Numerical study of turbulent flow-induced sound production in presence of a tooth-shaped obstacle: towards sibilant [s] physical modeling.

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Abstract

The sound generated during the production of the sibilant [s] results from the impact of a turbulent jet on the incisors. Physical modeling of this phenomenon depends on the characterization of the properties of the turbulent flow within the vocal tract and of the acoustic sources resulting from the presence of an obstacle in the path of the flow. The properties of the flow-induced noise strongly depend on several geometric parameters of which the influence has to be determined. In this paper, a simplified vocal tract/tooth geometric model is used to carry out a numerical study on the flow-induced noise generated by a tooth-shaped obstacle placed in a channel. The performed simulations bring out a link between the level of the generated noise and the aperture of the constriction formed by the obstacle.

Index Terms: sibilant, physical modeling, Large-Eddy Simulation, flow-induced noise

1. Introduction

The sibilant [s] is an unvoiced sound of speech which belongs to the fricative category. This type of sound results from the impact of a turbulent jet, formed in the vocal tract, on the incisors. The physical phenomena involved in the production of this sound are complex. However, experimental studies [1] characterized its main mechanisms and in particular the strong acoustic source resulting from the presence of an obstacle in a turbulent flow.

The modeling of the turbulent flow within the cavities and the constrictions of the vocal tract is essential to characterize the acoustic sources of the fricatives, but remains very complex. From predictions obtained with a Large-Eddy Simulation model and a simplified description of the vocal tract, [2] suggest that aeracoustic models of the turbulence in fricatives with a small number of geometric parameters can be developed but also that using very simplified description of turbulent jet doesn’t seem to be relevant for the modeling of fricatives. Complete aeracoustic models of the sibilant [s] production using simplified [3] or realistic [4] geometries of the vocal tract and the teeth were proposed but the influence of geometric parameters on the properties of the generated sound was not clearly determined.

Experimental in-vivo [5] and in-vitro [6] studies showed that small variations of the position of the tongue and the incisors can lead to significant changes in the spectral properties of the generated sound and therefore in the type of speech sound produced. Thus, a systematic analysis of the influence of different geometric parameters on the properties of the generated sound, from numerical aeracoustic simulation, appears to be a necessary phase in the development of a physical model of fricatives.

In this paper, a simplified vocal tract/tooth geometric model is used to carry out a numerical study on the flow-induced noise generated by a tooth-shaped obstacle placed in a channel. The influence of the aperture of the constriction formed by the obstacle on the sound level is particularly investigated.

2. Numerical simulations

2.1. Geometry, mesh and boundary conditions

Simulations were implemented using the geometry described in Fig. 1 and 2, and in Table 1. A generic tooth-shaped obstacle [7] was placed in a rectangular channel in order to create a constriction of which the height $H_C$ is the varying parameter in this study ($H_C = \{1, 2.5, 5, 7.5\}$ mm or expressed as a percentage of the channel height $H$, $H_C = H \times \{4\%, 10\%, 20\%, 30\%\}$). The value of the channel width to height ratio ($W/H \approx 4$) ensures that the simulated flow in the middle of the channel is weakly affected by the side walls and allows considering that the flow properties will mainly vary in the $(x, y)$ plane. The shape of the obstacle was defined with sizes and angles derived from morphological data relevant to the upper incisors [8, 9, 10]. An extending domain was added at the exit of the channel in order to simulate the flow behavior downstream of the constriction and in particular the formation of a turbulent jet due to the obstacle in the channel. The surrounding walls in the downstream domain were placed sufficiently far from the center of the channel so that the flow simulated in this domain can be considered as a free jet. All the corners around the obstacle and at the channel exit were rounded to obtain a smooth geometry. This allows avoiding singular points which can affect the computation.

The spatial discretization of the whole flow domain was carried out using Gridgen (Pointwise, Inc.). A structured mesh was defined by using hexahedral finite elements with smaller elements near the walls to take into account the boundary layer effects whereas it was coarser in the body of the flow. Besides, finer mesh was used within the constricted region and in the region where the turbulent jet is a priori located. Only low variations of the flow properties in the z-direction were expected so that the elements size in that direction was larger. In the different considered geometries, the total number of elements was about 6,000,000.

Boundary conditions were defined by specifying a uniform velocity profile at the channel entrance and a static pressure equal to 0 at the downstream domain exit. An additional condi-
Table 1: Quantities used in the model.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream Channel Length</td>
<td>( L_{up} )</td>
<td>80 mm</td>
<td>Downstream Domain Border Height</td>
<td>( H_{ext} )</td>
<td>30 mm</td>
</tr>
<tr>
<td>Downstream Channel Length</td>
<td>( L_{down} )</td>
<td>111 mm</td>
<td>Downstream Domain Border Width</td>
<td>( W_{ext} )</td>
<td>10 mm</td>
</tr>
<tr>
<td>Constriction Length</td>
<td>( L_T )</td>
<td>1.25 mm</td>
<td>Downstream Domain Vertical Angle</td>
<td>( \beta_{ext} )</td>
<td>20°</td>
</tr>
<tr>
<td>Channel Height</td>
<td>( H )</td>
<td>25 mm</td>
<td>Downstream Domain Horizontal Angle</td>
<td>( \theta_{ext} )</td>
<td>10°</td>
</tr>
<tr>
<td>Constriction Height</td>
<td>( H_C )</td>
<td>{1, 2.5, 5, 7.5} mm</td>
<td>Vertical Position of the Microphone</td>
<td>( L_{mic} )</td>
<td>200 mm</td>
</tr>
<tr>
<td>Channel Width</td>
<td>( W )</td>
<td>101 mm</td>
<td>Inlet Velocity</td>
<td>( U_{inlet} )</td>
<td>2.4 m ( \cdot ) s(^{-1} )</td>
</tr>
<tr>
<td>Obstacle Upstream Angle</td>
<td>( \alpha_1 )</td>
<td>107°</td>
<td>Air Kinematic Viscosity</td>
<td>( \nu )</td>
<td>( 1.5 \times 10^{-5} ) m(^2) ( \cdot ) s(^{-1} )</td>
</tr>
<tr>
<td>Obstacle Downstream Angle</td>
<td>( \alpha_2 )</td>
<td>90°</td>
<td>Reynolds Number</td>
<td>( \text{Re} )</td>
<td>4000</td>
</tr>
<tr>
<td>Downstream Domain Length</td>
<td>( L_{ext} )</td>
<td>240 mm</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1: Diagram of the model’s geometry in \((x, y)\) and \((x, z)\) planes.

Figure 2: Diagram of the tooth-shaped obstacle.

10\( \mu \text{s} \) time step was used for the three larger apertures \((H_C = H \times \{10\%, 20\%, 30\%\})\) and a 0.2\( \mu \text{s} \) time step was used for the smaller aperture \((H_C = H \times 4\%)\). Moreover, the inlet velocity was gradually increased during 10,000 time steps for the three larger apertures and during 30,000 time steps for the smaller aperture. Then 30,000 time steps for the three larger apertures and 50,000 time steps for the smaller aperture were simulated with the constant inlet velocity. The flow simulations were performed using \textit{NEC SX9} supercomputer allowing the computation of 10,000 time steps of the models in 13 hours.

2.3. Resulting sound

The sound generated by the flow was derived from the pressure computed on the surface of the obstacle (as shown in Fig 2) and using Curle’s formulation of Lighthill’s acoustic analogy \([13, 14]\). The position of the virtual microphone is indicated in Fig. 1 and Table 1. The equations were solved using the numerical solver included in \textit{Front Flow Blue 5}.

3. Simulation results and discussion

In this section, all the presented quantities are averaged over the simulation period during which the inlet velocity is constant. This duration is 300\( \mu \text{s} \) for the three larger apertures \((H_C = H \times \{10\%, 20\%, 30\%\})\) and 10\( \mu \text{s} \) for the smaller aperture \((H_C = H \times 4\%)\).

Fig. 3 presents the velocity magnitude field for the aperture \(H_C = H \times 20\%\). It shows that the jet formed due to the presence of the obstacle is relatively stable in the downstream region near the obstacle. Downstream of the channel exit, the jet...
becomes unstable so that the average velocity decreases rapidly as the distance from the obstacle increases and that the average jet becomes much wider than the constriction aperture. In the channel, especially in the constriction and upstream of the obstacle, the fluctuations of the velocity are very low, indicating that the simulated flows can mostly be considered laminar. Yet, in the case of the sibilant [s] production, the flow is already turbulent upstream of the teeth so that this aspect constitutes a limitation of the considered geometry in comparison to the real phenomenon. Fig. 4 shows that the vorticity is higher near the walls around the constrained region of the channel and that its maximum is located in the upstream part of the tip of the tooth-shaped obstacle. Moreover, the vorticity magnitude increases as the constriction aperture decreases so that the flow detachment is stronger and that the relative distance of the jet from the wall increases. Indeed, the acceleration of the flow in the y-direction from which a flow detachment from the obstacle wall induces indeed a strong acceleration of the flow in the y-direction from which a flow detachment from the obstacle wall results.

At the constriction exit, the velocity profiles are still asymmetric but they differ depending on the constriction aperture. Indeed, the acceleration of the flow in the y-direction increases as the aperture decreases so that the flow detachment is stronger and that the relative distance of the jet from the wall increases. It can be seen from Fig. 5 that the maximum of the velocity profile at position \( x = x_{T2} \) moves further from the wall when the constriction becomes more narrow. For \( H_C = H \times 4\% \), the velocity profile at this position is almost symmetric indicating that the turbulent jet is almost formed before the end of the constriction. This can also be observed from the vorticity field presented in Fig. 4a in which the high values are closer to the tip of the obstacle than in the vorticity field obtained for \( H_C = H \times 30\% \) and presented in Fig. 4b.

At the channel exit, the velocity profiles tend to have a more symmetric shape. However, the relative width to the constriction aperture \( H_C \). At the entrance of the constriction, the velocity profile is similar in the four considered cases. The profile is strongly asymmetric due to the asymmetry of the constriction. The higher velocity magnitude on the obstacle side mainly comes from the high y-component of the velocity. The obstacle induces indeed a strong acceleration of the flow in the y-direction from which a flow detachment from the obstacle wall results.

Figure 3: Average of the velocity magnitude field (in m s\(^{-1}\)) for the aperture \( H_C = H \times 20\% \) (in \((x, y, z = 0)\) plane).

Figure 4: Average of the vorticity magnitude field (in s\(^{-1}\)) (a) for the aperture \( H_C = H \times 4\% \) and (b) for the aperture \( H_C = H \times 30\% \) (in \((x, y, z = 0)\) plane).

Figure 5: Spanwise average velocity profiles at \( x = x_{T1} \), \( x = x_{T2} \) and \( x = x_{Out} \) (see Fig. 2) for the four apertures \( H_C = H \times \{4\%, 10\%, 20\%, 30\%\} \).

Figure 6: Spanwise average vorticity profiles at \( x = x_{T1} \), \( x = x_{T2} \) and \( x = x_{Out} \) (see Fig. 2) for the four apertures \( H_C = H \times \{4\%, 10\%, 20\%, 30\%\} \).
tion aperture of the formed jet increases as the constriction aperture decreases. In the same way, the distance of the maximum of the velocity profile from the channel lower wall increases. Moreover, it can be noticed from Fig. 5 that the profiles corresponding to the most narrow constrictions (\(H_C = H \times 4\%\) and 10\%) are more parabolic than the two others which are flatter across the core of the jet. This suggests that the jet is more laminar at the exit of the channel with the two smaller apertures.

For every considered constriction aperture, the turbulence is very low in the core of the flow around the constricted region. Besides, it can be seen from Fig. 6 that the vorticity remains relatively weak in the center part of the different profiles and that it is much stronger in the boundary layer of the jet. However, the absolute value of the vorticity magnitude decreases rapidly downstream of the obstacle. The generation of flow-induced noise is strongly linked to the value of vorticity so that it can be considered that the main sound source is located near the upstream part of the tip of the obstacle as shown in Fig. 4. In fact, the increase of the maximum value of the vorticity magnitude lead to an increase of the generated sound intensity. Thereby, it can be seen from Fig. 7 that the mean sound pressure level of the flow-induced noise increases as the constriction aperture decreases. The shapes of the spectra obtained for the three larger apertures appear to be very similar but their levels remain very low, below 75 dB. For \(H_C = H \times 4\%\), the level of the generated noise is much higher but the shape of the spectrum is very different from the others. However, the spectral analysis of the acoustic signal obtained for this aperture is less relevant than for the others since the flow simulation with the smaller constriction requires smaller time steps and consequently more computation time, so that the duration of the signal obtained in this study is shorter.

4. Conclusions

The numerical flow simulations performed in this study bring out a link between the level of the flow-induced noise due to a tooth-shaped obstacle in a channel and the aperture of the constriction formed by this obstacle. This simplified geometric model represents a first approach in the elaboration of a complete physical model of the sibilant [s] production of which the reality is much more complex.

In this model, the turbulence of the flow remains very low in comparison to measurements and observations of the real phenomenon. Moreover, the constriction in the mouth and the aperture between the teeth which allow the production of a hissing sound like [s] are much more narrow than the apertures considered in this study. In order to capture the turbulence of the flow and to account for very small constrictions, a very fine mesh is needed to perform accurate flow simulation.

The computation of the generated sound is also based on a simplified method in this study. Lighthill’s acoustic analogy is unable to take into account the influence of the resonance of the cavities upstream or downstream of the teeth on the radiated sound. Computational aeroacoustics based on numerical simulation would provide a more relevant modeling of the generated noise.

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6. References


