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COMPUTER MODELLING OF RELATIONS BETWEEN GLOTTAL AREA VARIATION AND SOUND PRESSURE LEVEL AT THE VIBRATING VOCAL FOLDS

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Summary: *The radiated sound pressure level (SPL) during phonation is known to be mainly regulated by lung pressure and glottal resistance (adduction), at the glottal level. Few results of glottal area variation in SPL control have been presented. The present study investigated the interrelations between sound pressure level at the supraglottal end of the glottis (SPL_{source}) and lung pressure, maximum amplitude of vocal fold vibration and maximum glottal area declination rate for different fundamental frequencies and prephonatory glottal widths (corresponding to phonation type). These data were generated by an aeroelastic model used for numerical simulations of vocal fold self-oscillations including the vocal folds collisions. The relations of SPL_{source} to the parameters studied were in general non-linear.*

1. Introduction

Subglottic (lung) pressure and laryngeal resistance are the main glottal parameters in the control of radiated sound pressure level during phonation (e.g. Isshiki, 1964). *SPL* has been reported to be a linear function of P_{sub} (Sundberg *et al*., 1999, 2005). Glottal flow velocity waveform, in other words the voice source, obtained by inverse filtering, has been studied extensively, for instance in relation to *SPL*.

In amplitude domain the first derivative of the voice source has been investigated, since it reflects the rate of change in the *AC* flow. The maximum flow declination rate (*MFDR*) of the glottal *AC* flow (the negative peak amplitude of the first derivative of the glottal flow velocity waveform) has been found to correlate strongly with sound pressure level (Fant, 1982; Holmberg *et al*., 1988; Gauffin and Sundberg, 1989; Sundberg *et al*., 1999) and with the slope of the source spectrum (Gauffin and Sundberg, 1989).

According to some studies, the relation between *MFDR* and *SPL* (e.g. Gauffin and Sundberg, 1989, Sundberg *et al*., 1999) is linear. However, there are also results suggesting that the relation between *MFDR* and *SPL* are not linear but that the increase in *MFDR* is more rapid at the lower end of the *SPL* range and that a plateau is reached at the highest *SPL* values (Fant *et al*., 1997; Alku *et al*., 1998, 1999; Vilkman *et al*., 2000, 2002). The amplitude

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quotient (*AQ*), obtained by dividing the peak-to-peak *AC* flow by the absolute amplitude of the negative peak of the first derivative of the flow waveform, has been used to characterize the voice source (Alku and Vilkman, 1996). Later, the normalized amplitude quotient (*NAQ*) was introduced (Alku *et al.*, 2002). There the effect of fundamental frequency (F_0) has been taken into account by multiplying *AQ* by the period length. *NAQ*, measured from two amplitude domain variables (maximum pulse amplitude in flow in litres per second and *MFDR* in flow in litres per second squared) gives a measure of glottal closing phase in seconds (for pulses with the shape of a triangle with a 90 degree angle, *NAQ* equals closing time (see Vilkman *et al*., 2002). *NAQ* decreases when *SPL* increases (Vilkman *et al*., 2002). *NAQ* has also been reported to differentiate between phonation types (normal and breathy, i.e. hypofunctional voice, and pressed, i.e. hyperfunctional voice). In physiological terms the phonation types differ in the amount of adduction used in relation to P_{sub} (see Alku *et al*., 2002).

There are few studies about glottal area variation in relation to *SPL*. A decrease in the relative glottal open time (open quotient, *OQ*, i.e. open time of the glottis divided by the period length) with rising *SPL* was reported by Timcke *et al.* (1958), using high-speed filming. Sonesson (1960), using photoglottography, reported a decrease in *OQ* and increase in speed quotient (*SQ*, i.e. opening time of the glottis divided by the closing time), the latter reflecting a relatively faster glottal closing, as *SPL* was increased. However, investigation of glottal area variation is inaccurate. Reflections and leakage of light through the tissue impair the reliability of photoglottography. The registration speed of even high-speed filming is not high enough. Furthermore, the study of the relations between P_{sub}, *SPL* and glottal flow parameters in human subjects is complicated by the fact that many parameters may vary simultaneously. For instance, F_0 tends to rise with *SPL* (Gramming *et al*., 1988; Vilkman *et al*., 2002) and also phonation type may change, both in raising *SPL* and in raising F_0.

In the present study a computer model was used to investigate the relations of SPL_{source} to P_{lungs}, maximum glottal opening (*GO*), which reflects the amplitude of vibration of the vocal folds, maximum area declination rate (*MADR*), and maximum area inclination rate (*MAIR*) for different F_0 levels and for different prephonatory glottal halfwidths (g_0), which reflect phonation type. Factors underlying *MADR* (amplitude *A* of the glottal area variation, and mean airflow rate *Q*) were also concerned.

2. Method

A. Aeroelastic model of the vocal fold self-oscillations

An aeroelastic computer model (see Horáček *et al*., 2005) with Hertz model of impact force during vocal fold collisions was used for the inspection of the glottal area variation during vocal fold vibration in relation to quantities encountered in speech modelling. The model has been tested (see Horáček *et al*., 2004 and 2005) and it has been found to yield values that correspond well with values obtained with living subjects and with excised larynges. A schematic presentation of the model can be seen in Fig. 1 and a brief description of the model is as follows.

The equation of motion for the two degrees of freedom vocal fold model can be written as

$$\overline{\mathbf{M}}\,\ddot{\mathbf{V}} + \overline{\mathbf{B}}\,\dot{\mathbf{V}} + \overline{\mathbf{K}}\,\mathbf{V} + \mathbf{F} = \mathbf{0}, \tag{1}$$

where $\overline{\mathbf{M}}, \overline{\mathbf{B}}, \overline{\mathbf{K}}$ are the structural mass, damping and stiffness matrices, ${}^{T}\mathbf{V}=[V_1(t),V_2(t)]$ is the vector for rotation and translation of the vocal fold-shaped element and the force vector ${}^{T}\mathbf{F} = [F_1(t),F_2(t)]$ given by nonlinear aerodynamic forces when the glottis is open:

$$F_{1,2}(t) = \rho \sum_{i,j=0}^{2} \sum_{k,l=0}^{2} {}^{1,2}K_{i,j,k,l} \left[V_1^{(i)}(t)\right]^k \left[V_2^{(j)}(t)\right]^l, \tag{2}$$

and by collision forces superimposed with the loading by the static pressure in lungs P_{lungs} when the glottis is closed:

$$\begin{aligned} F_1(t) &= F_H(t)\frac{L/2+l-x_{\max}(t)}{2l} + P_{lungs}\, h\, x_{\max}(t)\frac{L/2+l-x_{\max}(t)/2}{2l} \\ F_2(t) &= F_H(t)\frac{x_{\max}(t)-L/2+l}{2l} + P_{lungs}\, h\, x_{\max}(t)\frac{x_{\max}(t)/2-L/2+l}{2l} \end{aligned}, \tag{3}$$

where the superscripts above V_1 and V_2 denote the order of time derivatives, $K_{i,j,k,l}$ are aerodynamic coefficients, F_H is the Hertz impact force:

$$F_H = k_H \delta^{3/2}, \quad k_H \cong \frac{4}{3}\frac{E}{1-\nu^2}\sqrt{r}, \tag{4}$$

where δ is the penetration of the vocal fold element through the contact plane (see Fig. 1), E is Young's modulus of the vocal fold tissue, ν is the Poisson ratio, and r is the radius of curvature of the impacting surfaces, approximated by the shape $a(x)$ of the vocal fold model at the contact point $x_{\max}(t)$, l defines the position of two supporting springs, and h, L are the length and thickness of the vocal folds respectively (see Horáček *et al*., 2005). Symmetrical vocal fold oscillations are assumed, and only half of the glottis is modelled.

The function

$$a(x) = 1.858\,x - 159.86\,x^2 \tag{5}$$

approximated the geometry of the vocal folds. The airflow velocity U_0 at the inlet (x=0) to the glottal region is simply related to the mean glottal volume velocity

$$Q = U_0\, 2H_0\, h \tag{6}$$

and to the static pressure in the lungs

$$P_{lungs} = 1/2\ \rho\ U_0^{\,2}\left\{H_0/\left[H_0 - a(L)\right]\right\}^2, \tag{7}$$

which is constant during vocal fold collision, and equals the subglottic pressure P_{sub}; $2H_0$ is the width of the inferior inlet of the glottis, $2g(t)$ is the time-varying glottal width (see Fig. 1). From the vocal fold tissue density ρ_h=1020 kg/m^3, thickness L=6.8 mm and length h=10 mm of the vocal folds the eccentricity e and the three equivalent masses m_1, m_2 and m_3 were calculated. The air density was considered as ρ=1.2. kg/m^3, the distance between two springs was chosen as l=0.344L, which results from an optimization of the model related to the tuning of the fundamental frequency (Horáček *et al*., 2005).

A tuning procedure was used to adjust the stiffnesses c_1 and c_2 of the supporting springs in order to approximate the fundamental frequency F_0≅100-400 Hz by setting the natural frequencies f_1=F_0, f_2=F_0+5 Hz. The damping coefficients b_1 and b_2 were adjusted in order to approximate 3dB half-power bandwidths Δf_1 and Δf_2 of both resonances; Δf_1=23 Hz, Δf_2=29 Hz was considered here (see Švec *et al*., 2000). The prephonatory glottal half-width was varied in the range g_0=0.2-0.5 mm. Considering E=8000 Pa and ν=0.4, the coefficient in the impact Hertz model k_H≅730 Nm$^{-3/2}$.

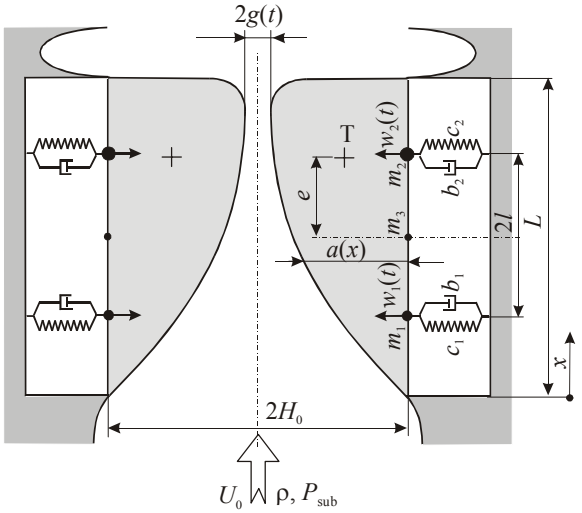


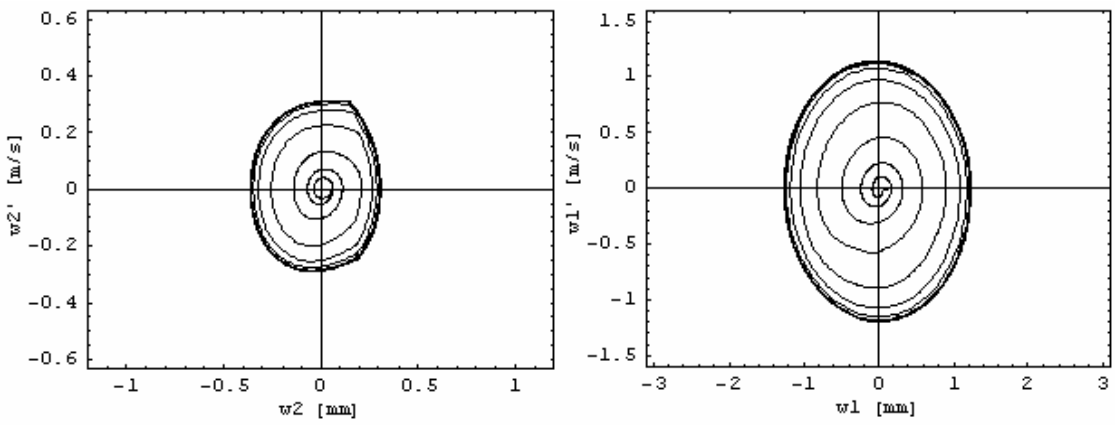
FIGURE 1. A scheme of the two degrees of freedom model for simulation of the vocal fold self-oscillations

For on-line computations, Eq. (1) was transformed into the system of four 1st order ordinary differential equations, and the 4th order Runge-Kutta method was used for the numerical simulations in time domain. The time step was varied in the range Δt=0.01-0.05 ms (smaller steps for higher F_0). An example of the output of the modelling is shown in Fig. 2.

B. Numerical simulations

The following procedure was adopted in the modelling. F_0 values were set at 100-400 Hz since these values correspond to those measured in the normal and loud speech of men and women (see e.g. Baken and Orlikoff, 2000; Laukkanen and Leino, 1999). The controlled parameter in the simulations was the mean flow velocity U_0 [m/s]. It was varied from the phonation threshold (P_{lungs} establishing loss of the aeroelastic stability of the system) up to a value which corresponds to the maximum flow rate Q=0.8 l/s, since values below that limit have been reported for normal subjects in speaking and singing (Hirano, 1981; Baken and Orlikoff, 2000). For the same reason, P_{lungs} values < 3000 Pa were considered. However, in many cases studied, the upper limit for P_{lungs} was given by the so-called phonation instability threshold pressure (*PIP*), above which the oscillations became irregular (chaotic or quasiperiodic). Prephonatory glottal width ($2g_0$) was varied in the range 0.4-1.0 mm. Glottal width values in that range can be found in the literature (Jiang and Titze, 1994; Berry *et al*., 1998 etc).

The following parameters (see Fig. 3) were automatically calculated on-line from the output quantities simulated in time domain:



(a) (b)

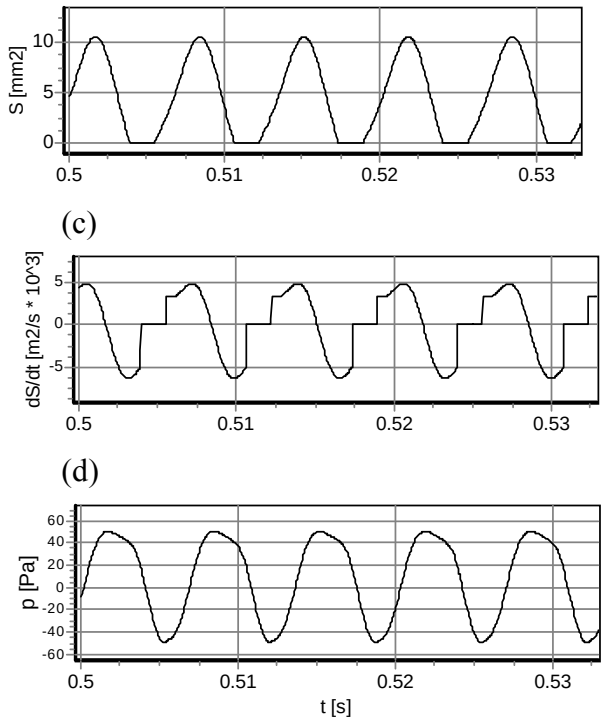


FIGURE 2. Example of the numerical simulation of the vocal fold self-oscillations: (a) and (b) motions $w_1(t)$ and $w_2(t)$ of the masses m_1 and m_2 in the phase plane in the starting phase of the simulation, (c) glottal area $S(t)$ after a limit cycle with regular impact oscillations was accomplished, (d) time derivative dS/dt of the glottal area, and (e) pressure $p(t)$ at the supraglottal end of the glottis.

a) maximum glottal opening

$$GO = \max\left(2g(\tau)\right), \quad t < \tau < t + T_0, \tag{8}$$

where T_0 is the period of self-oscillations,

b) relative closed time of the glottis, the closed quotient

$$CQ = \tau_c / T_0 \tag{9}$$

calculated from the glottal area waveform

$$S(t) = 2\, g(t)\, h, \tag{10}$$

b) speed quotient of the glottis

$$SQ = \tau_{op} / \tau_{cl}, \tag{11}$$

c) maximum area declination rate *MADR* defined as the absolute amplitude of the negative peak of the first derivative of the area waveform dS/dt,

d) maximum area inclination rate *MAIR* defined as the amplitude of the positive peak of the first derivative of the area waveform dS/dt.

MADR shows how fast the glottis closes, while *MAIR,* in turn, shows how fast it opens.

Near the phonation threshold, just before the vocal fold collisions appear, *MADR* can be estimated by the formula

$$MADR = h\, GO\, \pi\, F_0 \tag{12}$$

resulting from assumed harmonic vocal fold oscillations. After crossing the phonation threshold *MADR* can be estimated as Sundberg *et al*. (1993) estimated *MFDR* by the formula

$$MADR = k\, A\, F_0\, (SQ+1)/(1-CQ), \tag{13}$$

where k is a constant dependent on the function $S(t)$ in the closing phase, A is the amplitude of the glottal area (see Fig. 3).

SPL_{source} in dB was calculated from the air pressure $p(t)$ simulated in time domain at the end of the glottis ($x=L$-0.05 mm). The model does not include any acoustic-mechanic interaction between sub- and supraglottic spaces. In order to clarify the relations between variables and in order to make the results comparable with those reported in the literature (e.g. by Titze, 1992, 1993 and by Sundberg *et al*., 1999), P_{lungs} was also studied as normalized according to the phonation threshold pressure P_{th}. This fractional excess pressure over threshold (Titze, 1992, 1993) or normalized excess pressure P_{sen} (Sundberg *et al*., 1999) is defined as

$$P_{sen} = (P_{lungs} - P_{th})/P_{th} \tag{14}$$

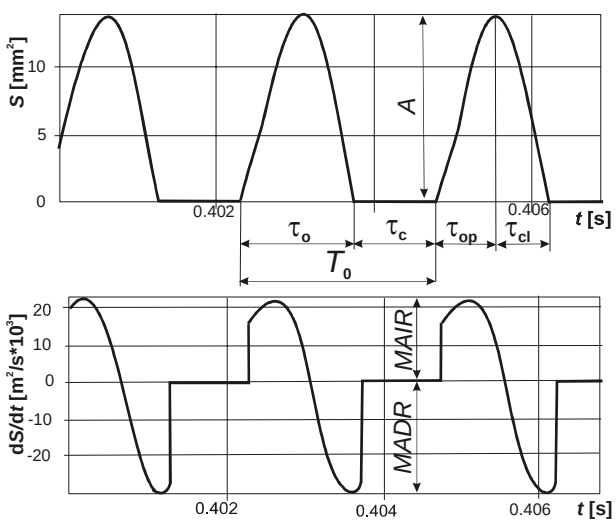


FIGURE 3. (a) Glottal area $S(t)$ and (b) time derivative dS/dt of the glottal area. T_0 is period time, τ_o is open time of the glottis, τ_c is closed time, τ_{op} is opening time, τ_{cl} is closing time, τ_c/T_0 is closed quotient CQ, τ_{op}/τ_{cl} is speed quotient SQ, A is amplitude of the glottal area, *MAIR* (maximum area inclination rate) is maximum positive amplitude of the area derivative, *MADR* (maximum area declination rate) is maximum negative amplitude of the area derivative.

3. Results

Figures 4-6 summarize the results for F_0 values of 100 Hz and 400 Hz studied.

It can be seen in Fig. 4 that, as could be expected, a higher P_{lungs} resulted in a higher SPL_{source}. The relation between SPL_{source} and P_{lungs} was not linear, however. At low P_{lungs} values the increase in SPL_{source} with P_{lungs} was very fast. A higher F_0 both required a higher P_{lungs} and also resulted in a higher SPL_{source}. This can be seen especially clearly in Fig. 4b, where SPL_{source} is shown as a function of P_{sen}. For a given $P_{lungs,}$ a smaller prephonatory glottal width yielded a higher SPL_{source} at all fundamental frequencies studied (Fig. 4a).

Figure 5 illustrates the relation between *MADR* and SPL_{source} and between *MADR* and P_{sen}. *MADR* increased together with SPL_{source} but the relation was not linear. At F_0=100-300 Hz for a small prephonatory glottal halfwidth (g_0=0.2-0.3 mm) the change in *MADR* was relatively fastest at the lowest P_{sen} values (for P_{sen} <1), while for wider glottal halfwidths (g_0=0.4-0.5 mm) the fastest relative increase in *MADR* occurred at intermediate P_{sen} values (P_{sen}=1-2.5). At F_0=400 Hz, the increase in *MADR* was already fast at the lowest P_{sen} values for all prephonatory glottal halfwidths. Except for the widest prephonatory glottal halfwidth values at F_0=300-400 Hz, a plateau in *MADR* was reached at the highest P_{sen} or SPL_{source} values. For the highest F_0 and g_0 values, a plateau in *MADR* would probably occur at higher P_{lungs} values than those considered here. For a given P_{sen}, *MADR* was higher for wider prephonatory glottal halfwidths and for higher F_0. In total, *MADR* obtained values between 0.0004 – 0.045 m^2/s.

Figure 6 shows variation of the amplitude of vibration *GO* as a function of P_{lungs} and P_{sen}. These non-linear relations can explain the non-linearities found in the relation between *MADR* and P_{lungs} or P_{sen}. At low P_{lungs} or P_{sen} values and for a small prephonatory glottal halfwidth the amplitude of vibration increased rapidly. For wide prephonatory glottal halfwidths the change in *GO* was slow at the lowest P_{sen} values. For all prephonatory glottal halfwidths the increase of *GO* with P_{lungs} or P_{sen} became slow and finally stopped at a certain point where the glottal opening obviously reached its limits. Thereafter a further increase in P_{lungs} or P_{sen} could not lead to either a higher amplitude of vibration of the vocal folds or to a faster closing of the glottis, reflected by *MADR*. The increase in *MADR* became clearly slower at those P_{lungs} or P_{sen} values where *GO* was approaching its limits. (see Fig. 5). *GO* varied between 0.5-3.1 mm in all cases, being larger for larger prephonatory glottal halfwidths. *GO* is naturally determined by the maximum dimensions of the glottal channel in the model, the prephonatory glottal halfwidth and stiffness of the vocal fold tissue, which was varied in order to vary F_0.

The absolute maximum of *GO* was about 3 times the prephonatory glottal width (2 g_0) at F_0 values 100-300 Hz, at 400 Hz it was about 2 times the prephonatory glottal width.

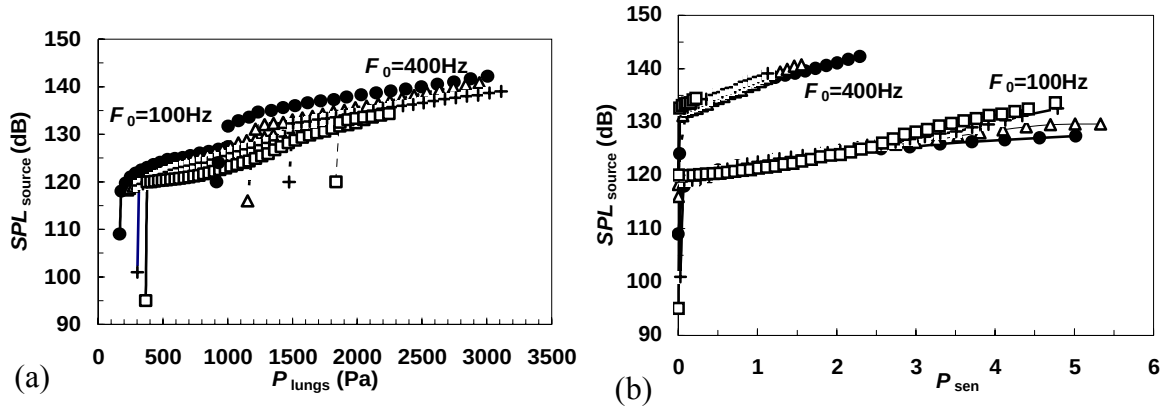


FIGURE 4. SPL_{source} at the supraglottal outlet of the glottis in relation to (a) lung pressure (P_{lungs}) and (b) normalized excess pressure (P_{sen}) for two fundamental frequencies (F_0=100 Hz and F_0=400 Hz) and four prephonatory glottal halfwidths (•...g_0=0.2 mm, Δ...g_0=0.3 mm, +...g_0=0.4 mm, □...g_0=0.5 mm).

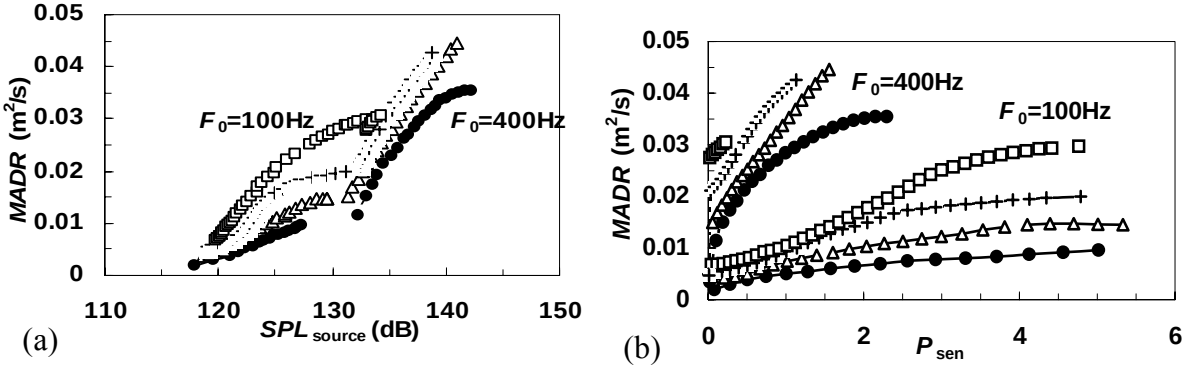


FIGURE 5. Maximum area declination rate (*MADR*) in relation to (a) SPL_{source} at the supraglottal outlet of the glottis and (b) normalized excess pressure (P_{sen}) for two fundamental frequencies (F_0=100 Hz and F_0=400 Hz) and four prephonatory glottal halfwidths (•...g_0=0.2mm, Δ...g_0=0.3 mm, +...g_0=0.4 mm, □...g_0=0.5 mm).

The increase in *GO* became very slow at about 82 % of the absolute maximum of *GO* when F_0 was100 Hz and the prephonatory glottal halfwidth g_0=0.2 mm and at F_0=400 Hz it was reached at 39% of maximum *GO*. For the wider prephonatory glottal halfwidths g_0=0.4-0.5 mm and for the highest F_0 values (300-400 Hz), the turning point of *GO* variation was most likely out of the P_{lungs} range studied.

A smaller prephonatory glottal halfwidth resulted in a higher SPL_{source}, as shown in Fig. 4. Since Figure 5 instead showed that *MADR* was lower for smaller prephonatory halfwidths, it is obvious that *MADR* alone did not account for the level of the acoustic pressure SPL_{source} generated by the model. *GO* increased together with P_{lungs} (P_{sen}) (see Figs. 6), *GO* level was lower for higher F_0, due to greater stiffness of the vocal fold.

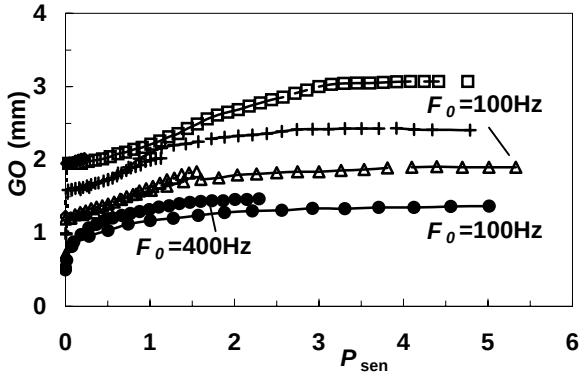


FIGURE 6. Maximum glottal opening (*GO*), reflecting the amplitude of vibration of the vocal folds in relation to normalized excess pressure (P_{sen}) for two fundamental frequencies (F_0=100 Hz and F_0=400 Hz) and four prephonatory glottal halfwidths (•...g_0=0.2 mm, Δ...g_0=0.3 mm, +...g_0=0.4 mm, □...g_0=0.5 mm).

4. Discussion

The results obtained with the model for SPL_{source} are in reasonable accordance with the principles of an approximate 6 dB increase in glottal source power for every doubling of excess pressure over threshold or for every doubling of F_0 (Titze, 1993). SPL_{source} did not seem to be a completely linear function of P_{lungs}. Instead, at lower P_{lungs} values the rise in SPL_{source} was very rapid compared to higher P_{lungs} values. This does not concur with the earlier findings of Sundberg *et al*. (1999 and 2005) for human subjects (and for radiated *SPL*). It is possible that the subjects have not started their phonation at their absolute phonation threshold values. By contrast, in modelling it was possible to increase the lung pressure in very small steps near the phonation threshold. The SPL_{source} variation range obtained in this study was ca 50 dB. Such ranges of radiated *SPL* have been reported for human subjects (Gramming, 1991; Laukkanen and Leino, 1999). Since the dB values as such were measured right above the vocal folds, they do not naturally correspond to the radiated *SPL* values reported for human subjects.

The absolute values obtained for *GO* (0.52-2.96 mm) are rational from the point of view of values reported for glottal amplitude. Berry *et al*. (1998) using a computer model of the vocal folds, joined to a vocal tract (F_0=150 Hz and P_{sub}=1000-1600 Pa), obtained a maximum vibratory amplitude of the vocal folds *GO*=1.3-1.7 mm. Titze (1993, 1999) estimated *GO* values of 1-2 mm.

Taking into account the *MADR* values obtained (0.0004 – 0.045 m^2/s) and the vocal fold length considered h=10 mm, the maximum closing speed within the model varied between 0.04 and 4.5 m/s. Vilkman *et al*. (2002) reported amplitude quotient (*AQ*) values that suggest a glottal closing time of 0.56-3.53 ms. For an amplitude of one millimetre of vibration of the vocal folds this would mean an average glottal closing speed of 0.28 – 1.79 m/s. This is naturally only a rough estimate, since *AQ*, for instance, corresponds to glottal closing time only for triangular pulses (Vilkman *et al*., 2002).

According to the results of the present study, *MADR* was in a non-linear relation to P_{lungs} and SPL_{source} the increase in *MADR* being faster at low P_{lungs} or SPL_{source} values and approaching a plateau at high P_{lungs} or SPL_{source} levels. This result seems to be in line with the results obtained by Alku *et al*. (2001) and Vilkman *et al*. (2002) for voice source parameters. However, Sundberg *et al*. (1999) reported a linear relation between *MFDR* and (radiated) *SPL*. In addition to the reason mentioned above concerning the discrepancy between modelling and measurements, we must here also take into account the fact that there is no proof of a close linear relation between *MADR*, i.e. between glottal area, and flow rate. Differences in the actual *SPL* or P_{sub} (P_{lungs}) levels studied as well as differences in interpreting the results may also explain the discrepancy between the results of the present study and those of Sundberg *et al*. (1999). On the basis of the figure (Fig. 5) presented by

Sundberg *et al*. (1999) it would be entirely feasible to conclude that the relation between *MFDR* and P_{sen} is non-linear.

The non-linearities in the changes of *MADR* as a function of P_{lungs} (or P_{sen}) seemed to be related to the non-linear increase in the amplitude of vibration (*GO*) of the vocal folds with increase of P_{lungs} (or P_{sen}). The relatively faster increase in these variables for lower P_{lungs} or SPL_{source} and for smaller prephonatory glottal halfwidths most likely reflects a vigorous co-presence of the aerodynamic, inertia and elasticity forces near the phonation threshold where the aeroelastic system crosses the stability boundaries. At higher P_{lungs} values the glottal opening *GO* reaches its limits and an increase in P_{lungs} cannot increase the amplitude of vibration or the glottal closing speed any further.

MADR was always larger than *MAIR*, which is to be expected. Glottal closing speed is the main source of acoustic excitation of the vocal tract and therefore mainly responsible for *SPL*. However, the results suggested that *MAIR* has an increasing effect on SPL_{source} at the highest intensities where *MADR* is already approaching its limits. This seems to concur with the results obtained by Alku *et al*. (2001) and Vilkman *et al*. (2002) for human subjects using inverse filtering. This secondary excitation related to glottal opening speed has also been discussed by Fant (Fant, 1997; Fant *et al*., 1987). It has been claimed that a secondary excitation cannot have much effect on *SPL* since it occurs in a phase when the glottis is open and therefore the subglottal damping is high (Fant, 1987). However, Alku *et al*. (2001) concluded that in human subjects the secondary excitation may have an effect since it occurs at the highest *SPL* levels, where also F_0 is typically high (short period time) and the voice production pressed, and therefore the effect of damping is diminished.

MADR was higher for higher F_0 and for wider prephonatory glottal halfwidths g_0 (see Fig. 6). Since glottal closing speed is related to the voice source spectrum (Gauffin and Sundberg, 1989), we might postulate that prephonatory glottal width – or phonation type – has a remarkable effect on spectral changes related to *SPL* variation. The effect of g_0 on *GO* and *MADR* was clearly dependent on $P_{lungs,}$ which is to be expected, given that phonation type is defined through the relation between adduction and P_{lungs}. At high P_{lungs} values a sufficiently wide prephonatory glottal halfwidth enabled the widest *GO* and, thus, the highest *MADR*.

For wider prephonatory glottal halfwidths, *MADR* seems to be the main determinant of SPL_{source}. The results naturally concern only glottal *SPL* and area variation. However, the results are well in line with those obtained by Alku *et al*. (2001) and Vilkman *et al*. (2002) for voice source variation in living subjects (phonating vowel [a]), using inverse filtering. It seems plausible that the voice source variation to a large extent reflects the glottal area variation. This is in accordance with the source-filter theory of voice production (van den Berg, 1958, Fant, 1960, Flanagan, 1972). As long as the glottal impedance is clearly higher than the input impedance of the vocal tract, the effect of acoustic coupling on vocal fold vibration is likely to be negligible (Rothenberg and Zahorian, 1977). This condition should hold for open vowels and for fundamental frequencies well below the first formant. On the other hand, it is of course possible, for instance, to increase the glottal flow and thus *MFDR* and *SPL* (radiated) without necessarily affecting the maximum amplitude of vocal fold vibration (e.g. in case where *GO* has reached its limits). According to Sundberg *et al*. (2005) the peak-to-peak amplitude of the glottal flow is the main determinant of *SPL* at high subglottal pressures. Fundamental frequency as such also affects *SPL* (see Fig. 5). When the period length decreases, *MFDR* or *MADR* increases. For a higher F_0 a higher P_{lungs} is also required. Furthermore, if *SPL* is calculated over several periods, the number of cycles per time unit raises the *SPL* somewhat.

5. Conclusions

According to the results obtained with an aeroelastic model of voice production for prescribed fundamental frequencies in the range of 100-400 Hz, *SPL* regulation at the glottal level was dependent on P_{lungs} level and the prephonatory glottal halfwidth g_0.

The relations of SPL_{source} and *MADR* to P_{lungs} were non-linear, the increase in these parameters with P_{lungs} being faster at lower P_{lungs}. *MADR* seemed to be the main determinant of SPL_{source}. The increase of *MADR* reached a plateau at higher P_{lungs} values together with *GO*. *MADR* was greater with a greater g_0 and a higher F_0. *MAIR* was always smaller than the absolute values of *MADR*, and therefore its role in SPL_{source} control is secondary.

The model has been tested and found to yield results comparable to those obtained in humans and with excised larynges. On the other hand, the fact that no interactions between vocal fold vibrations and the acoustic properties of the supra- or subglottal spaces are modelled may limit conclusions on the basis of the results of the present study. This needs to be investigated further.

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