
# The Coanda effect and asymmetries in vocal fold models during phonation

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The possibility of having an asymmetrical flow through the glottis (Coanda effect) is often reported in the literature as an overlooked feature which could have important effects. Assuming a certain geometry of divergent vocal folds, we show how Thwaites boundary layer theory gives an analytical result for the separation point of a subglottal jet through the glottis. This allows us to predict the width of the glottal jet when it separates from the wall as occurs in the Coanda effect. The result is in agreement with previous empirical observations of glottal jet separation width. To test the impact of the Coanda effect on vocal fold oscillations predicted by means of two mass vocal fold models, we show results of simulations with and without the asymmetric lateral pressure force induced by the Coanda effect. We study the effect with symmetrical and asymmetrical mechanical properties of the two vocal folds. We find that there is a minor effect of flow asymmetry on the result for the symmetrical vocal folds, while the effect is more complex in the asymmetrical fold case. We suggest paths for future research involving the flow separation effects on vocal fold oscillation.

# 1 Introduction

The Coanda effect has long been discussed for its contribution to the dynamics of vocal folds, among other aerodynamic phenomena. The possibility of the occurrence of the Coanda effect during the closing cycle of the vocal folds has been experimentally observed in experiments on both static and dynamic vocal fold replicas[2][4]. It was proposed in Hirschberg[3] to employ a model for a suction force imposed by the Coanda effect which utilises the boundary layer theory of Thwaites to account for the flow separation. This can be applied to two dimensional flow models of the vocal folds, of which there are many. Recently, Erath[5] have applied their own empirically derived model for the Coanda effect to a popular two mass model of the vocal folds, and have found some very interesting dynamical results. They also investigated the effect in the case of vocal folds with a mechanical asymmetry, similar to asymmetric vocal fold stiffnesses in pathological vocal folds.

The flow separation model of Hirschberg[3] differs already from that of Erath[4] in its employment of the theory of Thwaites to predict the force on the vocal folds due to the flow separation. In addition, we are interested in investigating a lumped element model of the vocal folds which has recently become of interest due to its simplicity and use of the rationale that the vocal folds move in a wave-like, "flapping" manner due to the supplied subglottal and supraglottal pressure. Hence, our basic model differs from that of [4] in that it employs this method of motion of the vocal cords, as well as the force asymmetry due to the bending jet which is calculated as a suction balance as is explain in Hirschberg[3].

# 2 Model

For the numerical experiments, we employed a lumped element physical model of the vocal folds, which operates similarly to usual two mass models, but with the rationale that the displacement of the mass further downstream eventually becomes the same as that of the one upstream after a time delay $\tau$. For simplicity, we do not assume acoustical coupling to the vocal tract or trachea, but rather simply pressure supplied by the lungs.

For the equations of motion, we determine the displacement of the vocal folds from some equilibrium point with respect to the central axis of the glottis. This displacement is calculated at the midpoint of the glottis. We have

$$\begin{aligned} M_i\ddot{x}_i + &(B_i + H(-a_{min}(x_l,x_r))Bc_i)\dot{x}_i + K_i x_i \\ &= F_s(x_l,x_r,t) + \mathbf{1}_i(t)F_{coanda}(x_l,x_r,\gamma_i,\gamma_{tot}) \end{aligned}$$

where $i = l, r$ correspond to the two opposing left and right vocal fold masses, $x_i$ their displacement from equilibrium, $M_i$ their mass, $B_i$ the damping ratio (to which is added $Bc_i$ when collision occurs between the vocal folds), $K_i$ the damping coefficient, and $F_s$ the force on the vocal folds due to subglottal pressure, $a_{min}(x_l, x_r)$ is the minimum cross-sectional width of the vocal folds, $H(x)$ is the standard one-dimensional Heaviside step function, $\mathbf{1}_R(t)$ takes the values of either 0 or 1, depending on whether the Coanda effect is applied to the left or right vocal fold, respectively, $\mathbf{1}_L(t) = 1 - \mathbf{1}_R(t)$, $F_{coanda}$ is the force we impose due to the jet bending, $\gamma_i$ is the diverging angle of the one vocal fold, and $\gamma_{tot}$ is the total angle intended by the two vocal folds. $\mathbf{1}_R(t)$ is programmed according the behavior of the jet attachment we wish to simulate, ie. $\mathbf{1}_R \equiv 1$ if the jet attaches to the right vocal fold always. Otherwise, it is randomly determined, and we assume that it stays attached to the same vocal fold until the glottis closes.

We use a wave model to determine the displacements at the glottal exit and entrance of the vocal folds. That is, for $x_{i,u}$ and $x_{i,d}$ the displacements at the glottal exit and entrance, respectively, we have $x_{i,d} = x_i(t - \tau/2)$ and $x_{i,u} = x_i(t+\tau/2)$. This gives us $a_{min} = x_{r,0} + x_{l,0} + argmin\{x_{r,u} + x_{l,u}, x_{r,d} + x_{l,d}\}$, with $x_{0,l}$ and $x_{0,r}$ the rest displacement positions of the left and right vocal folds respectively. For the force due to the subglottal pressure source, we have

$$F_s(x_l,x_r,t) = \begin{cases} \int_0^{x_s} P_B(y,t)dy, & a_{min}(x_l,x_r) > 0, \\ P_s(t)/2, & a_{min}(x_l,x_r) \leq 0. \end{cases}$$

where $P_B(y, t)$ is the pressure at distance $y$ downstream of the glottal entrance determined by applying the equation of Bernoulli from a point upstream and $x_s$ is the distance of the flow separation downstream from the glottal entrance, which is $x_s = L$ the glottal length for diverging vocal fold geometry and $x_s = 1.6a_{min}$ (see Appendix) given a diverging vocal fold geometry and the total diverging angle greater than $\pi/30$ as determined by fluid experiments with diffusors [4]. Otherwise, if the vocal folds are diverging but their total diverging angle is less than $\pi/30$, we assume separation at the glottal exit.

For the physical parameters, we set $M = M_l = M_r = 0.1$g, $K = K_r = 50$N/m, $K_l = QK$ with $Q$ varied between 0.4 and 1 to test the effects of stiffness asymmetries which correspond to vocal fold pathologies, $B_r = 0.2\sqrt{K_r M}, B_l = 0.2\sqrt{K_l M}, Bc_r = 3B_r$, and $Bc_l = 3B_l$. We used the time delay value $\tau = 0.001$ seconds. Pressure was varied between 182Pa and 1200Pa, as 182 Pa corresponds to the onset of self-sustained oscillations in our model, and 1200Pa is roughly the upper threshold of human phonation.

For the Coanda force, we apply to one vocal fold the additional suction force proposed in [3]

$$F_{coanda}(x_r, x_l, \gamma, \gamma_{tot}) = a_s \rho U_B^2(x_r, x_l, t)\sin(\gamma) \\ \times H(-a_{min}(x_r, x_l))H(\gamma_{tot} - \pi/30),$$

where $U_B$ is the air velocity at the separation point as determined by the Bernoulli equation, $\rho$ is the density of air, and $a_s$ is the cross-sectional width of the vocal tract at the separation point.

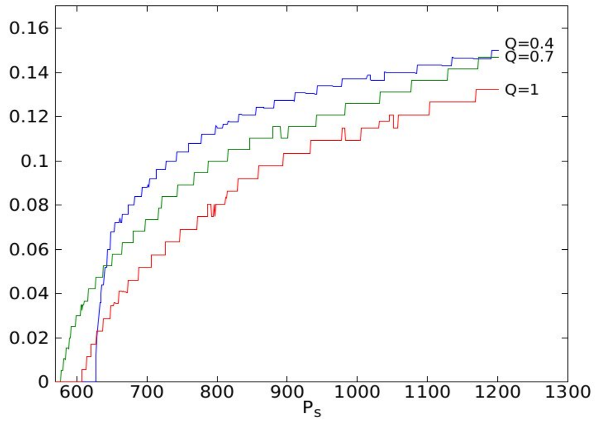
However, the main purpose of these experiments was to discover the effect of the contribution of the force due to the jet suction. Therefore, when we wanted to observe the vocal fold dynamics without the Coanda force, we would set $F_{coanda} \equiv 0$.

# 3 Results

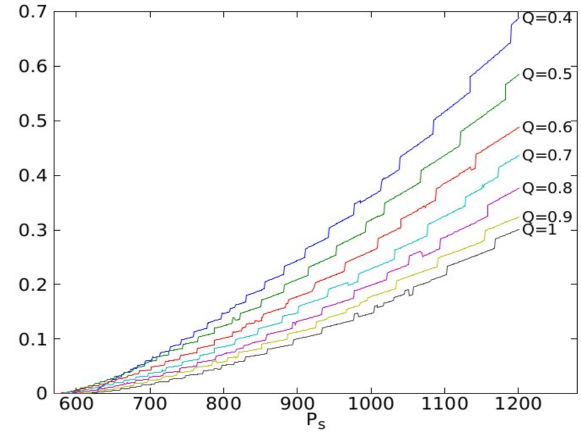
It was found (and expected) that when the two vocal folds are mechanically symmetric, there is little difference made by the Coanda effect. As in reality, the closing phase of the vocal folds is the only point during which the Coanda effect has an opportunity to occur, and this makes up about 3/10 of the entire opening-closing cycle of the folds. We found that the period of activation for the Coanda effect is generally less than 15% of the glottal cycle for typical phonation pressures, for all mechanical asymmetry values $Q$, see Figure 1(a). Further, the force imposed by the bending of the jet is not very large compared to the force of the jet before separation. We see in Figure 1(c) that the magnitude of the total contribution by the force due to the jet bending is less than 2% of the total applied force without the bending force applied. In none of in our simulations was a change in the fundamental frequency of vocal fold oscillation caused by the addition of the force due to the bending jet.

We also varied the asymmetry of the stiffness of the vocal folds, which corresponds to maladies such as vocal fold paralysis in reality. In general, as subglottal pressure increases from phonation onset, we see that below a certain threshold, the glottal angle does not surpass $\pi/30$, hence the Coanda effect does not occur, but after this threshold is passed, the Coanda effect occurs for all greater pressure values. This is visible from the commencement of the data in Figure 1.

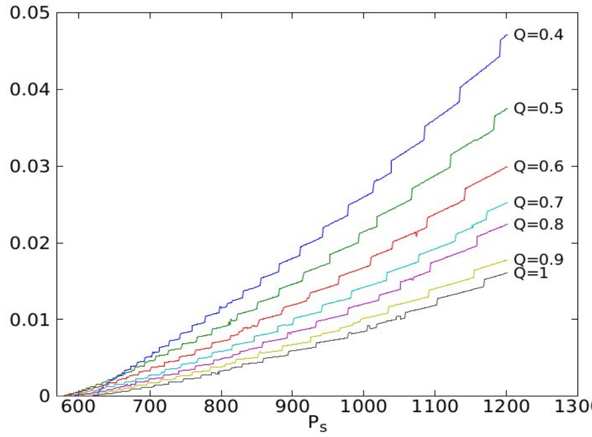
However, the contribution of the jet bending force is significant compared to the total force applied to the vocal folds during the closing cycle. The ratio of the total contribution of the jet bending force compared to the usual force is shown in Figure 1(b). For symmetric




(a) Portion of the entire glottal cycle during which the jet bending force is applied, ie. $\gamma_{tot} > \pi/30$.




(b) Fraction of the closing force due to the jet bending versus the usual closing force: $\int_{t_0}^{t_{close}} F_{coanda}\ dt / \int_{t_0}^{t_{close}} F_s\ dt$, where $t_0$ is some time at which the glottis is open and commences its closing cycle, and $t_{close}$ is the next time at which the glottis becomes closed.




(c) Fraction of the force due to the jet bending versus the usual force over the entire glottal cycle: $\int_{t_0}^{t_0+T} |F_{coanda}|\ dt / \int_{t_0}^{t_0+T} |F_s|\ dt$, where $T$ is the period of the glottal cycle and $t_0$ any time after stable oscillations commence.

Figure 1: Data for simulations with jet attachment always to the same vocal fold, ie. $\mathbf{1}_R \equiv 1$. Data for the random wall attachment had very similar profiles, with variation of less than 5% from the graphed data for the closing force and total force ratios.

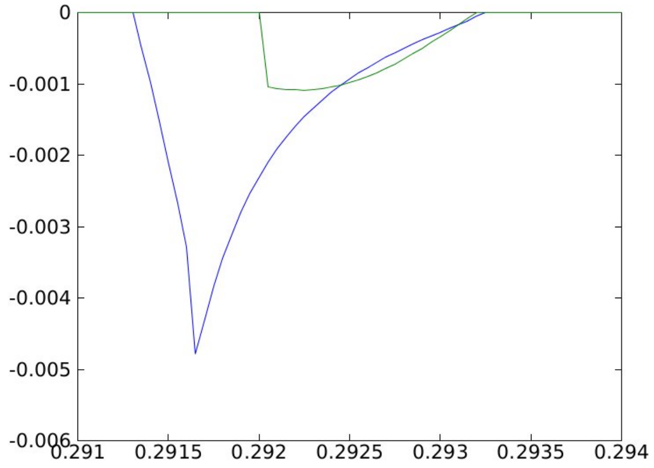



Figure 2: Typical closing force profiles, for subglottal pressure 1200 Pa and symmetrical vocal folds ($Q = 1$), and force in N/m over a duration of 3 milliseconds encompassing the glottal closing cycle. $F_{coanda}$ in green, $F_s$ in blue.

vocal folds, it climbs from 0 to about 30% at maximum subglottal pressure, while for grossly asymmetric vocal folds with asymmetry factor $Q = 0.4$, the contribution achieves nearly 70% of the usual force at the highest subglottal pressure. We show a typical profile of the usual closing force along with the jet bending force during the closing cycle in Figure 2, for symmetric vocal folds and with subglottal pressure 1200 Pa.

In addition, for the grossest mechanical asymmetry factor $Q = 0.4$ we tested, we found erratic behavior just after phonation onset where the Coanda effect was activated in a small low pressure region. This resulted in a brief difference in the vocal fold phase ratio from what would occur without the jet bending force, though even without the jet bending force this is already a quite erratic pressure region of the vocal fold oscillation.

# 4 Conclusion

For further work to be more realistic about the onset of the Coanda effect, it should be determined more accurately the criteria required to trigger the Coanda effect. The criterion that the total angle must be greater than $\pi/30$ is only based on empirical observations for static diffusors [4], and indeed triggering the onset this way in vocal fold models adds an unrealistic discontinuity in the force on the vocal folds, not to mention the jet width at separation.

Further, we should determine more accurately a precise value or the dynamics of the parameter $\tau$, as it controls how much the upper and lower vocal fold masses are in or out of phase, and hence how large is the total angle $\gamma_{tot}$. We have seen much more significant variation caused by the force due to the bending jet at values of $\tau > 0.002$ seconds, such as the Coanda effect commencing for subglottal pressures below 400 Pa, differences in fundamental frequency, and significant phase asymmetry between the left and right vocal folds when a mechanical asymmetry is imposed.

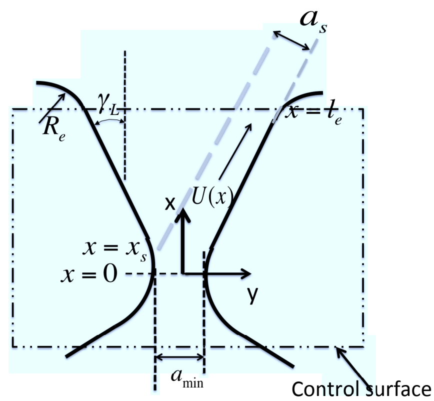



Figure 3: Sketch of the geometry of the glottis showing an asymmetric flow due to attachment of the free jet downstream of the neck to the right wall of the diverging part of the channel.

It has also been observed in flow visualisation experiments with static vocal folds that sometimes the jet bends again at the glottal exit, resulting in an additional force on whichever vocal fold the jet is attached to[6]. We have yet to develop the theory for this behavior, which we expect to be nontrivial. Further, it is erroneous to ignore the viscousness of the boundary layer of the flow in the glottis as we have done. This is not a very grave effect, but it results in a thinner effective jet thickness in the glottis. The calculation of the effect of the viscosity is suggested in [6]. We are working further on an implementation for this effect in our vocal fold model. However we believe it to be of interest to show the results of the more basic approximation for the force asymmetry as we have done as this has not been explored in the literature.

# A Derivation of jet width at flow separation

We show how to theoretically calculate the jet separation width when the Coanda effect occurs. We start with the equation of Thwaites for steady flow in a channel [8], which relates momentum thickness $\Theta(x)$ at some distance $x$ from the initial position $x_0$, which we can treat with generality as 0, and bulk flow velocity $U(x)$ in a uniform flow. The equation states

$$\Theta(x)^2 U(x)^6 - \Theta_0^2 U_0^6 = 0.45\nu \int_0^x U(y)^5 dy, \qquad (1)$$

where $\Theta_0 = \Theta(x_0)$, $U_0 = U(x_0)$, and $\nu$ is the kinematic viscosity of air.

Considering conservation of momentum $U(x)a(x) = U(y)a(y)$ for all points $x_0 \leq x, y \leq x_s$ in the steady region of the flow with $x_s$ the separatioin point (after which the flow is not assumed to be steady nor centered on a relatively straight streamline), where $a(x)$ is the cross-sectional area of the channel at point $x$, if we evaluate (1) at the separation point $x = x_s$, we find

$$\Theta_s^2 = 0.45\nu U_B^{-1} a_s^5 \int_0^{x_s} a(y)^{-5} dy + \Theta_0^2 (a_s/a_0)^6, \quad (2)$$

where $U_B$ is the bulk flow velocity at the separation point, $a_0 = a(0)$, $a_s = a(x_s)$, and $\Theta_s = \Theta(x_s)$. However, we assume that the glottal geometry is roughly linear, ie. $a(x) = a_0 + x\tan(\gamma_R + \gamma_L)$, where $\gamma_R$ and $\gamma_L$ are as in Figure 3. For brevity we denote $\gamma := \tan(\gamma_R + \gamma_L)$. This gives the integral in (2) the simpler form $\int_0^{x_s} a(y)^{-5} dy = (1/4\gamma)(a_0^{-4} - a_s^{-4})$, allowing us to write

$$\Theta_s^2 = 0.45\nu U_B^{-1} \frac{1}{4\gamma} a_s \left( (a_s/a_0)^4 - 1 \right) + \Theta_0^2 (a_s/a_0)^6. \quad (3)$$

Now, Thwaites [9] says that flow separation occurs when the shape parameter $\lambda$ defined by

$$\lambda(x) = \frac{\Theta(x)^2}{\nu} \frac{dU(x)}{dx} \quad (4)$$

takes the empirically derived value $\lambda(x_s) = -0.09$. However, [7] have approximated this separation value from theoretical criterion as $\lambda(x_s) = -0.0992$.

From conservation of momentum, we of course have

$$\frac{dU(x)}{dx} = -U_B a_s \gamma a(x)^{-2}. \quad (5)$$

Therefore, evaluating (5) and (3) at the separation point $x = x_s$ and plugging these into (4) gives us

$$-0.09 = \lambda(x_s) = \frac{0.45}{4}(1 - (a_s/a_0)^4) - \Theta_0^2 a_s^5 a_0^{-6} \gamma \nu^{-1}. \quad (6)$$

We can reasonably assume that $\Theta_0 \approx 0$ as the momentum thickness $\Theta_0$ is quite negligible at the glottal entrance $x = 0$. Therefore, we find the significant result from (6) that

$$\frac{a_s}{a_0} = \left( 1 + \frac{0.09 \times 4}{0.45} \right)^{1/4} \approx 1.1583,$$

which we round to 1.6 in our model. Taking Pelorson et al's [7] value of $\lambda(x_s) = -0.0992$, we find similarly that $\frac{a_s}{a_0} \approx 1.18$. These values surprisingly corroborate experimentally validated standards for jet width at flow separation in vocal fold models, which tend to place $a_s$ between $1.15a_0$ and $1.20a_0$.

# References


[1] R.D. Blevins, *Applied Fluid Dynamics Handbook*, Van Nostrand Reinhold Co., NY (1984).

[2] P. Sidlof, O. Doaré, O. Cadot, A. Chaigne, Measurement of flow separation in a human vocal folds model, *Experiments in Fluids*, **51**, 123-136 (2011).

[3] A. Hirschberg, Comments on "A theoretical model of the pressure field arising from asymmetric intraglottal flows applied to a two-mass model of the vocal folds", *J. Acoust. Soc. Am.*, **134**, 9-12 (2013).

[4] B. D. Erath and M. W. Plesniak, An investigation of asymmetric flow features in a scaled-up model of the human vocal folds, *Experiments in Fluids*, **49**, 131-146 (2010).

[5] B. D. Erath, M. Zañartu, S. D. Peterson, and M. W. Plesniak, "Nonlinear vocal fold dynamics resulting from asymmetric fluid loading on a two-mass model of speech", *CHAOS*, **21** (3), 033113 (2011).

[6] A. Hirschberg, J. Haas, X. Pelorson, "Assymmetry in lateral forces on vocal folds due to the the Coanda effect", Congrès Français d'Acoustique 2014, Poitiers, April 2014.

[7] X. Pelorson, A. Hirschberg, A. P. J. Wijnands and H. M. A. Bailliet, "Description of the flow through in-vitro models of the glottis during phonation," Act. Acust. 3, 191-202 (1995).

[8] H. Schlichting, *Boundary-Layer Theory*, Sixth edition, McGraw-Hill Book Company, NY (1968).

[9] B. Thwaites, Approximate calculation of the laminar boundary layer, *Aero. Quartely*, **I**, 245-280 (1949).