From in-vivo data to mechanical replica: the case of sibilant noise

Y. Fujiso et A. Van Hirtum
GIPSA-lab, 11 rue des Mathématiques, 38402 Saint Martin D'Hères Cedex, France
annemie.van-hirtum@gipsa-lab.grenoble-inp.fr
Sibilant fricative speech production emerges from the interaction of a (jet) flow with the surrounding vocal tract (walls, tooth, articulators and lips). Consequently, sibilant fricative noise depends on geometrical as well as flow properties. Nevertheless, few studies deal with the impact of flow properties other than the volume flow rate (loudness level) on the noise produced. In this work, an experimental study is presented using a reconstructed constant oral cavity during human sibilant production. It is aimed to assess the potential impact of initial flow conditions upstream from jet formation and jet impact on sibilant fricative noise. The velocity distribution of the flow upstream from the sibilant groove is characterized by its statistical moments for different air supplies resulting in different inlet conditions. Spectral features of the noise produced are quantified. It is concluded that initial conditions can not be neglected.

1 Introduction

The underlying mechanism of sibilant fricative sound production is generally described as noise produced due to the interaction of a turbulent jet, issued from a constriction somewhere in the vocal tract, with a downstream wall or obstacle [13, 14]. Screening of geometric and flow parameters during human sibilant fricative phoneme production enabled to establish the major impact on acoustic sibilant features such as spectral properties or loudness level [6]. Flow and geometrical parameters during human sibilant production are inherently correlated and show a large inter- and intra-speaker variability [8]. To overcome these difficulties proper to human sibilant phoneme data, several studies rely on ex-vivo data – following experimental, numerical or modeling studies – in order to single out an individual sibilant production parameter (either geometric or flow) and to study its impact for sibilant sound production [13, 7, 5, 16, 11, 2].

The cited studies either do not mention flow conditions upstream from jet formation or suppose laminar upstream flow, whereas from literature focusing on jet development it is known that initial conditions, i.e. upstream flow conditions, will affect jet formation and downstream flow dynamics. Since jet formation is an essential part of sibilant fricative production, it is motivated to reflect on the potential impact of upstream flow conditions on jet formation and on the subsequent noise produced within the framework of sibilant fricative production. In order to ascertain decorrelated geometrical and flow properties and in order to ascertain a pertinent geometry, we rely not on a human speaker, but on a reconstructed – and hence constant – vocal tract geometry obtained from a cone-beam computed tomography (CT) scan during production of the phoneme /s/. We measured the acoustic outcome for airflow through this geometry for different upstream flow profiles.

2 Method

2.1 Reconstructed geometry

A cone-beam CT scan (CB MercuRay, 512 slices of 512×512 pixels with accuracy ±0.1mm) was made for a single adult male subject ‘KN’ (Japanese native speaker, normal sitting position) while uttering phoneme /s/ at ‘medium’ loudness level (≈21/1 min), so that the articulators positions (teeth, tongue, lips) corresponded to a sibilant /s/ sound articulation. The imaging process lasted about 10s. The oral cavity volume and its shape were reconstructed using a marching cube method and an optical modeling machine (SOU 2 600GS, material TSR-829) with spatial accuracy ±0.1mm [10, 9]. Consequently, the combined maximal error resulting from the imaging process and the optical reconstruction yielded ±0.2mm. The reconstructed geometry (sectional CT scan data slice) is depicted in Fig. 1(a) and a sectional view and front of a three-dimensional plaster model is illustrated in Fig. 1(b). The length of the reconstructed portion is 37mm. The minimum area within the constricted passage of length ≈ 22mm yielded 3.5mm² corresponding to a minimum hydraulic diameter of 2.1mm. The inlet portion of the reconstructed portion is of elliptical shape (major axis 17mm and minor axis 11mm) with hydraulic diameter 13mm. A mechanical vocal tract replica for sibilant /s/ was obtained by smoothly connecting an upstream circular duct, shown in Fig. 1(c) with length 120mm, inlet diameter 20mm and outlet diameter 8 mm, to the rigid reconstructed geometry (plaster or transparent) with elliptical inlet. The length of the connecting portion is 30mm so that based on the converging angle (9°) the flow in the connecting portion is un stalled [1].

The upstream circular duct represents the portion of the vocal tract from the larynx up to the reconstructed portion characterising /s/. In the following, upstream flow conditions are determined at the outlet of the circular duct (exit diameter 8mm or area A = 50mm²). The total length of the mechanical replica was 18cm which corresponds to the averaged length of the vocal tract of an adult male subject [3, 14]. The complete replica is illustrated in Fig. 1(d).

2.2 Flow supply and flow measurements

Airflow is provided to the replica illustrated in Fig. 1(d) in different ways. Firstly, a human subject blows into the replica. Secondly, a flow facility is used to provide airflow at a constant pressure. The flow facility consists of an air compressor (Atlas Copco GA7), followed by a pressure regulator (Norgren type 11-818-987) providing an airflow at constant pressure. The volume flow rate Q is controlled by a secondary manual valve placed downstream the regulator and measured by a thermal mass flow meter (model 4043 TSI) with an accuracy of 2% of its reading. To homogenize the flow, a settling chamber is used with volume 0.4×0.4×0.5m³ to which a series of 3 perforated plates with holes of diameter 1.5mm (spaced 0.8mm) are added. The walls of the settling chamber are tapered with acoustic foam (SE50-AL-ML Elastomer Solutions) in order to avoid acoustic resonances. In addition, a grid can be inserted between the settling chamber and the replica.

In order to characterize flow conditions, the flow velocity is measured at the exit of the circular upstream duct using hotfilm (TSI 1201-20) in combination with a IFA 300 anemometer (TSI). The hot film is calibrated according to the technique described in [4] which results in a calibration curve fitted on a fourth order polynomial law. The hot film is mounted on a two dimensional stage positioning system (Chuo preci-
at 5kHz during ≥ 4s consecutively for human blowing and 30s consecutively for flow facility use. Statistical quantities (first up to the fourth moment) of the velocity distribution at each spacial position are obtained from instantaneous velocity measurements to which a 10Hz high pass filter and a 10kHz low pass filter is applied. The local mean velocity \( U_L \), local turbulence intensity \( T_u \), skewness \( S_u \) and flatness \( F_u \) are considered as a function of centerline velocity Reynolds number \( Re_u = U_c D/ν \) with kinematic viscosity of air \( ν = 1.5 \times 10^{-5} \text{m}^2/\text{s} \), in order to characterise the initial flow conditions upstream from the reconstructed portion [12].

### 2.3 Acoustic measurements

Acoustic measurements with the reconstructed geometry for different flow supplies described in the previous section 2.2, i.e. human blowing, flow facility with grid and flow facility without grid, were conducted using a quasi-anechoic chamber [15] by connecting the outlet of the replica to the opening into the quasi-anechoic chamber as illustrated in Fig. 2. The quasi-anechoic chamber has dimensions 2.07m×2.10m×2.14m (volume 9.3m³) and is equipped with a pressure-field Bruel & Kjaer microphone (B&K 4192, frequency response 20Hz-20kHz, preamplifier B&K 2669 and +30dB B&K amplifier 5935). The microphone (sampling frequency 44.1kHz) was located at the same height as the replica but with an angle of 37° with respect to its centerline, in the horizontal plane. The volume flow rates were chosen following loudness instructions suitable to characterize fricatives [6]: ‘soft’ (≈11l/min, bulk velocity \( U_b ≈ 4\text{m/s} \), ‘medium’ (≈21l/min, bulk velocity \( U_b ≈ 7\text{m/s} \) and ‘loud’ (≈45l/min, bulk velocity \( U_b ≈ 15\text{m/s} \)). A qualitative estimation of the volume flow rate associated with each loudness level was obtained using the volume flow meter (TSI-4000 series) in combination with the loudness instruction and confirmed by integration of the transverse mean velocity profile. An overview of the loudness instruction and corresponding volume flow rate \( Q \) and centerline velocity Reynolds number \( Re_u \) at the exit of the circular tube shown in Fig. 1(c), is given in Table 1.

Spectral features of the radiated acoustic pressure signals are derived from the acoustic spectra \( L_p \) as a function of physical frequency \( f \). The acoustic spectra are obtained as the energy normalized sound pressure level (SPL) of the Welch averaged Power Spectral Density \( P(f) \) of the measured acoustic pressure signal [17, 6]:

\[
L_p(f) \approx 10 \cdot \log_{10} \left( \frac{P(f)}{P_{ref}} \right),
\]

with \( P_{ref} = 2 \cdot 10^{-5} \text{Pa} \). Concretely, the time-averaging of the periodograms is performed using Hamming windowed energy normalized time segments of fixed length (6ms) with

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<td>Soft</td>
<td>11</td>
<td>2850</td>
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<tr>
<td>Medium</td>
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### 1. Summary of flow conditions for human blowing

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**Figure 1:** a) Illustration of CT scan data slice during an /s/ utterance showing the characterizing constricted airflow passage. b) Three-dimensional plaster reconstruction of a human oral cavity while pronouncing /s/ (dimensions in mm). c) Upstream circular duct and d) Complete replica consisting of upstream circular duct (pink, length 120mm) to which the three-dimensional reconstructed geometry (blue, length 37mm) is smoothly (green, length 30mm) mounted.

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**Table 1:** Summary of flow conditions for human blowing used for acoustic measurements: loudness instruction and corresponding volume flow rate \( Q \) and Reynolds number \( Re_u \) at the exit of the circular tube shown in Fig. 1(c).
50% overlap. The sound pressure level spectra are parameterised by considering the total power of the acoustic pressure signal $P$, dynamic amplitude $A_d$, peak frequency $f_0$, and spectral linear regression slopes $S_1$ ($f_{\text{min}} \leq f \leq f_0$, with $f_{\text{min}}$ the frequency associated with minimum spectral amplitude, positive slope) and $S_2$ ($f_0 \leq f \leq 20\text{kHz}$, negative slope) in accordance with features exploded for human fricative phoneme characterisation [6, 14].

Figure 2: Overview of acoustic measurement setup. The microphone is positioned at an angle of $37^\circ$ with respect to the main airflow direction in the horizontal plane $(xz)$.

3 Results

3.1 Upstream flow characterisation

In this section, we evaluate the impact of the used air supply on initial flow conditions from velocity measurements at the exit of the circular duct (shown in Fig. 1(c), following the methodology outlined in section 2.2). Transverse velocity profiles from the duct center ($y/D = 0$) up to the duct wall ($y/D = 0.5$) are illustrated in Fig. 3 for different air supplies (human blowing or flow facility use for $Re_c \approx 1800$ or $Q \approx 71/\text{min}$) and Reynolds numbers $Re_c$ (flow facility for $Re_c \approx 1800, 4000, 12000$ or $Q \approx 7, 18, 55/\text{min}$). Normalized mean transverse velocity profiles $U/U_c$ (Fig. 3(a)) are characterized by an almost uniform ($U/U_c > 0.9$) core region ($|y/D| < 0.3$) regardless of flow supply or Reynolds number $Re_c$. The normalized mean velocity profile within the boundary layer enveloping the core region is observed to depend on the Reynolds number and less on the flow facility. The measured mean velocity profiles approximate therefore a top-hat velocity profile for which the boundary layer displacement thickness depends on Reynolds number [12]. As a result, mean velocity profiles characterizing laminar or turbulent pipe flow are not relevant as illustrated in Fig. 3(a). The corresponding transverse profiles of the turbulence intensity (Fig. 3(b)) are affected significantly by Reynolds number $Re_c$ ($\Delta T_u \geq 2\%$) as well as air supply ($\Delta T_u \geq 4\%$) regardless of transverse position $y/D$, i.e. the turbulence intensity varies within the core region as well as within the boundary layer depending on flow supply or Reynolds number $Re_c$. Moreover, it is seen that turbulence intensities associated with human blowing are high compared to those resulting from flow facility use and this within the core region as well as within the boundary layer.

In order to characterize initial flow conditions further, velocity moments at the center of the duct ($y/D = 0$) are considered (Fig. 4) as a function of Reynolds number 500 < $Re_c$ < 15000 (1 < $U_c$ < 25) and flow supply (see section 2.2: human blowing, use of flow facility without and with additional inlet grid). The centerline turbulence intensity $T_u$ (Fig. 4(a)) is seen to be largely affected by the flow supply since turbulence intensities observed for human blowing ($T_u \geq 3\%$) exceeds the turbulence level for turbulent flow when using flow supply without ($T_u \leq 2\%$) and with an inlet grid ($T_u \leq 3.2\%$). Increasing the Reynolds number $Re_c$ is seen to result in an increase of the turbulence intensity $T_u$ regardless of the flow supply. It is further noted that, whereas for human blowing turbulent flow is observed regardless $Re_c$, increasing the Reynolds number is seen to trigger a transition of laminar ($T_u < 0.5\%$) to turbulent flow. The use of an inlet grid is seen firstly to decrease Reynolds numbers at which transition from laminar to turbulent regime occur (e.g. reduces the transition onset from $Re_u \approx 7000$ to $Re_u \approx 2000$) and secondly to favor the turbulence intensity level the turbulent regime as is expected for grid turbulence. The increase of the turbulence intensity with Reynolds number is in contrast with the decrease of turbulence intensity expected for pipe flow, but in case of human blowing the tendency can be expressed by a quadratic polynomial law for which the coefficient of determination yields

Figure 3: Transverse ($0 \leq y/D \leq 0.5$) velocity profiles as a function of Reynolds numbers $Re_c$ and air supply – human blowing ($\circ, \bullet$) and flow facility use ($+, \times, \triangle$): a) normalized mean velocity $U/U_c$ (symbols) and developed laminar (full line – parabolic) and turbulent (dashed line – power-law) pipe flows, b) turbulence intensity $T_u$. 

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Figure 4: Centerline initial velocity statistical features as a function of Reynolds number $Re_c$ and flow supply (human blowing – filled circle, flow facility without (+) and with (×) inlet grid). The gray shaded area indicates the feature range covering 95% of the values observed for human blowing: a) turbulence intensity $Tu_{c,c}$ and a quadratic fit (full line) of $Tu_{c,c}(Re_c) (R^2 = 0.5)$, b) skewness $Su_{c,c}$ and $Su_{c,c} = 0$ (dashed line) and c) flatness $Fu_{c,c}$ and $Fu_{c,c} = 3$ (dashed line).

$R^2 = 0.5$. Moreover, it is observed that the turbulence intensity increases more rapidly when the flow is supplied by human blowing than when a flow facility is used. The skewness $Su_{c,c}$ (Fig. 4(b)) and flatness $Fu_{c,c}$ (Fig. 4(c)) of the center velocity distribution as a function of Reynolds number further illustrates the impact of the flow supply on initial flow conditions. Values characterizing a Gaussian velocity distribution ($Su_{c,c} = 0$ and $Fu_{c,c} = 3$) provide an approximation for human blowing regardless the Reynolds number $Re_c$ and provide a poor description for the values observed when a flow facility is used, e.g. for Reynolds numbers $Re_c$ associated with the transition regime.

### 3.2 Acoustic characterisation

In the previous section 3.1, a significant variation of initial flow conditions due to varying the flow supply is shown and quantified in terms of statistical moments. From the characterization of the initial velocity profile discussed in section 3.1, it is seen that assessed flow conditions when a flow facility is used correspond to a Reynolds number $Re_c$ within the laminar, transition and turbulent regime. In order to search the influence of the variation of initial flow conditions on the variation of the radiated noise outcome we consider acoustic features derived from the gathered sound spectra as outlined in section 2.3 with the setup illustrated in Fig. 2. The power of the acoustic signal $P$, dynamic amplitude $Ad_f$, frequency with maximal acoustic energy $f_{max}$ and spectral slopes $S_{1,2}$ are plotted in Fig. 5 as a function of Reynolds number $Re_c$ for different air supply methods. For air supplied by human blowing we consider a limited number of flow conditions summarized in Table 1 resulting from the loudness instructions (‘soft’, ‘medium’ or ‘loud’) and we will vary the Reynolds number $Re_c$ within this range for air supplied using the flow facility (with grid and without grid). The general tendencies of the acoustic features are similar regardless the air supply and are within the range of values observed for air supplied by human blowing. Nevertheless, important quantitative differences are seen to occur, which are observed to increase with Reynolds number $Re_c$ when considering air supplied by the air facility with and without grid. This last observation points to a different contribution of the velocity fluctuations to the noise produced following different inlet condition, which following Fig. 4 becomes more important as the Reynolds number increases. Concretely, the measured acoustic power $P$ (Fig. 5(a)) and dynamic amplitude $Ad_f$ (Fig. 5(b)) increases strongly ($P$ with $\approx 50\%$ and $Ad_f$ with $\approx 25\%$) for Reynolds numbers in the range $Re_c \approx 7000$ when a grid is used whereas the transition regime seems to limit $P$ and $Ad_f$ in absence of a grid. The same way, the magnitude of the negative spectral slope characterizing the high frequency range $S_2$ is more important ($S_2$ with $\approx 25\%$) in absence of a grid than when a grid is used. The variation in terms of positive spectral slope characterizing the lower frequency range $S_1$ is less pronounced. The same holds for the variation observed for the frequency $f_{max}$ associated with maximal spectral energy. In both cases we observe an important dynamic with Reynolds number $Re_c$ such as the shift in $f_{max}$ $\approx 7.5$ kHz for $Re_c \leq 3500$ to $f_{max} \approx 11$ kHz for $Re_c > 3500$. Note, that despite the constant geometry small differences are still observed ($\leq 10\%$ for $f_{max}$). With respect to the features derived for human blowing it is interesting to note that for $Ad_f$ and $P$ observed values approximate values obtained for air supply with a flow facility without grid use, whereas for spectral slopes and in particular for $S_2$ acoustic features resulting from human blowing approximate features observed for air supplied with a flow facility with grid. Finally, it is seen that for high Reynolds numbers frequency associated with maximum spectral energy is increased compared to values obtained using a flow facility.
4 Conclusion

The current paper showed based on an analysis of acoustical features of noise produced from flow through a reconstructed and constant geometry (vocal tract during phoneme /s/) that the variation of flow properties upstream from the sibilant groove influence the spectral properties of the noise produced. This is an important finding since initial flow conditions are not considered in physical speech production studies. The current experimental results show that initial conditions need to be quantified and can not be neglected.

References


Figure 5: Spectral features of acoustic signal as a function of air supply and resulting flow conditions (human blowing, compressed air with and without inlet grid).