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VOCAL TRACT TURBULENCE AND RECORDER SOUND – A CFD APPROACH

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ABSTRACT

Whether it is possible to change the timbre during recorder playing is a much debated question among recorder players. Chen et al. (2007) showed that it is indeed possible to alter the timbre of the recorder as a player. As the underlying mechanism is not clear, a large eddy fluid simulation in two dimensions of four different vocal tract shapes has been carried out. One vocal tract is straight, the second one has a constriction in the back, the third one has a constriction in the front and the last one is a short reference model. The velocities and the pressure point to the hypothesis that turbulence created in the front of the mouth cavity is associated with lesser correlated velocities in the jet region and reduced harmonics.

Keywords: *recorder, flue instrument, turbulence, vocal tract*

1. INTRODUCTION

Although the recorder is present in European culture at least since the middle ages [1], there is still no theoretical framework how to elicit different timbres as a player for a given pitch. Colorful recorder playing has first documented about 70 years ago by Frans Brüggen but until today, players struggle to reproduce this except very few virtuosi. A better understanding of virtuoso recorder techniques could make them accessible for more people. From a physical perspective, the recorder consists of an edge tone which is additionally enslaved by a resonator [2], [3]. This means, that the frequency of the recorder is strongly coupled to the blowing speed which guides the oscillation frequency of the jet [4]. However, there are some loopholes that have the potential to alter the timbre without changing the pitch (for an overview see [5]).

The most researched one sees the windway as the neck of a Helmholtz resonator sitting on the volume of the mouth cavity [6], [7]. This effect has also been examined with fluid simulations on an organ pipe with its chamber [8], [9]. Depending whether the frequency of the Helmholtz resonator is above or below the fundamental of the flue instrument, in-phase or anti-phase oscillations are elicited in the jet. The anti-phase oscillation leads to a more stable tone when the frequency of the Helmholtz is below the fundamental of the instrument [8], [9]. Moreover, possible alterations of the harmonics are discussed [6], [7]. Further in this paper this, will be called the Helmholtz effect. Another mechanism is the production of turbulence in the vocal tract. A spectral analysis revealed different timbres of a virtuoso recorder player when playing the same instrument [10]. After some hypotheses [10] as well as a first fluid simulation [5], it is still unclear, how the turbulence finds its way from the mouth to the sound. This is the scope of this paper.

Transient fluid simulations are well suited as a major contribution to tackle this problem because of their ability to deliver values of all relevant physical quantities at every point in time and space. Due to the 3D nature of turbulence and the different energy cascades [11], a thorough investigation would require several 3D Large-Eddy-Simulations (LES). This would ask for an enormous amount of calculation time and careful selection which data to write out. To facilitate this decision, 2D-simulations have been carried out to develop a qualitative hypothesis for more detailed testing e.g. a possible 3D-simulation.

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2. METHOD

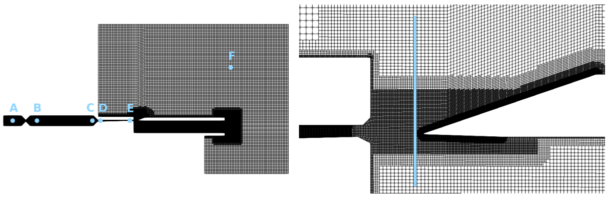

Figure 1: Mesh with sample locations in blue.

To investigate the influence of turbulence in the mouth cavity on the recorder sound, LES-simulations have been carried out. Four different shapes of "mouth cavities" have been tested (fig. 2): The first one is a straight tube. The second one has a constriction in the back and the third one in the front. It is expected, that the flow separates after the constriction to create shear turbulence. Moreover, a short model has been created to distinguish the influence of turbulence from the Helmholtz effect. The dimensions of the mouth cavities are very roughly estimated after [12] with a length of $14.8\,\mathrm{cm}$ and a diameter of $1.63\,\mathrm{cm}$ for the straight vocal tract and the ones with the constrictions in the front. The short vocal tract has the same volume as the front chamber of the mouth cavity with the constriction in the front. The simulations are run with OpenFOAM v2406 and its compressible solver rhoPimpleFoam. The numerics mostly follow [13] because the source code is online and some of his results have been confirmed by experiments [13] and a 3D simulation [14]. The turbulence is modelled with a one-equation-eddy model. The spacial derivatives are discretized with a filtered version of the central differencing scheme to obtain sharp gradients for the jet and suppress oscillations. The temperature is set to $293\,\mathrm{K}$ while the pressure is set to $101\,325\,\mathrm{Pa}$. The boundary conditions consist inter alia of an inlet with constant velocity of $1.17\,\mathrm{m\,s^{-1}}$, acoustically hard walls, a wave transmissive outlet for the pressure combined with an outlet velocity condition with a zero gradient outflow velocity for the air leaving the domain and a calculated inflow velocity for reverse flow into the domain.

The windway and labium of the recorder are built after an f-alto recorder by Johann Pörschmann (about 1680–1757) at the Musikhistorisk Museum in Copenhagen, inventory number CL 417 [15]. The measurements of the chamfers and the position of the labium's tip are lacking in this plan and estimated following the advice of recorder maker Geri Bollinger. The resonator consists of a straight tube with a length of $14.3\,\mathrm{cm}$ and a diameter of $1.93\,\mathrm{cm}$. When creating the mesh, emphasis has been given to a fine grid in the windway, the jet region, around the labium and at the walls (fig. 1). This results in grid sizes between $197\,057$ cells for the short vocal tract and $219\,384$ cells for the straight vocal tract. The simulations are run for $0.1\,\mathrm{s}$ with a time-step of $2.5 \times 10^{-6}\,\mathrm{s}$.

3. RESULTS AND DISCUSSION

In this section, we follow the flow from the vocal tract over the windway and the jet to the sound spectra.

3.1 Creation of Turbulence in the Vocal Tract

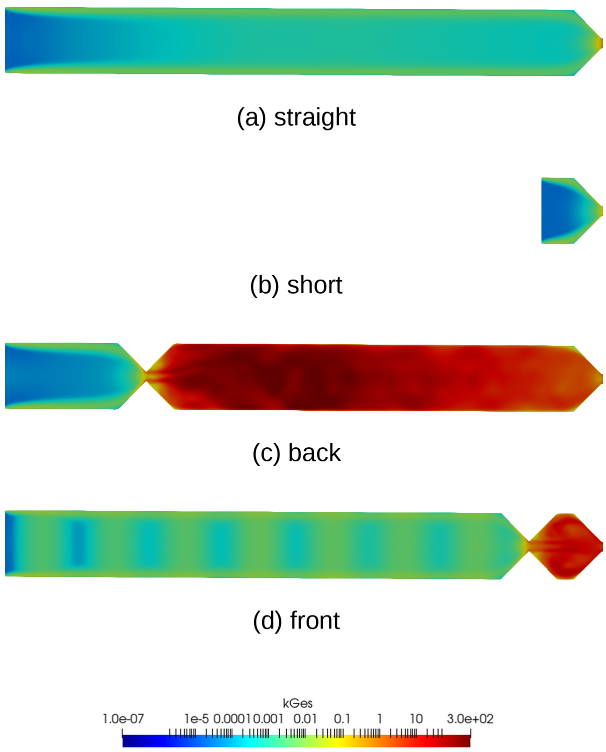

Figure 2: Logarithmically scaled turbulent kinetic energy in the vocal tract after $0.1\,\mathrm{s}$. The constrictions lead to boundary layer separation and create shear turbulence.

As we can see in fig. 2 taken after $0.1\,\mathrm{s}$, the constriction creates shear turbulence by boundary layer separation. The image of the constriction in the back shows the typical growth and the decay of shear turbulence without extra energy supply in the direction of the flow. The energy spectra obtained from the autocorrelation of the velocity component in the mean flow direction show a clear periodicity for the straight and short vocal tracts while there is a typical line at the turbulent locations after the constrictions. The decay of the turbulence of the constriction in the back is also reflected on the spectrum, as harmonic components begin to reappear. This can be seen for example on the energy spectrum of the flow direction velocity in fig. 3 compared to the similar spectra of the straight vocal tract.

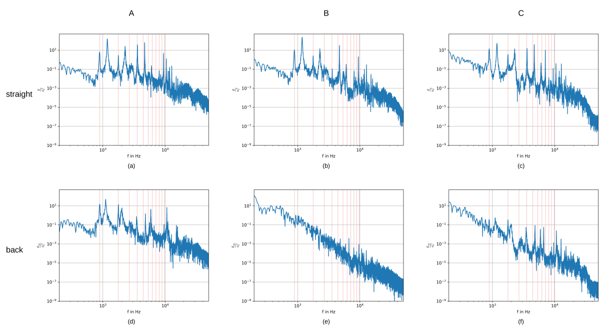

Figure 3: Energy spectra of the velocity fluctuations in the mean flow direction in the vocal tract. The first line shows the straight vocal tract as a comparison while the second line shows the spectra of the constriction in the back before (A), after (B) and long after the constriction (C).

3.2 Turbulence in the Windway

The energy spectrum in the direction along the windway can be seen in fig. 4. The first probe point, D, lies $1.428\,57\,\mathrm{mm}$ after its entrance while the second probe point is located at $55.98\,\mathrm{mm}$ from the entrance, right above the lower chamfer, E (fig. 1). The spectra in fig. 4 show a blend of the acoustic and the flow field. The pink lines show multiples of the fundamental of $891\,\mathrm{Hz}$ while the dark red lines show multiples of the resonance frequency of the windway around $2858\,\mathrm{Hz}$ up to $10\,000\,\mathrm{Hz}$. The gray area shows the minimum eddy frequencies stemming from the turbulence in the windway between 7400 and $60\,000\,\mathrm{Hz}$. They are estimated by Taylor's hypothesis with a windway diameter of $9\,\mathrm{mm}$ at its entrance and $23\,\mathrm{mm}$ at its narrowest point where the flow separates from the lower chamfer to form the jet.

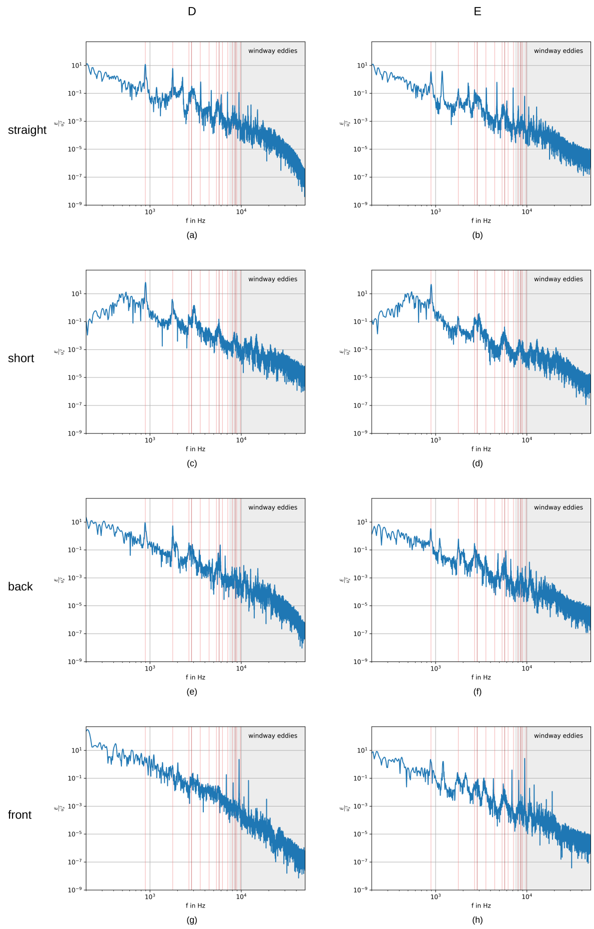

Figure 4: Energy spectrum of the velocity fluctuations in the x-direction from 0.02 to $0.1\,\mathrm{s}$ at the windway entrance and at the separation point at its exit.

In general, the spectra show some harmonic peaks associated with the sound field, a more or less logarithmically declining noise floor as well as some inharmonic peaks. Some of them are multiples of the estimated resonance frequency of the windway while others could descend from the flow field as documented by [16] and [9] for the sound pressure levels. The straight vocal tract has the clearest and best aligned harmonics. The spectra of the short vocal tract show less harmonics with broader peaks and very clear windway resonances. The spectra of constriction in the back shows less aligned higher harmonics than the spectrum of straight vocal tract particularly above 4000 Hz. At the entrance, there are almost no harmonics discernible for the spectrum of the constriction in the front while they reappear with broad peaks and reduced amplitudes at the windway exit. Next, we are looking closer into the gray regions of fig. 4 which would allow for isotropic eddies in the windway. Except for the short vocal tract, all spectra show more energy at these frequencies at the exit of the windway compared to its entrance possibly because of the wall boundary layer of the windway. The reason for the exception of the short vocal tract is not known. The two vocal tracts with constrictions exhibit slightly enhanced amplitudes above 30 000 Hz. All in all, the different geometries show already different turbulence structures when leaving the windway with the straight vocal tract being the most harmonic and the constriction in front showing the most high-frequency peaks. A detailed analysis in this region has to be used with great caution because of the convection in the windway, the different energy cascade between 2D and 3D could play a major role.

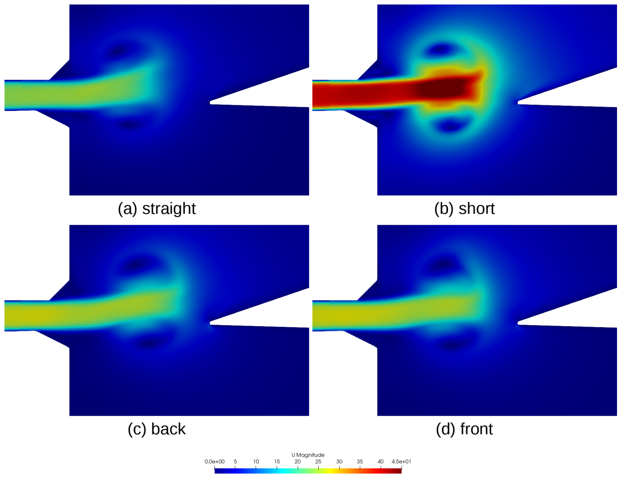

Figure 5: Jet velocity magnitude after 0.001 68 s for the straight, front and back condition and after 0.0008 s for the short vocal tract. The different histories of the jet are amplified by the Kelvin-Helmholtz instability.

3.3 Jet Velocities

The development of the jet velocities can be analyzed in two consecutive time windows. When the flow enters the cutup as a jet for the first time, it is mainly influenced by the Kelvin-Helmholtz instability (KHI) reflecting its aerodynamic history. After the resonator delivers its feedback over the time, interesting correlations of the jet velocities can be spotted and it seems more to behave like a complex system.

3.3.1 Initial Kelvin-Helmholtz Instability

Fig. 5 shows the Kelvin-Helmholtz instability of the velocity magnitude of the jet after 0.001 68 s for the straight, front and back condition and after 0.0008 s for the short vocal tract. At this moment, the initial shockwave [13] has already been reflected on the jet and it might also pertain to the perturbations of the jet amplified by the KHI.

The differences between the images reflect the different histories of the jets before arriving at the cut-up. The straight vocal tract shows the biggest upward bending of the jet. This initial upward-bending is clearly reduced for the short vocal tract due to its higher momentum. This condition shows a higher velocity at this initial stage because the air is more compressed in the mouth cavity before entering the windway due to the proximity of the inlet to the windway entrance. However, this enourmous velocity difference disappears in the steady-state. The constrictions show lower velocity gradients especially when the constriction is in front and thus flatter velocity profiles due to the upstream turbulence in accordance with [17].

3.3.2 Velocity Correlations During the Steady-State

To capture the vertically oscillating jet, a line sample of the velocities has been drawn perpendicularly through it 2.6364 mm away from the windway exit as shown in fig. 1. At this location, the vertical oscillation of the jet is well developed, but it is not yet highly asymmetrical due to the labium. The x-component of the velocity in the mean flow direction shows the position of the jet over time until 0.1 s (fig. 6).

The time development of the jet position is mirrored by the pressure evolution at 17 cm away from the labium above the foot as we can see at the example of the straight vocal tract. At first, an oscillation forms until 0.005 s and grows up to 0.023 s. During the growth, the velocities around the jet align their movement with the jet. The steady-state is temporarily disturbed between 0.042 s and 0.05 s by an exception in the velocities with a simulta-

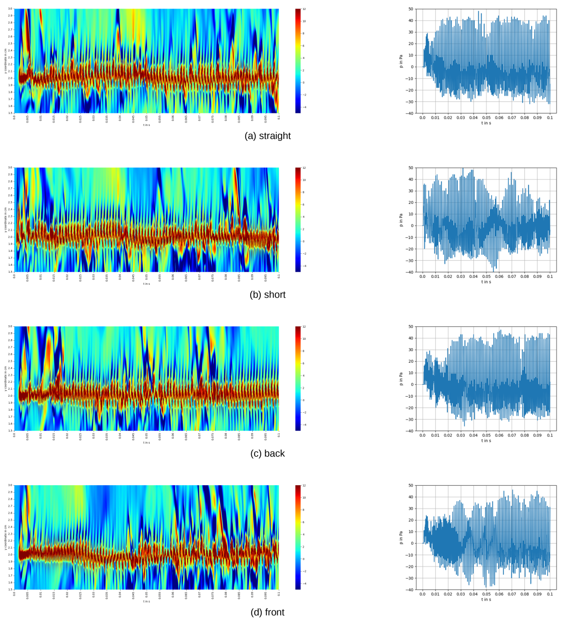

Figure 6: Left: Horizontal velocity component of a sample line perpendicular to the jet plotted over the time until $0.1\,\mathrm{s}$. Right: corresponding pressure amplitudes $17\,\mathrm{cm}$ away from the labium above the foot at point F.

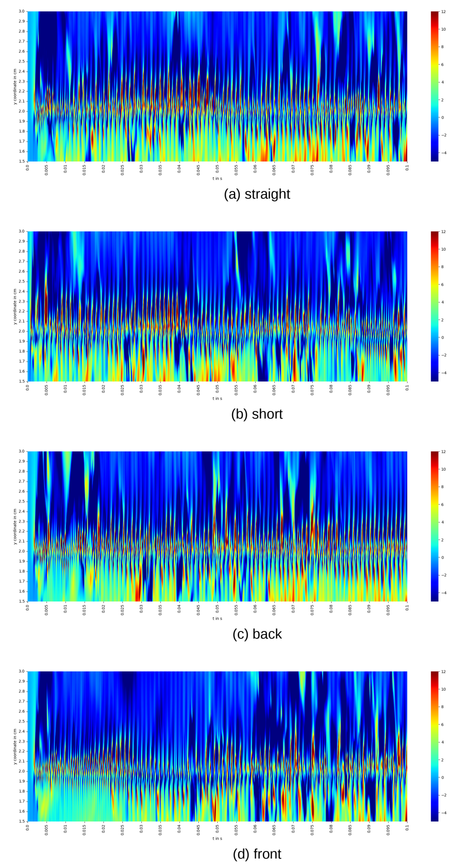

Figure 7: Vertical velocity component of a sample line perpendicular to the jet plotted over the time until $0.1\,\mathrm{s}$.

neous reduction in sound pressure. The short vocal tract has a shorter initial transient and a less stable steady-state. From $0.0885\,\mathrm{s}$ and $0.096\,\mathrm{s}$, the recorder overblows. This dependence of the overblowing on the geometry of the vocal tract could hint to [4] who have shown that trained recorder players can enlarge the hysteresis of their instrument with respect to overblowing. The constriction in the back exhibits a longer transient up until $0.038\,\mathrm{s}$. Here, we can also watch the oscillations around the jet and the pressure amplitude grow together. The constriction in the front has a very long transient and growth until $0.028\,\mathrm{s}$ with very regular movements although it has some difficulties to take along as much air around the jet as the other conditions. Then, the the jet gets more irregular up to $0.028\,\mathrm{s}$ settling into a steady-state with a varying amplitude and surrounded by some quite far-reaching non-periodic velocity fluctuations.

While the x-component reveals the position of the jet, the y-component tells us something about its vertical movement (fig. 7).

During the steady-state, the heatmaps show different levels of variability of the vertical jet movement over time. Moreover, this jet movement influences the air around it up to different distances. To obtain a numerical value associated with these effects, the correlation function of the time evolutions of each sample point with a point in the middle of the jet has been taken. Fig. 8 shows the L1-norm of each correlation function depending on the y-coordinate.

The correlations are the highest inside the resonator. The reflection of the sound waves in this region could support the strong correlation. A second peak can be observed in the jet and a third one above the jet in the cut-up and slightly outside of the instrument. The image shows an

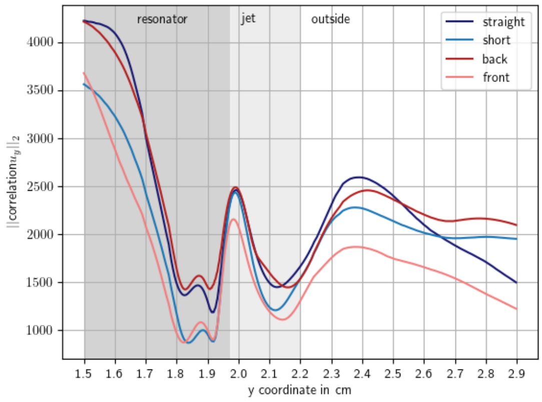

Figure 8: Correlation norm of the time evolution of each sample point with a point in the jet.

interaction between the size of the mouth cavity and the turbulence with enhanced correlations for a larger vocal tract and less turbulence. This is most prominent in in the cut-up peak outside of the jet and the resonator. Moreover, the difference between the front and the short condition suggest a second possibility to alter the sound next to the proposed Helmholtz effect.

3.4 Radiated Sound Spectra

The radiated sound spectra in fig.9 are taken 17 cm away from the labium above the foot from 0.02 to 0.1 s during the quasi-stationary state with a sample rate of 10^5 Hz. This gives a frequency resolution of 12.07 Hz. All the fundamentals are at 891 Hz. The spectrum of the straight vocal tract shows the clearest harmonics with the narrowest peaks. In this, the first and second harmonic are most prominent. In comparison, the spectra of the short vocal tract and the constriction in the back differ slightly while the spectrum in the front shows clear changes. The spectrum of the short vocal tract shows slightly wider peaks and tightened octaves as overtones. The first and second harmonic are a little bit weaker. The sound spectrum of the constriction in the back also displays slightly wider harmonics. In this case, the first and second harmonic are as strong as in the spectrum of the straight vocal tract with weakened third and fourth harmonics. In general, these changes are rather small and it would be interesting if they can be perceived. In contrast, the spectrum with the constriction in the front only shows a strong first harmonic with a weaker second and higher harmonics not discernible from the background. The first and second harmonic are considerably broader. Moreover, it displays some extra energy in the frequencies around the second harmonic and between 6000 and 7000 Hz. This rich fundamental and the enhanced noise floor between 6000 and 7000 Hz match with the virtuoso recorder technique described and recorded by [10] although the slightly enhanced noise could be just by chance. However, they report altering the position of the soft palate, a different body movement that is not necessarily associated with creating shear turbulence, so additional effects such as the Helmholtz effect could also play a role.

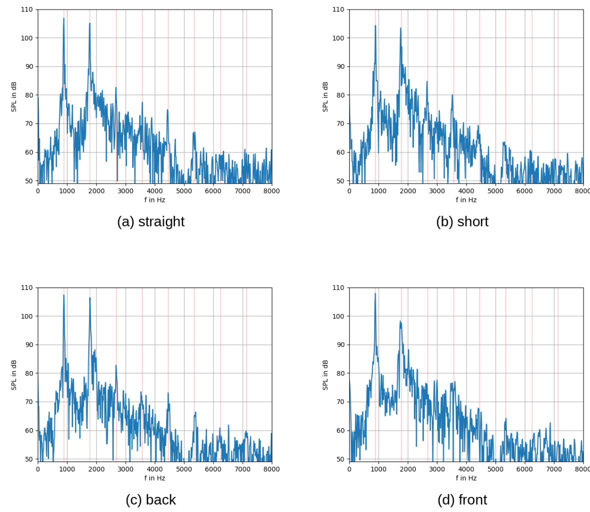

Figure 9: Pressure spectra during the quasi-stationary state from 0.02 to 0.1 s. The constrictions are associated with less clear harmonics in the sound spectrum.

In general, these results raise the questions whether the feedback between the jet and the resonator or the KHI plays the leading role for a timbre change with turbulence in the mouth cavity.

4. CONCLUSION

The results show changes throughout the instrument in the flow and the radiated sound pressure with the geometry in the vocal tract. The data from the short vocal tract differ clearly from the changes seen in the vocal tract with a constriction in the front. This points to a second possibility to alter the sound for a given pitch next to the Helmholtz effect. We propose that this could work in two steps: First, the shear turbulence in the mouth influences the initial KHI by mostly by aerodynamic effects. In the second step, the instrument behaves like a complex system with the feedback between the jet and the resonator additionally altering resulting sound pressure. Moreover, the comparison between the constrictions in the front and in the back suggest that turbulence might be most efficient to alter the sound when created at the right spot in the mouth. These effects are associated with reduced harmonics when the constriction is in the front. However, this is only a first dip into the mechanism behind a possible vocal tract influence on the sound of a flue instrument. 2D turbulence has a different energy cascade which is also not accounted for by the used turbulence model. Therefore, the results need to be checked with a more resource consuming 3D simulation and experiments now that we have some better idea, which data could be useful to write out. Further simulations would also require a mesh quality study. In the meanwhile, recorder players could test whether this concept and some basic knowledge about turbulence could be artistically useful.

5. ACKNOWLEDGMENTS

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