in the case without a tone hole. Without a tone hole, only a single phase change is observed at the geometrical centre of the bore.

A phase change in the flow for the case of the 9 mm default tone hole is observed in Fig. 6 at approximately $x = 207$ mm, where the velocity smoothly continues to decrease until right before the tone hole at $x = 333$ mm. At the tone hole, a sharp phase change occurs, after which the flow velocity is at its highest and starts to decrease again. When comparing the amplitude before and after this phase change, the amplitude is higher before the tone hole. Last, a smooth phase change occurs at around $x = 429$ mm.

A higher noise level was observed in the last measurement window, located at the open end of the tube. This was likely due to slightly noisier measurements, potentially caused by the change in particle concentration or different laser intensity. However, this noise does not hinder our ability to observe trends and analyse the data.

Focusing on a 2D view of the flow at the tone hole region, in Fig. 7 we show two time instants of flow with streamlines overlaid on the resultant velocity magnitude $|U|$. The instants are taken at the corresponding colour of squares in Fig. 5(a). The resultant velocity is calculated as a Euclidean sum of the horizontal and vertical velocity

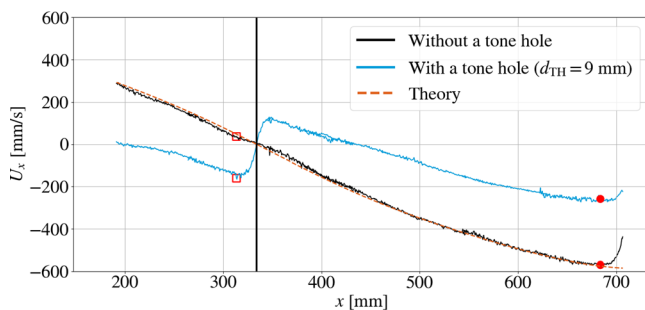


FIG. 6. Matched instants in time of band-passed horizontal flow velocity U_x for no tone hole and for a 9 mm default tone hole at $t = 5.7$ ms. The velocity is displayed at $y = 0$ mm for all x . A black vertical line marks the centre of the tone hole. The theoretical flow velocity for the case without a tone hole is also shown. The red squares and dots correspond to the time instants indicated in Fig. 5(a) and 5(b).

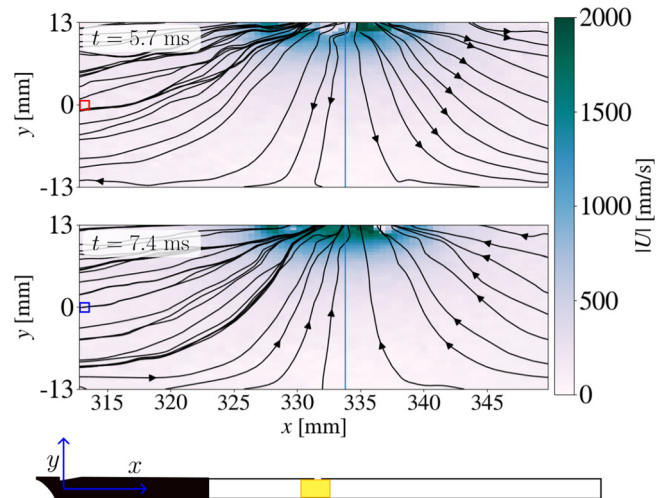


FIG. 7. Contour and streamlines of the flow velocity magnitude around the tone hole for the 09F case. Time instants shown are roughly half a period apart, with the top representing flow during entrainment, the bottom during outflow. Red and blue squares show location of velocity data, which correspond to time instants in Fig. 5(a). A blue vertical line marks the centre location of the tone hole. The yellow rectangle in the diagram at the bottom shows the size and location of the FoV.

magnitudes. The time instants show opposing phases, which is visible in the direction of the streamlines. It can be observed that the streamlines bunch up at the upstream edge of the tone hole during both phases. Each of the time instants also displays an opposing state of the flow at the tone hole. At the time instant of 5.7 ms (top), streamlines under the tone hole point away from the tone hole, indicating the state of entrainment and at the time instant of 7.4 ms (bottom), streamlines point towards the tone hole, indicating outflow.

These observations represent a single moment in time, with instants selected to complete the full FoV (Fig. 6) or show a selected region (Fig. 7). Temporal analysis in Fig. 5 shows velocity at a single point of our FoV for cases with and without a tone hole. To further study the influence of a tone hole, the amplitude of the fluctuating flow is analysed. This is achieved by calculating the root mean square (RMS) of the flow, as outlined in Sec. IV B.

B. Amplitude of the fluctuating flow

The amplitude of the fluctuating flow is analysed through RMS values. Flow velocity RMS values have been extracted for every point in the FoV (see Fig. 8). For the analysis, besides the high pass filtering mentioned previously, no further fitting or altering of the data is performed. The measurements were taken at steady state, with care to keep input conditions constant. Figure 8 shows the horizontal U_{xRMS} , vertical U_{yRMS} , and resultant $|U|_{RMS}$ flow velocity RMS over the FoV.

From Fig. 8, it can be observed that the horizontal velocity fluctuations U_{xRMS} are dominant inside the tube, with an exception of the localised velocity fluctuations near the tone hole. At the tone hole, a higher velocity fluctuation

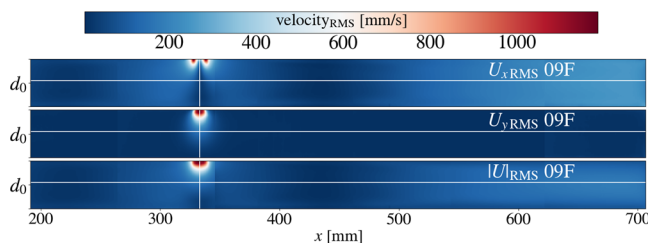


FIG. 8. 2D RMS of flow velocity magnitude $|U|_{\text{RMS}}$ (bottom), horizontal flow component $U_{x\text{RMS}}$ (top), and vertical flow component $U_{y\text{RMS}}$ (middle) inside the recorder with a 9 mm default tone hole. d_0 is the diameter of the tube, marking that the FoV vertically is wall-to-wall. The horizontal axis spans the whole length of the transparent tube.

amplitude is observed in both horizontal and vertical velocity components, which is visible by higher RMS values. These high RMS values are generated by the flow reversal at the tone hole, alternating between outflow and entrainment. The horizontal velocity RMS maximum is observed at the edges of the tone hole, while the vertical velocity RMS maximum is observed at the centre of the tone hole. Similar patterns can be observed in pulsed synthetic jets.³⁶

Apart from the high fluctuation of velocity near the tone hole, the vertical velocity component cannot provide further insight into the standing wave behaviour outside the localised tone hole influence region. This is due to its low magnitude, which cannot be easily resolved via PIV measurements. In contrast, the horizontal velocity is sufficiently high to allow analysis of standing wave behaviours. Therefore, we chose to focus solely on the horizontal velocity component for subsequent analyses of standing waves along the tube. Some discontinuities at the connections of the acquisition windows may be observed due to the separate measurements that were carried out to obtain the full FoV.

1. Horizontal flow velocity fluctuation

We extracted velocity RMS values along the tube and normalised them to the mouth pressure level, as shown in Figs. 9 and 10. The values are obtained at $y = 1$ mm, which is marked with a white horizontal line in Fig. 8. Figure 9 displays the velocity flow with the default tone hole of varying diameters, and Fig. 10 displays flow velocity RMS of varying tone hole shapes for two diameters.

Looking at these plots (Figs. 9 and 10), some trends can be observed when focusing on the local minimum and maximum RMS values and their locations.

In both figures, it can be seen that the maximum velocity RMS before the tone hole is higher than the maximum right after the tone hole due to sound radiation at the tone hole. The ratio of $U_{x\text{RMS}}$ across the tone hole, defined as the maximum $U_{x\text{RMS}}$ upstream over the maximum $U_{x\text{RMS}}$ downstream of the tone hole, is inversely proportional to the tone hole diameter.

The flow velocity with tall tone holes (see Fig. 10) exhibits significantly higher $U_{x\text{RMS}}$ values at the end of the tube compared to the other cases (default or undercut).

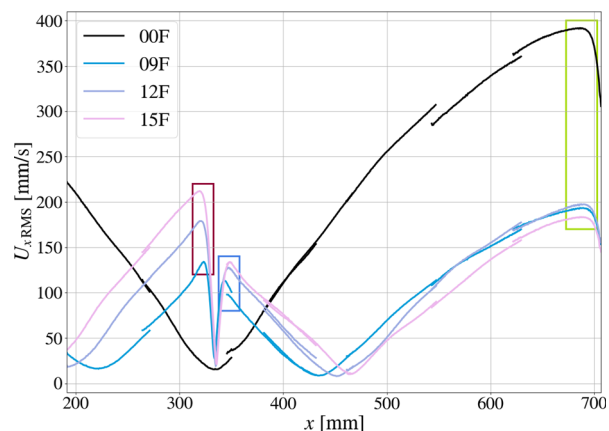


FIG. 9. Tone hole diameter influence on the flow velocity RMS. Four experimental cases are presented, one without a tone hole and three with default shape of a tone hole with different diameters. Coloured rectangles mark areas from which the values for Fig. 11 were extracted. The horizontal axis spans the whole length of the transparent tube.

Looking at the $U_{x\text{RMS}}$ in the case of undercut tone holes, the RMS is higher at the end of the tube for $d_{\text{TH}} = 9$ mm compared to the corresponding diameter default tone hole, while the default and undercut cases with $d_{\text{TH}} = 15$ mm match in amplitude.

The increase in RMS peak values at the tone hole is due to flow reversal at the tone hole, where larger hole sizes result in greater mass flow exchange with the outer environment during the pulsations.

The undercut tone holes (09R and 15R) have similar RMS values and minima location to the default tone holes (09 and 15). However, for the taller tone holes (09T and 15T), the RMS peak values are lower and the minima location downstream of the tone hole is closer to the tone hole in comparison to the other shapes. These differences can be attributed to the increased height of the tone hole, which creates higher pressure resistance, reducing the mass flow exchange during the pulsation. Thus, the highest $U_{x\text{RMS}}$

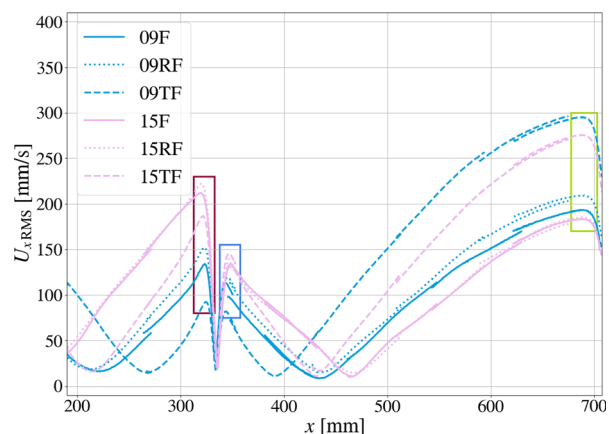


FIG. 10. Tone hole shape influence on the flow velocity RMS. Six experimental cases are presented, tall, default, and undercut shapes with 9 and 15 mm diameters. Coloured rectangles mark areas from which the values for Fig. 11 were extracted. The horizontal axis spans the whole length of the transparent tube.

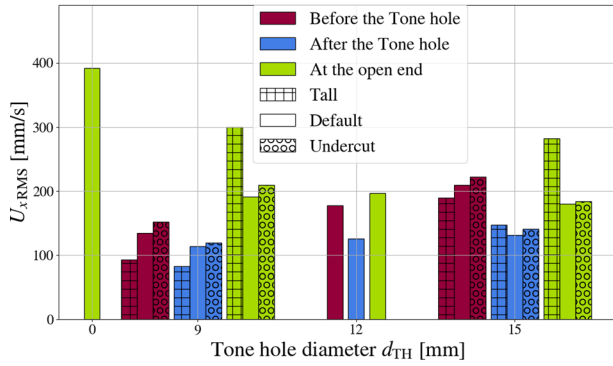


FIG. 11. Extracted maximum RMS values from Figs. 9 and 10, taken from areas just before and after the tone hole, as well as at the open end of the tube. These areas are marked in Figs. 9 and 10 with corresponding colour rectangles. The shape of the tone hole is indicated by the pattern, while the colour represents the respective area. Different tone hole diameters are grouped along the x axis.

peaks appear at the open end with tall tone holes, approaching the flow condition without a tone hole.

The discussed flow RMS local peak values at different areas of interest are extracted and summarised in Fig. 11. The plot displays RMS values from Figs. 9 and 10 at the maximum locations before and after the tone hole, as well as at the end of the tube. The colour in the bar plot indicates the location where the RMS value was calculated, while the pattern indicates the shape of the tone hole. There are three groups of bars for every diameter of the tone hole. The case of no tone hole is also shown on the left side of the plot.

The minima after the tone hole, due to wave propagation to the end of the tube, are located further downstream for increasing tone hole diameter (as seen in Figs. 9 and 10). These flow nodes correspond to pressure antinodes inside the tube, and their location depends on the playing frequency.

Figure 12 presents fundamental frequency f_0 versus the location of this fluctuating flow velocity node x_n . We observe that there is a roughly linear relationship between the fundamental frequency and the node location. It hints

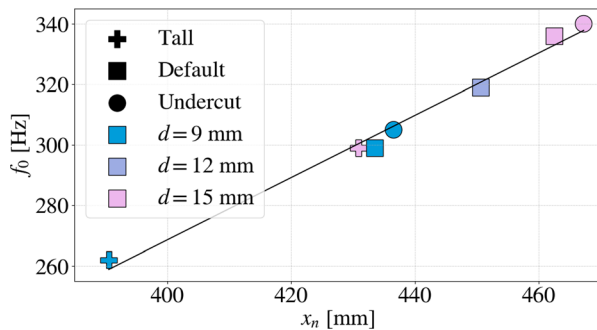


FIG. 12. Fundamental frequency f_0 versus the velocity node location x_n after the tone hole for all the tone hole cases. Marker shapes refer to different shapes of the tone hole, while the colour indicates the diameter. The black line is a fit to the data.

that f_0 or node position can be accurately inferred from one to another with minimal error.

2. Flow velocity fluctuation fields

Figure 13 shows the horizontal velocity fluctuation amplitudes for all the experimental cases over the FoV 200 mm around the tone hole. Comparing velocity fluctuation fields of all the different cases, we can observe that the location of the high RMS follows the diameter change. This high RMS is localised strictly at the edges of the tone holes, which define the shear layer of the pulsating jet generated at the tone hole.

Another related local effect is the local minimum, which we can observe in Fig. 13 in the horizontal velocity RMS right under the tone hole, which extends through the whole height of the tube. These minima seem to grow wider away from the tone hole (downwards) and correspond to the location where $U_{y,RMS}$ is high (see Fig. 8), suggesting a redistribution of energy among the two velocity components ($U_{x,RMS}$ and $U_{y,RMS}$) due to the pulsating flow at the tone hole. Looking further at Fig. 13, a slight downstream shift is also present, with the local minimum area being tilted towards the open end. It is possible that this happens due to

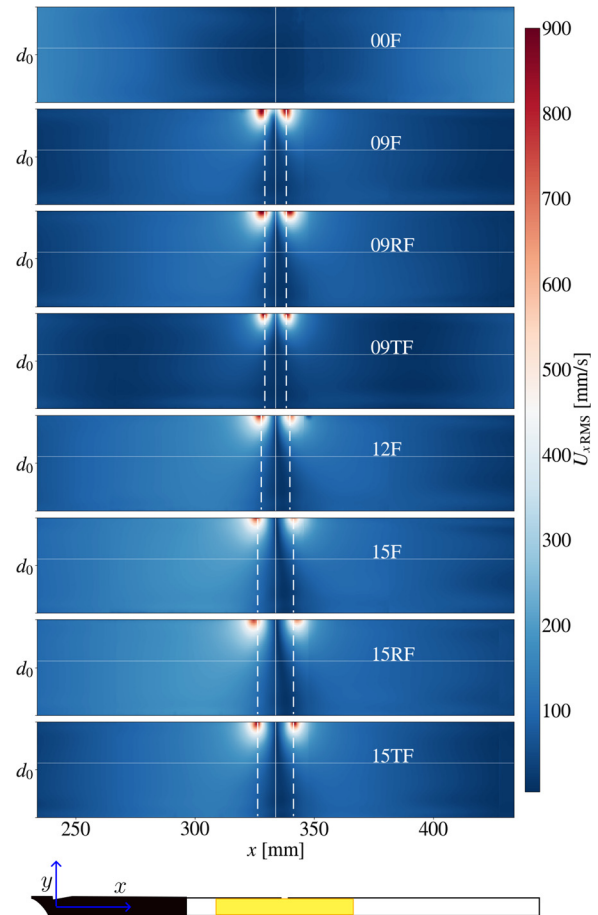


FIG. 13. 2D horizontal velocity RMS $U_{x,RMS}$. A white horizontal line marks the y location from which values for one-dimensional plots are extracted in Figs. 9 and 10. A vertical white line marks the centre of the tone hole, and dashed lines mark the contours of the chimney width. The yellow rectangle in the diagram at the bottom shows the size and location of the FoV.

the mean flow that carries fluctuations along the tube as they spread away from the tone hole.

Comparing the magnitudes of RMS in Fig. 13 for 9 mm diameter default and tall tone holes' (09F and 09TF) velocity RMS, one can notice that regions of high RMS values are similar in magnitude but larger in area in the default case. For the 15 mm diameter tall tone hole (15TF), the peak values are higher compared to the same diameter default case (15F). It is also possible to observe that, away from the tone hole, RMS values are overall higher for the default case. Looking at the undercut cases (09RF and 15RF), velocity RMS is very similar to the default cases (09F and 15F), respectively. It is a common practice by instrument makers to undercut some tone holes specifically in order to adjust the pitch and improve the quality of the tone hole. Therefore, in Sec. IV C, we are further analysing the effect of undercutting on the flow in the frequency domain.

C. Frequency domain analysis

Frequency domain analysis is carried out to investigate the effect of tone hole undercutting on the flow velocity spectral characteristics. To perform this investigation over the full FoV, a single value needs to be obtained at every measurement location. The recorder spectrum is dominated by the fundamental.⁵ Thus, we have chosen to define T_1 as the magnitude m_0 of the fundamental frequency over the magnitudes m_n of all the evaluated harmonics:

$$T_1 = \frac{m_0}{\sum_{n=0}^{N-1} m_n}. \quad (1)$$

The five lower harmonics can be clearly identified in the measured horizontal flow. Therefore, we choose $N = 5$ in Eq. (1).

The first step is to automatically identify the fundamental frequency for each experimental case at every measured point. Fundamental frequencies are identified by locating the highest frequency peak within the 200–400 Hz range. This range was set to ensure the identification of all potential fundamental frequencies without involving higher harmonics. Once the fundamental frequency is determined, subsequent harmonics are calculated by multiplying the frequency by $(n + 1 \pm \epsilon)$. We set $\epsilon = 0.01$ to allow for slight variations of the peak location with the highest magnitude. The small ϵ is necessary due to possible inaccuracies in the detection algorithm. The strong harmonic characteristics of the signal enable reliable automatic detection of the harmonic peaks.

The value of T_1 gives a numerical evaluation of how high the magnitude of the fundamental is, relative to all the harmonics present. Figure 14 shows spectra at two different locations from the same measurement, one at a location where T_1 is low and one where it is high. As we can observe, when T_1 is low, the fundamental is weaker, while some of

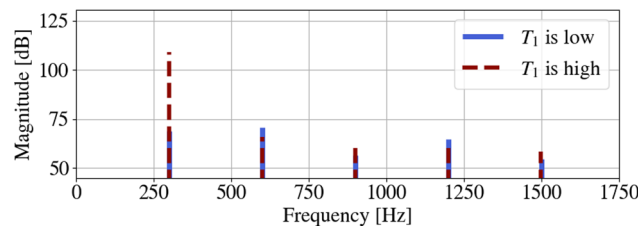


FIG. 14. Frequency peaks at the high and low fundamental frequency contribution locations, marked with white dots in Fig. 15 for the case of a 9 mm default tone hole.

the other harmonics are stronger than in the case where T_1 is high.

Figure 15 shows T_1 over the full FoV for default and undercut tone holes. We can observe that the undercutting did have a significant influence on the flow in the 9 mm tone hole case. For the default case (no undercutting), the plot displays larger areas where f_0 is not strongly dominant and the areas where f_0 is dominant are smaller and not so intense. At the very edges of the tone hole, we can observe a reduced T_1 when compared to the undercut case. This might be due to less stable flow, caused by the sharp edge of the tone hole, because unstable flow might have more complex spectra. This remains to be studied more in depth in future experiments.

For the 15 mm diameter tone holes, undercutting had smaller influence on the flow spectra purity. Although the previous observation of larger areas of lower T_1 in the case of no undercutting remain true, local tone hole influence on the spectra seems negligible.

The lowest T_1 regions in all the cases correspond to the low RMS regions shown in Fig. 10. This aligns to the previous suggestion that the minimum after the tone hole is a node of the standing wave formed in the tube.

Figure 16 presents the magnitudes of the fundamental and the first two harmonics of the horizontal flow for the cases of default and undercut tone holes over the full length FoV. The magnitude of the fundamental frequency is about a factor of 10 larger than that of higher harmonics. Hence, the magnitude plot of the fundamental in Fig. 16 is similar to the T_1 plot in Fig. 15. Higher harmonics reveal higher magnitude localised at the edges of the tone hole in non-undercut cases. The difference in the higher harmonics magnitude in this region is more noticeable in the case of the

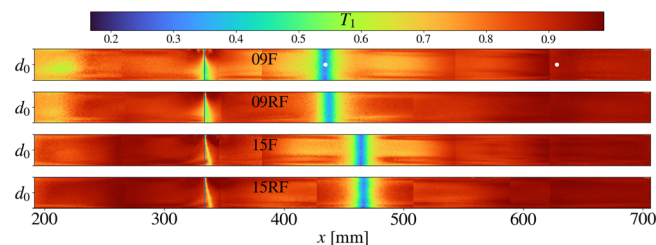


FIG. 15. T_1 Comparison between default and undercut tone holes for diameters of 9 mm and 15 mm. White dots mark locations from which the spectra were computed in Fig. 14. y is wall-to-wall, x is the whole length of the transparent tube.

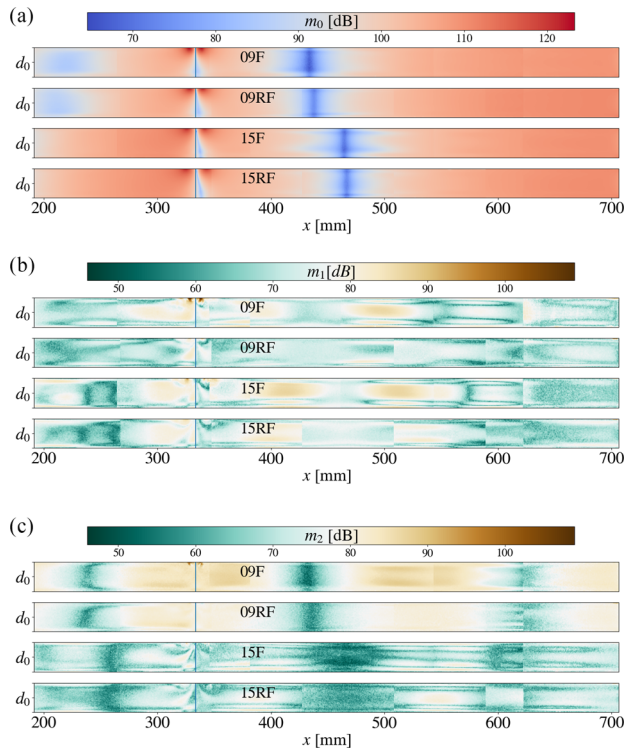


FIG. 16. Magnitudes of the fundamental, first, and second harmonics (m_0 , m_1 , and m_2 , respectively), extracted from the horizontal velocity component. y is wall-to-wall, x is the whole length of the transparent tube.

9 mm tone hole, but it is still visible for the 15 mm tone hole. Interestingly, vertical banding is observed around $x = 600$ mm. This banding of alternating low and medium magnitude might indicate the presence of vertical modes inside the recorder bore.⁵

Figure 17 presents the magnitudes of the fundamental and the first two harmonics of the vertical flow for the cases of default and undercut tone holes. The vertical velocity component exhibited a low magnitude in all of the regions except for the localised region beneath the tone hole with respect to the horizontal velocity component.

In all cases, the fundamental frequency in Fig. 17 has a significantly higher magnitude compared to the first and second harmonics. When comparing these higher harmonics

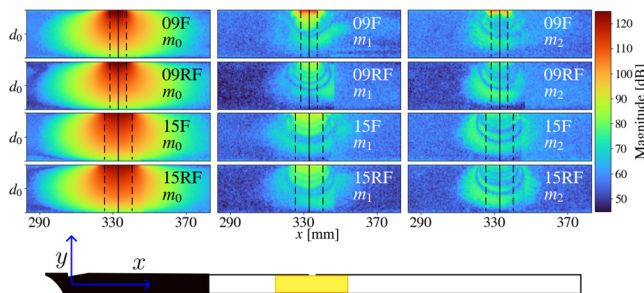


FIG. 17. Magnitudes of the fundamental, first, and second harmonics, calculated from vertical flow velocity. FoV is 120 mm around the tone hole centre. y is wall-to-wall. Vertical lines mark the tone hole centre. The yellow rectangle in the diagram at the bottom shows the size and location of the FoV.

between the undercut and default cases, it is evident that for the 9 mm tone hole, the flow with default case exhibits stronger higher harmonics than the undercut one. For the 15 mm tone hole, the default case flow still has stronger higher harmonics, but the difference is less pronounced than in the smaller diameter case. Similar to the horizontal velocity higher harmonics analysis, the vertical velocity harmonics display alternating regions of high and low magnitude at the tone hole location. These regions might indicate the presence of higher modes, which are circular rather than vertical, in comparison to the horizontal velocity component.

D. Vorticity

Building on the observations described in Sec. IVC, our next step is to assess whether undercutting affects vorticity and to explore any correlation between vorticity and spectral content. Vortex formation and turbulence in the presence of a T-junction was discussed by Hofmans in 1998.³⁷ Our PIV measurements reveal formation of vortices in the tone hole region. To quantify the vorticity, curl values were extracted at each point in the vector field. Curl is calculated as a difference between a velocity gradient in x and y axes, and it represents the tendency of a flow to rotate around a given point.³⁸ The magnitude of the vorticity is related to the strength of the velocity gradient, and the sign is related to the direction of the gradient.

Positive values correspond to counterclockwise rotation, whereas negative values correspond to clockwise rotation. Figure 18 highlights how undercutting significantly suppresses rotational flow structures compared to sharp-edged tone holes. FoV is 30×12.5 mm², centred around the tone hole, including just the region where curl values were significant.

The 9 mm diameter tone hole created stronger shear in the flow, mainly due to the generation of vortices and the separation region at the edges of the tone hole.^{8,9,28} Shear under the default tone hole is indicated by the high curl values. In contrast, the 15 mm diameter tone hole had a smaller

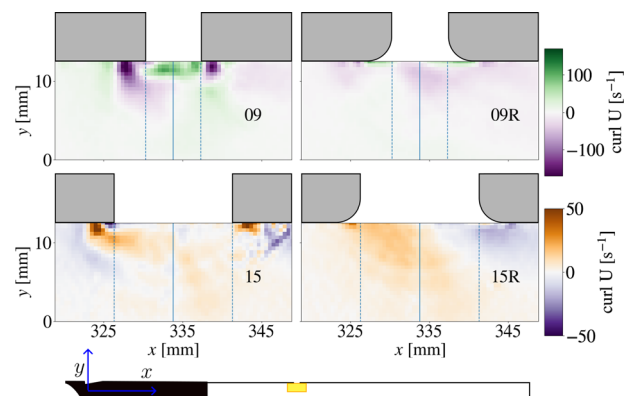


FIG. 18. Time averaged 2D curl. Vertical solid lines mark the location of the tone holes, while dashed lines mark the edges of the tone holes. The yellow rectangle in the diagram at the bottom shows the size and location of the FoV.

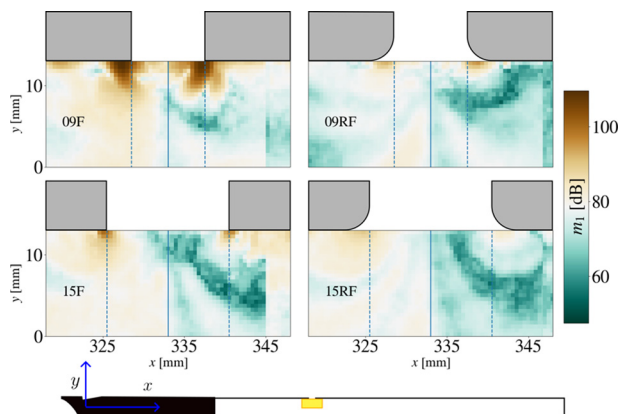


FIG. 19. Magnitude of the first harmonics m_1 , extracted from the horizontal velocity component. Dashed vertical lines outline the chimney boundaries, while a solid line marks the centre of the tone hole. The yellow rectangle in the diagram at the bottom shows the size and location of the FoV.

influence, with curl values more than three times lower. In the following videos (Mm. 1–Mm. 4), particle motion is shown for tone holes with differing geometries.

- Mm. 1. An animation of the pulsating mass flow exchange at the 9 mm default tone hole.
- Mm. 2. An animation of the pulsating mass flow exchange at the 9 mm undercut tone hole.
- Mm. 3. An animation of the pulsating mass flow exchange at the 15 mm default tone hole.
- Mm. 4. An animation of the pulsating mass flow exchange at the 15 mm undercut tone hole.

The effect of vorticity on the acoustics of a wind instrument is still to be further explored. These results illustrate the possibility to analyse vorticity using PIV measurements, showing clear differences between the flow inside a recorder with a tone hole that is not undercut and a tone hole that is.

In general, we observed that undercutting is less significant for the higher diameter tone hole as seen by the magnitude of the time averaged curl in Fig. 18. Further work is required to quantify the magnitude of this effect.

Additionally, we have found some similarities between the curl values and the magnitude of higher harmonics, specifically the harmonic above the fundamental, m_1 . Figure 19 displays a cropped version of m_1 from Fig. 16 focusing on a FoV identical to the one displaying curl values in Fig. 18. In Fig. 19, we can observe high magnitude regions similar to the high curl regions in Fig. 18. To identify if the vortices are oscillating at higher frequencies, causing this local increase in m_1 , more experiments are needed.

V. CONCLUSIONS

In this study, we have shown that PIV is a valid and effective method for investigating the acoustics of wind instruments, particularly with respect to understanding the

flow behaviour inside wind instruments. Our findings demonstrate that steady-state experiments can be reliably conducted and that stitching together the FoVs is a worthwhile approach, providing a measurement over the full instrument length. The time- and frequency-domain analyses that were performed, as well as the vorticity analysis, reveal that time resolved PIV measurement data are rich with extractable information. These measurements reveal fundamental principles of tone hole acoustics and show that methods applied here can be used in future research, provided that an appropriate temporal resolution is chosen. This includes investigating more musically relevant scenarios such as tone holes closer to the open end and cross-fingerings.

We have found that in the presence of a single tone hole at the acoustic centre of a simplified wind-instrument-like apparatus, RMS plots reveal significant flow velocity fluctuations at audible frequencies after the location of the tone hole. The tallest tone holes produced the strongest fluctuations. However, all configurations showed substantial flow oscillation. In the case of the largest diameter tone hole, the flow velocity RMS after the tone hole was the smallest.

Additionally, analyses of higher harmonic spatial patterns appear to show higher-order, non-longitudinal mode excitation. The horizontal velocity contains vertical modes at various locations along the bore. When considering the higher harmonics of the vertical velocity, circular modes are observed in the tone hole region. Furthermore, significant vortex formation at the edge of the tone hole is evident when the tone hole is not undercut.

This study demonstrates the capabilities of PIV measurements to examine flow behaviour, which is otherwise difficult to observe. The measurements presented here, while performed on an artificial setup, could also be adapted to analyse more realistic, musical scenarios. In addition to offering new insights regarding the flow inside an acoustic tube, they could also aid during the manufacturing process of wind instruments.

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AUTHOR DECLARATIONS

T.L. was in charge of conceptualization, data curation, formal analysis, investigation, methodology, visualisation, and writing the original draft. G.C.A.C. helped out during the steps of the experimental campaign and preparation for it, as well as instructing T.L. about how to use the resources,

including the software and hardware of PIV. G.C.A.C. also took part in writing Sec. III A as well as reviewing the final submission. A.S. provided the team with resources critical for the experimental campaign. V.C. took on a supervisory role, assisting in the conceptualisation and formal analysis, as well as helping during the draft writing and providing review and editing of the final submission. V.C. acquired the financial support for the project leading to this publication.

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.13919050>, Ref. 39.

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