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The air jet development in organ pipe tone attack caused by voicing adjustments

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Abstract

The contribution presents the results of a research on differences in development of air jet flux in labium of an organ pipe caused by different voicing adjustments. Air jets of tone starting transients were observed by laser PIV on a single rectangular open pipe with transparent walls in varied combinations of the upper lip height and the flue slit area. The visualizations of the air jet velocity vectors are presented in slides issued gradually in time and they are linked to the sound pressure and to the descriptions of sound quality obtained in listening test.

Keywords: Organ pipe, Air jet, Voicing

1 INTRODUCTION

The development of sound onset of an organ pipe is of importance to its sound character and has been subject of extensive interest both in research as well as in the practice of organ voicing, building and restauration (see e.g. 1, 2, 3, 4, 5, 6 for an overview of such works). As of recently, new acoustic and optical methods became available (see e.g. 15) enabling for an improved observation of the associated phenomena e.g. (7, 8, 9, 10). The present study therefore focused on documenting and interpreting the tone-onset development a jet flow of air in the labium in relation to modification of select voicing adjustments.

Since the air-jet is very sensitive to changes in the surrounding boundary (Kelvin-Helmholtz instability), an amplification of small disturbances in air-jet surface occurs also in the context of sound onset (5). Based on the measured data, it is hypothesised that small increments of sound pressure or velocity at the jet boundary cause deflections in the path of the jet and the sound pressure fluctuations in the labium which observably influence the jet routing after a time-delay determined by the path to the end of pipe and back, and moreover alter the labial sound pressure even further.

To measure the effect of different voicing parameters on the air-jet, an experimental transparent pipe and windchest was constructed, allowing for variance of windchest air pressure upper lip height (cut-up) and flue slit area (breadth) was used and documented by means Particle Image Velocimetry method PIV see e.g. (11). The presented visualizations of onset air-jet velocity vectors are also accompanied by synchronised time courses of recorded sound pressure and sound quality descriptors obtained in a listening test.

Under standard conditions, tracing the air jet in transient events using PIV is limited to use of a high speed camera and an illumination with double pulse laser at high sampling frequency. It has been observed in previous experimental measurements that the tone onsets of pipes with stable windchest pressure and valve opening are largely repeatable. A simpler, low frequency laser and the method of gradual shifts of snapshot time frames against a trigger reference on repeated onset sounding can therefore be possibly used for the observations, and was used in this study.

2 EXPERIMENT and METHOD

An experimental wooden open principal pipe (f0 ≈ 207 Hz, inner length 718 mm and rectangle area 55 x 45 mm) with an all Plexiglas (polymer of methyl acrylate) walls and adjustable position of wooden kernel (see Figure 2) was used in the study (since PIV laser visualizations of labium air jets require a pipe with transparent upper lip and at least two side walls).

2.1 Sound and jet recordings

Voicing parameters on experimental pipe were gradually adjusted in a 10 to 26 mm range for the cut-up *height* (1 mm increments), in a 0,4 to 3,25 mm range for its *breadth* (0,15 mm increments) and in a 392,3 to 980,7 Pa range for *air pressure* (98,07 Pa increments); the ranges deviate around an optimal best-sound setting (best voicing positions: 18 mm; 1,35 mm; 588.42 Pa). Only a selection of the obtained variants is however presented in this study (e.g. with air pressure 588.42 Pa).

The air system was controlled using an electromagnetic valve (pressure instability was <1%). The sound was recorded in anechoic room (Neumann KU100 dummy head at 1 m distance 20^{o} in front to labium, A/D 24 bit, sample rate192 kHz, calibrated on 0 dB SPL, temperature 22°C, humidity 41%). The sound records and PIV tracking were triggered by an electric signal on the valve opening.

Windchest air was seeded with glycerin micro particles generated by Safex FOG 2010 Plus instrument. The particles were illuminated using a double pulse laser with 15 Hz double-pulse frequency (with 6.10^{-6} s interval between the double pulses). Single PIV double pulse snapshots were captured intervals shifted consecutively stepwise relative to a trigger (signal of a valve opening; shifting step 5.10^{-4} s) on repeated sounding of the tone. On a single voicing setting, the results were also compared to results of continual PIV measurement with laser with 2 kHz frequency (the laser was unavailable for other observations). The differences in the development of jet positions in time (and also of the sound pressure amplitudes) were considered as negligible (the timings in between tone soundings changed at maximum 5.10^{-4} s). The high speed camera (Phantom SpeedSense 9060) was set to capture a side view of the labial space (33 x 53 mm), the PIV interrogation area was 8 x 8 pixel (≈ 0,33 x 0,33 mm).

The subjective verbal descriptions of the tone onset were collected in a listening test. Binaurally recorded tones of 300 ms length were standardized with 75 ms fade outs and were used as stimuli. The tests were performed on a PC in the listening test editor software (LiTeD; © the authors institute). The stimuli were presented using Sennheiser HE60 headphones (calibrated on KU100) and were evaluated by ten experienced subjects (organ voicers and sound engineers). Frequent verbal descriptors utilized by most respondents were used to describe the tone transient and are presented together with the recorded graph of sound pressure development (see Figures 1, 4, 5).

3 RESULTS

The voicing adjustments result not only in changes to the character of jet oscillation but also to the character of jet oscillation development. Due to page count limit, only three representative voicing adjustments are documented herein: the best voicing position (18 mm and 1,35 mm), lowered cut-up (15 mm and 12 mm), broader and thicker slit (2,00 mm 0,9 mm) are presented, all displaying a typical variance in an air particle velocity and upper labium arrival time of the jet. The associated jet developments are documented in Figures 1, 3, 5, where slides with particle velocity vectors are ordered in *triads of columns* top-down left-right for each time interval from valve opening (the time is shown in the header of each column triad). The shapes of jet and vortexes are distinguishable from the surroundings as grey contrast areas. The shades of grey correspond to lengths of velocity vectors (darker area represents higher velocity; scale shadings are constant through columns). The velocity vector arrows can also be discerned at higher magnifications of the document. The kern (with visible slit gap) and upper lip tip outlines are depicted in red. The numbers between columns quote the approximate phase angle of the in-out movements of the jet (relative to in-out times of a regularly oscillating jet; 90^{o} represents a maximum jet protrusion). The particle velocity, measured immediately above the slit in a particular time after a valve opening (e.g. for a 36,5 ms time, the velocity is shown as $v_{36,5} = 1{,}0\ \mathrm{ms}^{-1}$), is presented in Figure 1, 4, 5 under the slides (at the bottom) together with verbal descriptions from the listening test. A sound pressure graph is also included in Figures 1, 4, 5, below the first *triads of columns*. The lines in the graph mark out the triple time-sections, where the snapshots were made for each slide in the column.

The slides show the type of first outburst from the slit is associated with changes and deviations to the jet route through a two possible feedback mechanisms. The acceleration and deceleration of air particles in specific areas of the labia (which can be identified in slides or between adjoining slides as change in grey intensity or as progression of the length of velocity vector arrows) is associated with a temporal and local changes of the air density and pressure at a given location. The manner of a first release of particles from the slit therefore likely predetermines, through acoustic feedback, the succeeding jet route and causes a jet declination. At low thickness of the slit (here 0,9) or high pressures (not presented) interruption of the stream of the jet can be observed: e.g. see slide 3 in column 1 in Figure 1 (at 0,0375 s), where the velocity of particles is decreased amidst an active jet. A feedback repeating increase in outward protrusion of the jet can then be observed (with the reflection propagation delay) when such pressure discontinuity occurs.

In the observations, a first feedback can be seen as associated with a *back wall reflection*. It can be observed gradual changes of velocities above the slit (positive sound pressure) correspond to changes in outward oriented velocity vectors after reflection, with successive extended deflection of the jet. The pressure behind the jet also decreases during its outward deflection. Then after the conclusion of the *back wall reflection event* the velocity vectors are oriented inward. This is accompanied by a larger jet deflection to the inside. On our experimental pipe, the periodicity of the jet out – in movement was shorter than the PIV step 5.10^{-4} s and the effect is under sampled in slides; the changes in jet routing can, however, still be followed across the slides in the columns.

Next feedback is associated with a reflection from an *open end of pipe*. The feedback is characterized by an inversion of phase of the pressure radiated through the pipe after reflection. The open end reflects the initial sound pressure as the negative, the reflected sound velocity vectors are oriented inwards, and also the jet deviates to the inside. The inward and outward jet deflections we can be repeatedly observed in all Figures 1, 4, 5.

4 CONCLSION

The differences between the settings of used voicing parameters were observed as associated with stabilisation of the length of the jet oscillation and irregularity of jet movements. Both are observed as connected to aspects of a first outburst and to the velocity of air particles in the jet on the route to the upper lip. Smaller air pressure in windchest or the broader slit area is associated with lower speed of air-jet particles and with a more continuous first outburst. The pressure changes (sound pressure) in the labium produced by such outburst are also continuous. This is theorised to be associated to regularity of time-delayed pressure changes reflected from the pipe end and back wall (which periodically change the jet direction).

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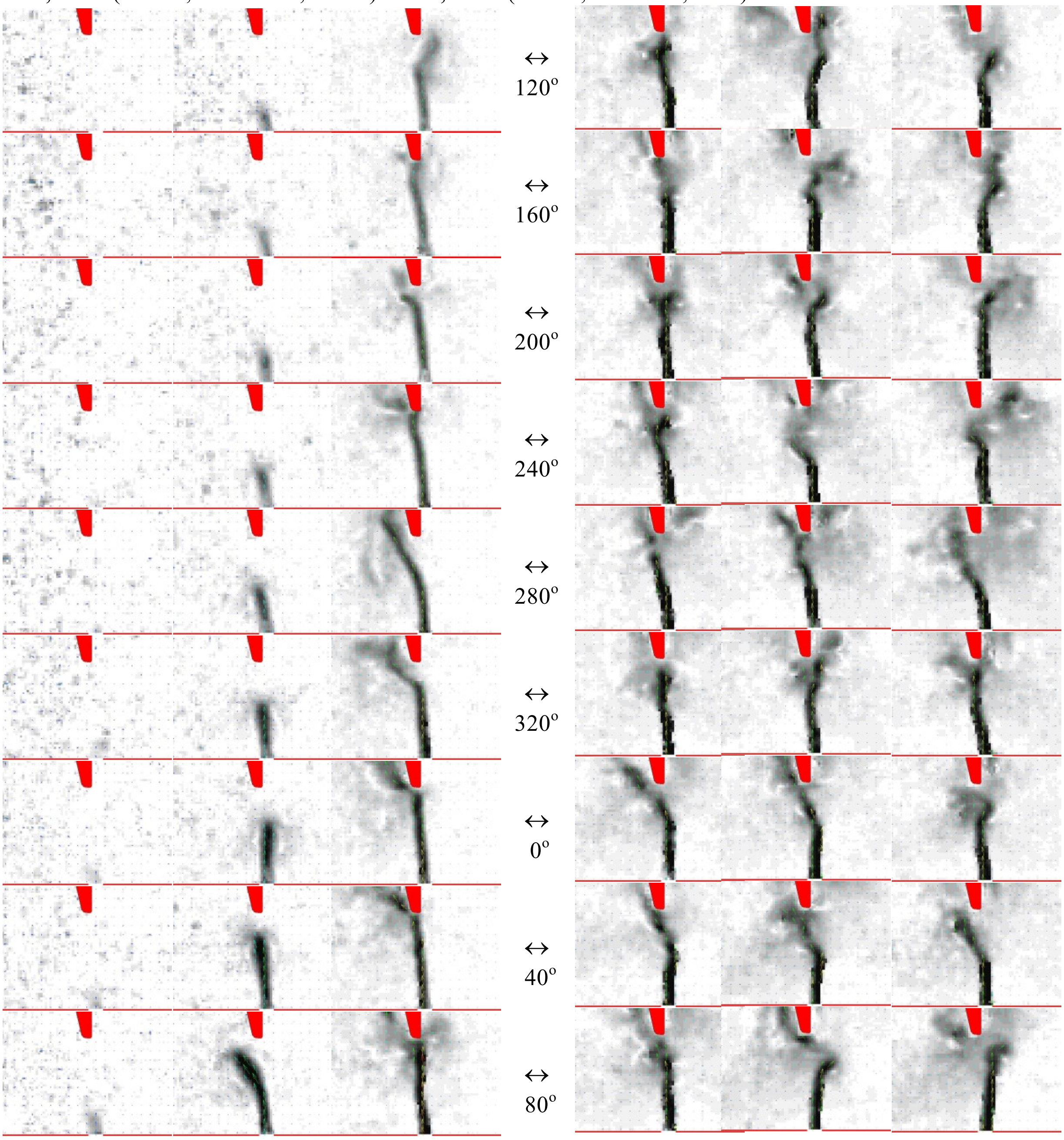
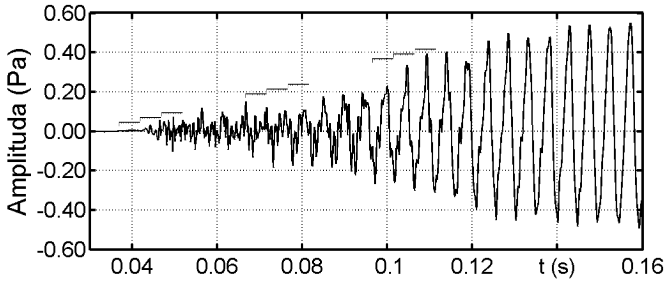
15 0,90 60 (from 0,0365 s to 0,0495 s) **15 0,90 60** (from 0,064 s to 0,077 s)





Velocity (m/s) in jet from a time (ms) after valve opening:

$v_{36,5}$ 1,0; $v_{40,5}$ 2,5; v_{45} 8,5; $v_{49,5}$ 17; $v_{>60}$ 19,7;

Verbal description of perceived sound quality:

strong; slow; fizzy; rustle; hard; sharp; bright; diapason; expressive; concrete; distinct;

15 0,90 60 (from 0,0915 s to 0,1045 s)

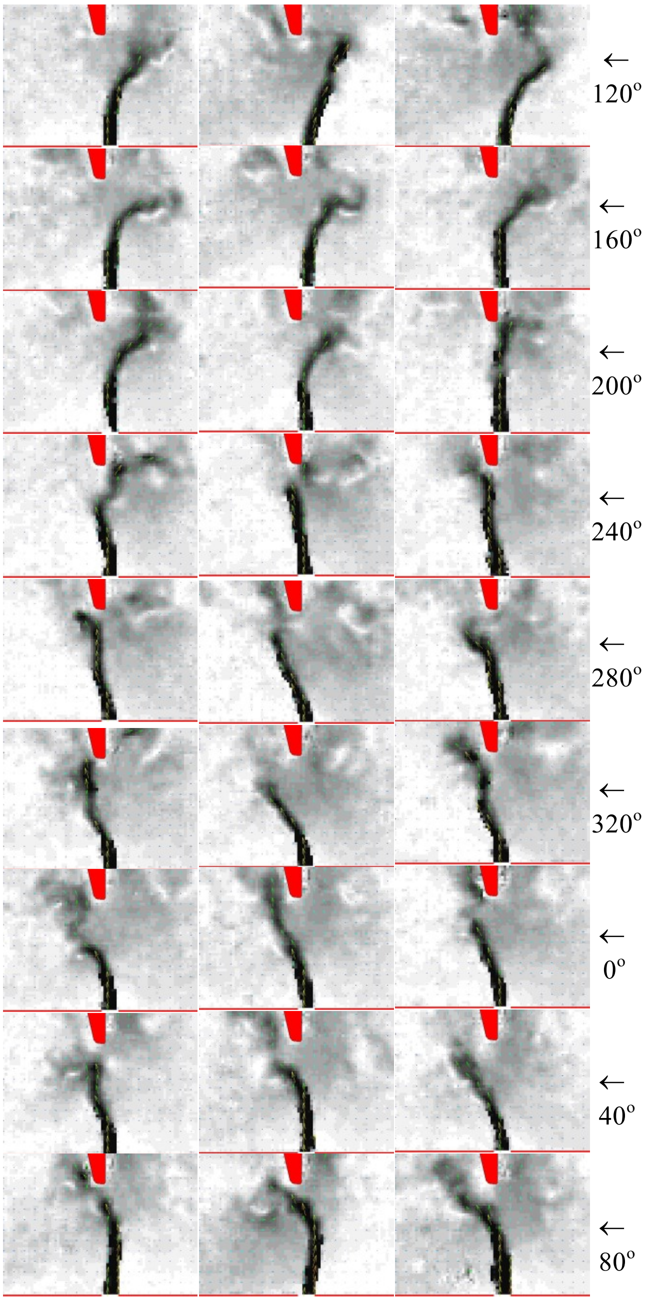


Figure 1. (*Top*) The 3x3x9 slides with velocity vectors of labial air jet for the 15-0,90 voicing adjustment in the times shown above (from first slide in column 1 to last in column 3). (*Previous page bottom Left*) The lines in the sound pressure time development mark the timing of slides presented in separate columns; (*Right*) jet particle velocity and verbal descriptions of perception of the tone attack.

Figure 2. The adjustable experimental pipe with transparent walls

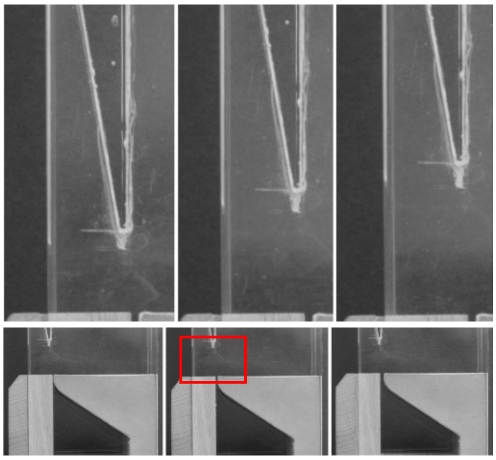
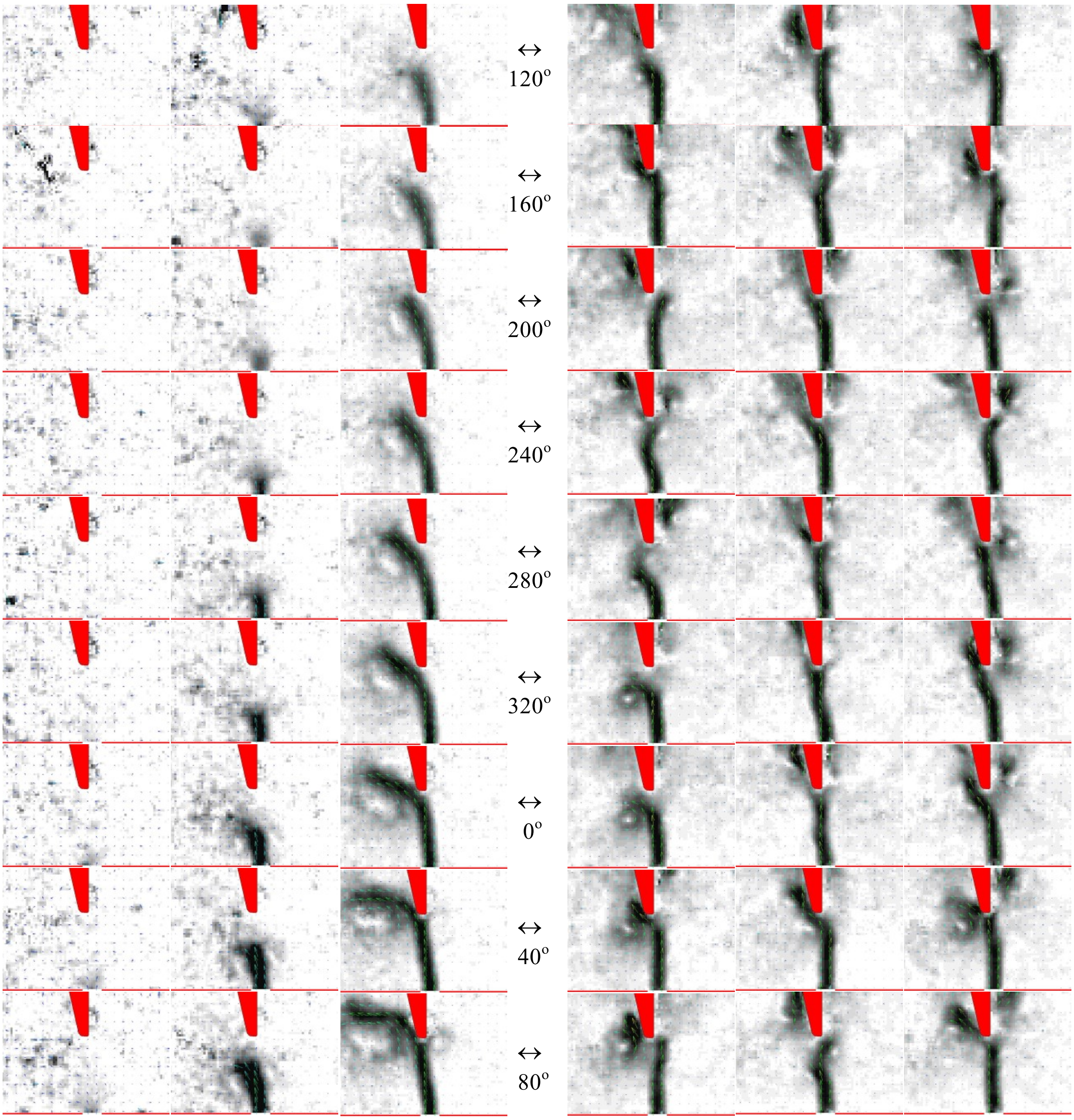
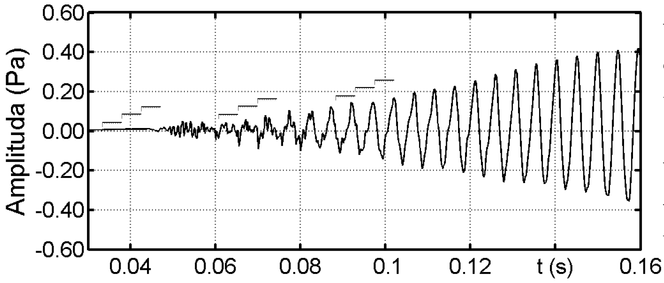


Figure 3. The adjustment range of upper lip height and flue slit area. Optimum voicing adjustment (cut-up height 18 mm, slit breadth 1,35 mm) is shown in the middle. The PIV area used in presented slides is marked by red rectangle.

12 2,00 (from 0,033 s to 0,046 s) **12 2,00** (from 0,0605 s to 0,0735 s)





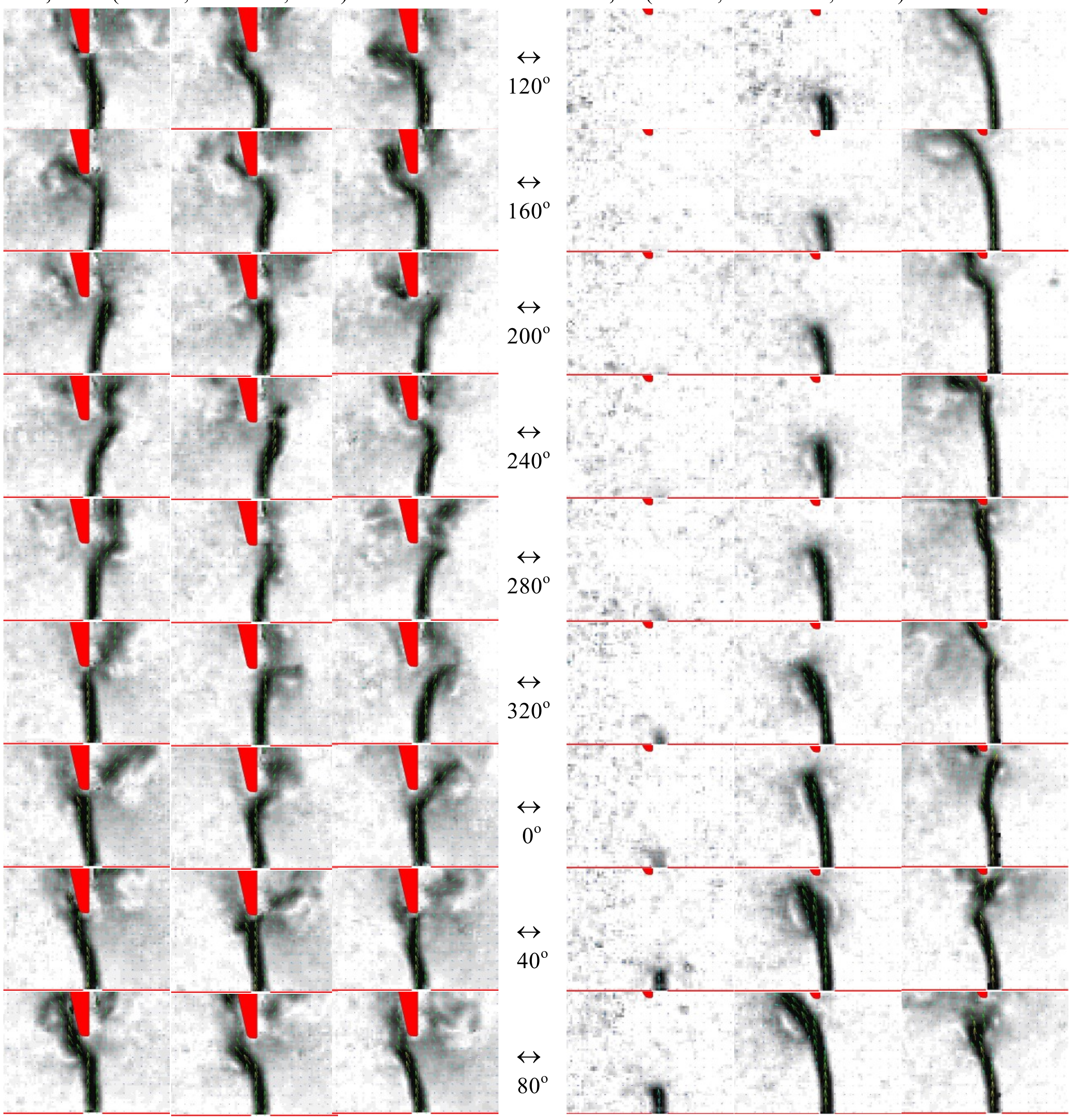
Velocity (m/s) in jet from a time (ms) after valve opening:

v_{33} 0,7; v_{37} 3,7; $v_{41,5}$ 9,2; v_{46} 12,5; $v_{>50}$ 13,5;

Verbal description of perceived sound quality:

weak; slow; rounded; smooth; dark; obtuse; rustle; under-excited; fluty;

12 2,00 60 (from 0,088 s to 0,101 s) **18 1,35** (from 0,0325 s to 0,0455 s)



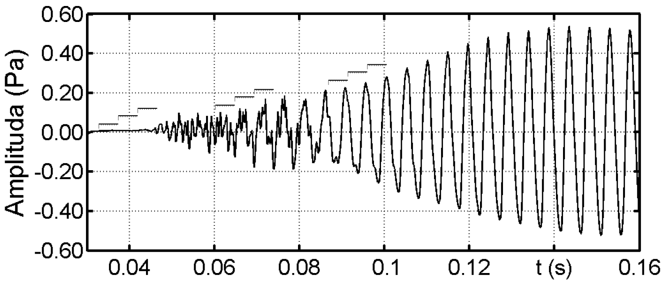
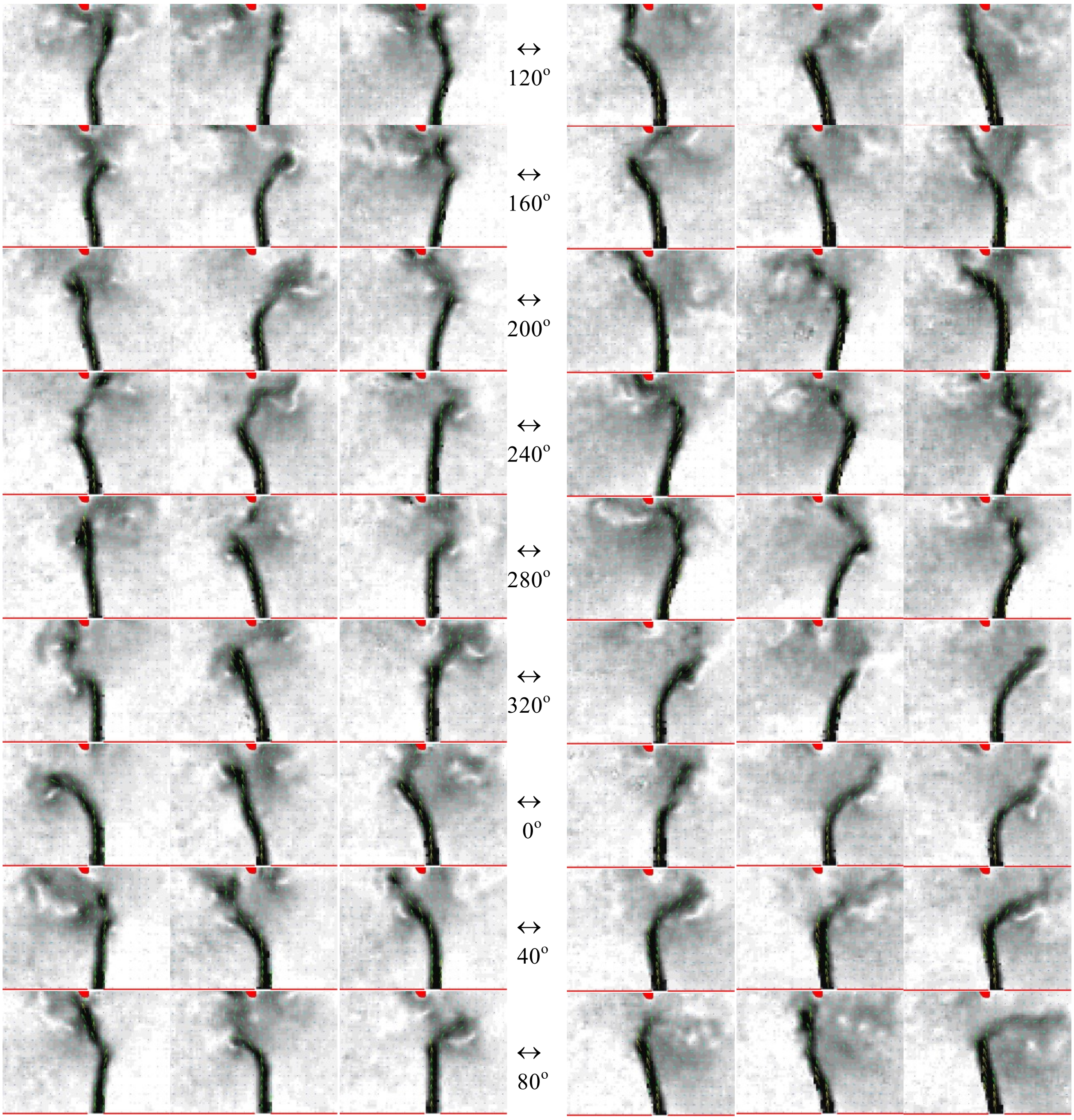


Figure 4. (*Top*) The 3x3x9 slides with velocity vectors of labial air jet for the 12-2,00 voicing adjustment in the times shown above (from first slide in column 1 to last in column 3). (*Previous page bottom Left*) The lines in the sound pressure time development mark the timing of slides presented in separate columns; (*Right*) the jet particle velocity and the verbal descriptions of perception of the tone attack.

18 1,35 (from 0,06 s to 0,073 s) **18 1,35** (from 0,0875 s to 0,1005 s)



Velocity (m/s) in jet from a time (ms) after valve opening:

$v_{32,5}$ 1,2; $v_{36,5}$ 4,9; v_{41} 913; $v_{45,5}$ 14,5; $v_{>50}$ 16,5;

Verbal description of perceived sound quality:

quick; rounded; dark; mellow; obtuse;
veiled; full; clean; copula like;

Figure 5. (*Top*) The 3x3x9 slides with velocity vectors of labial air jet for the 18-1,35 voicing adjustment (from first slide in column 1 to last in column 3, times shown above); (*Left*) the jet particle velocity and the verbal descriptions of the tone attack perception.

(*Previous page bottom Right*) The lines in the sound pressure time development mark the timing of slides presented in separate columns.