The effect of acoustical feedback on buzzing. From lips to vocal folds ?

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Introduction

The interaction of expiratory airflow with the vocal folds tissues is known to be the primary source of human voiced sound production. The airflow through the larynx induces instability of the vocal folds. The resulting vocal fold vibrations modulate the airflow giving rise to a periodic sequence of pressure pulses which propagates through the vocal tract and is radiated as voiced sound. Modeling of the ongoing fluid-structure interaction and the vocal fold oscillations is important in the understanding of phonation, the synthesizing of voiced sound and the study of voice disorders.

Physical modeling of the vocal folds and the 3D fluid-structure interaction between the living tissues and the airflow has a long and rich history [4]. Simplifications of the physical reality are favoured due to a historical interest for speech control and synthesis applications which requires a limited number of physiological meaningfull and measurable model parameters. Therefore physical models strive to represent the main features of phonation while assuming severe simplifications in the biomechanical structure and fluid mechanical flow modeling.

A major simplification in the physical models is the assumption of the separation or the independence of voice source and filter. The source-filter separation neglects pressure reverberations in the vocal tract and as such assumes no impact of acoustical feedback on the dynamics of vocal folds oscillations.

The wide and successfull application of the resulting vocal folds models proofs the assumption to hold in normal speech conditions. However the hypothesis is shown to be of limited efficiency in abnormal speech conditions like singing or pathologies. Under these conditions the source is coupled to the vocal tract and/or the trachea meaning that pressure reverberations may return to the vocal folds and hence influence vocal folds oscillation. Therefore the impact of the delayed feedback of acoustical pressure reverberations on the vocal fold dynamics need to be considered. The time delay is determined by the speed of sound.

The study of acoustical feedback in speech benefits from the study of wind instruments in musical acoustics where acoustical coupling is an essential feature in the sound generation process [2, 3].

The approach presented in [2] is applied to study the effect of acoustical feedback on a lip replica [5] oscillatory behaviour. The on- and offset of oscillation for different mechanical boundary conditions is discussed considering oscillatory frequency and lung pressure as control parameter. The results are discussed with respect to vocal folds.

Experimental procedure

The replica and experimental set-up is detailed in [5]. Briefly the replica (width 0.024m), either presenting lips or vocal folds, consists of two connected latex tubes filled with water. The internal pressure P_{in} is imposed and controlled before and during each experiment, which is referred to as the constant volume operation mode in [5]. An upstream pipe (length L_u=0.36m) connects the replica to a volume reservoir ($V_l = 0.68m^3$) supplying a static pressure P_l. To study the effects of acoustical feedback and the relevance of the replica as either lip model are vocal fold model experiments have been performed without (L_d=0m) and with a downstream pipe of length L_d=0.49m (typical for a musical instrument) and L_d=0.16m (typical for a vocal tract). The pipes diameter yields $0.03m$. The pressures just upstream P_u and just downstream P_d of the replica were measured. The replica-opening H and lip oscillatory frequency (in dynamical experiments) was measured by means of an optical system as in [2]. The transfer function between H and a broad band noise signal driving a loudspeaker placed just downstream at $L_d = 0$ is used to determine the mechanical response of the replica. Without flow $P_l = 0$ the replica is just closed when $P_{in} = 9.1kPa$. The mechanical response of the replica is measured for $P_{in} \leq 9.1kPa$. The threshold $P_{l,th}$ for sustained oscillation to occur was determined by listening to the sound-production of the set-up and confirmed by the appearance of a line spectrum in the frequency response.

Modeling of replica dynamics

A two-degree of freedom model has been used to predict the self-sustained oscillations of the replica in the test set-up. The replica is modelled as a one degree of freedom one-mass spring-mass-damper system. This approach is proposed by [2] in order to model the lips of a brass player assuming small variations around equilibrium. In [1] one-delayed-mass model of the vocal folds is derived from the original two-mass model. After linearisation the dynamics is described by

$$\frac{d^2h}{dt^2} + \frac{\omega_L}{Q_L}\frac{dh}{dt} + \omega_L^2 h = -A_d p_d + A_u p_u, \qquad (1)$$

where h is the alternating part of the replica opening $H = \overline{h} + h$, ω_L is the mechanical resonance of the replica, p_d and p_u are the alternating parts of respectively P_d and P_u and A_d and A_u are the corresponding ratios of the effective surface areas and the effective mass of the replica [2]. The factors A_d and A_u are positive for an outward striking valve and negative for an inward striking valve. The acoustics of the upstream (i=u) or downstream (i=d) pipe are taken into account by assuming a single acoustical resonance $\omega_i = 2\pi f_i$. With $p_i = d\psi/dt$, Q_i the quality factor, Z_i the peak value of the acoustical impedance at ω_i and ϕ_i the unsteady component of the volume flow through the replica the following equation holds:

$$\frac{d^2\psi}{dt^2} + \frac{\omega_i}{Q_i}\frac{d\psi}{dt} + \omega_i^2\psi = \frac{Z_i\omega_i}{Q_i}\phi_i. \qquad (2)$$

Neglecting pressure losses in the ducts, using a quasi-steady incompressible flow approximation and with ρ the mean density of air, $\overline{u}$ the mean flow velocity and $\overline{p}_l$ the upstream lung pressure and applying flow conservation results in respectively equation 3 and equation 4 in case of the lips [2] and vocal folds [1]:

$$\phi_i = \left(-\frac{b\overline{h}}{\rho\overline{u}}\right)(p_d - p_u) + (b\overline{u})\,h, \quad \overline{u} = \sqrt{\frac{2\overline{p}_l}{\rho}} \qquad (3)$$

$$\phi_i = \left(-\frac{b\overline{h}}{1.4\rho\overline{u}}\right)(p_d - p_u) + (b\overline{u})\,h, \quad \overline{u} = \sqrt{\frac{\overline{p}_l}{0.69\rho}} \qquad (4)$$

Applying linear stability analysis as in [2] allows to obtain the oscillation frequency f_{res} and threshold $P_l = P_{l,th}$ from the eigenvalues of the system. In the next section experimental results are compared to model predictions.

Results

Part a of Figure 1 shows the measured $P_{l,th}$ for the onset of self sustained oscillations for different values of P_{in} and L_d. A minimum $P_{l,th}$ is reached at $P_{in} = 9.1kPa$. The threshold $P_{l,th}$ and the uncertainty are much higher without ($L_d = 0m$) as with ($L_d = 0.49m$) acoustical feedback. Measured values for $L_d = 0m$ and $L_d = 0.16m$ are similar. The lack of stability without acoustical feedback indicates that the replica is a poor vocal fold model since vocal folds do not display a strong coupling with acoustical resonances. Part b of Figure 1 illustrates the influence of L_d on f_{res} as function of P_l for $P_{in} = 9.1kPa$. As a reference the lines corresponding to the quarter wavelength resonance frequencies $f_u = 240Hz$ and $f_d = 170Hz$ of respectively the upstream pipe $L_u = 0.36m$ and $L_d = 0.49m$ are indicated. For $L_d = 0.49m$ f_{res} is close to the pipe resonance $f_d = 170Hz$. In case of $L_d = 0m$ and $L_d = 0.16m$ two different oscillation modes are observed depending on P_l. For $P_l \leq 5kPa$ the found f_{res} is close to the third mechanical resonance ($\pm 230Hz$) and above $P_l \geq 6kPa$ f_{res} drops to the second mechanical resonance ($\pm 160Hz$). The data obtained from the transfer function measurements are used as input to a linear stability analysis of the one-mass-model from [2] and [1] in case of the lips and the vocal folds as outlined in the previous section. The predicted $P_{l,th}$ and f_{res} as function of P_{in} for $L_d = 0.49m$ are illustrated in respectively part c and d of Figure 1. The peak in $P_{l,th}$ around $P_{in} \simeq 7500Pa$ coincides with a change from the third to the second mechanical resonance from low to high P_{in}-values. The one-mass-model fails to predict the observed oscillatory frequencies for $L_d = 0m$ and $L_d = 0.16m$ which is in agreement with the findings of [2]. Differences with the observations described in [2] are probably due to differences in mechanical boundary conditions, which stresses the importance of the boundary conditions as in [5].

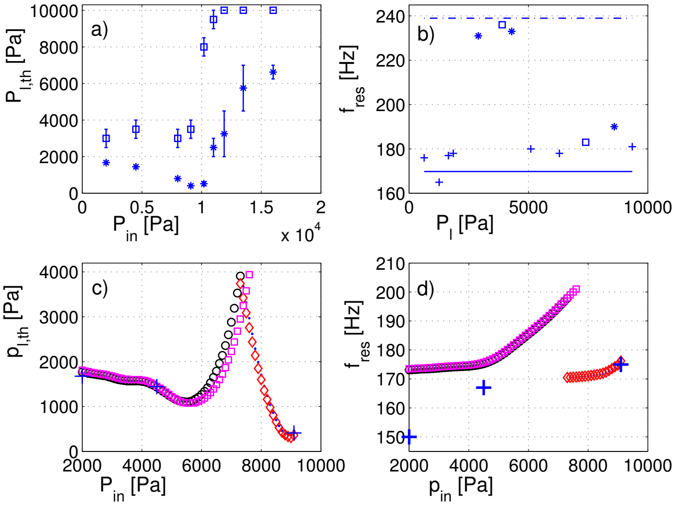

Figure 1: (a) measured $P_{l,th}$ as function of P_{in} for $L_d = 0m$ [□] and $L_d = 0.49m$ [+]. (b) measured f_{res} as function of P_l for $L_d = 0m$ [□], $L_d = 0.16m$ [$*$] and $L_d = 0.49m$ [+]. The full and dotted lines indicates $f_d = 170Hz$ and $f_u = 240Hz$. (c) predicted $P_{l,th}$ as function of P_{in} for $L_d = 0.49m$ (d) predicted f_{res} as function of P_{in} for $L_d = 0.49m$. In (c),(d) corresponds [□], [◇] to lip and [o], [•] to vocal fold model predicted values obtained with respectively the third and second mechanical resonance ω_L, [+] indicates measured values.

Conclusion

The replica is found to be a good model restricted to conditions where there is a strong coupling between downstream acoustics as is the case for lips, but not for vocal folds. In these conditions $P_{l,th}$ and f_{res} are well predicted by a linear stability analysis of the one-mass model.

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