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On the meaning and accuracy of the pressure–flow technique to determine constriction areas within the vocal tract

Xavier Pelorson *

Institut de la Communication Parlée, INPG-University Stendhal, UMR CNRS Q5009, 46 Avenue Félix Viallet, F-38031 Grenoble Cedex, France

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Abstract

Since Warren and DuBois (D.W. Warren, A.B. DuBois, Cleft Palate Journal 1 (1964) 52–71), the "Pressure–Flow technique" has been widely used to estimate constriction areas within the vocal tract. In this paper, three fundamental questions regarding this technique are addressed: (1) What exactly is measured (minimum, maximum or "mean" areas)? (2) What degree of accuracy can be expected from this technique? (3) To what extent can this method be applied to unsteady flow conditions? A theoretical and experimental study based on a mechanical vocal tract model, including various constriction shapes, is presented. The pressure–flow technique is shown to be relatively insensitive to the exact constriction shape (circular, uniform or diverging), and the estimated area to be close to the minimum area of the constriction. This result can be theoretically rationalised by considering that in all cases studied here, the flow separation point is always close to the minimum constriction. Compared with much more complex viscous flow solutions, a simple one-dimensional flow model is shown to yield fair estimates of the areas (within 20%), except for low Reynolds numbers flows. The empirical head-loss factor, or flow coefficient, $k = 0.65$, sometimes used, appears to be disputable and is probably due to an experimental artefact. Lastly these results are extended to the case of unsteady flow. © 2001 Elsevier Science B.V. All rights reserved.

Zusammenfassung

Seit den Arbeiten von Warren und DuBuis (D.W. Warren, A.B. DuBois, Cleft Palate Journal 1 (1964) 52–71), ist die "Druck–Flusstechnik" oft benutzt worden, um Schätzungen der Konstriktionsfläche der Vokaltrakt zu erhalten. Dieser Artikel versucht, drei grundlegende Fragen zu beantworten, was diese Technik betrifft: (1) Welche Menge wird gemessen (die minimale, maximale oder "durchschnittliche" Fläche)? (2) Welche Genauigkeit kann man von dieser Technik erwarten? (3) Ist es möglich, diese Technik auf die Bedingungen von instationärem Abfluss anzuwenden? Hier wird eine theoretische und experimentelle Studie beschrieben, die ein Modell der Vokaltrakt benutzt, das verschiedene Konstriktionsformen darstellen kann. Es wird gezeigt, daß die genaue Form der Konstriktion (kreisförmig, gleichförmig oder auseinanderlaufend) wenig Einfluss auf die "Druck-Flusstechnik" hat, und es erscheint, daß die geschätzte Fläche nahe der kleinsten Fläche der Konstriktion ist. Dieses Ergebnis kann in der Theorie durch die Tatsache erklärt werden, daß in allen hier untersuchten Fällen der Trennungspunkt des Abflusses immer nahe an der Stelle der kleinsten Konstriktion ist. Im Vergleich zu anderen komplexeren Lösungen liefert ein einfaches eindimensionales Modell bereits eine vernünftige Schätzung der Flächen (mit einem Spielraum von ca. 20%) außer für niedrige

* Corresponding author. Fax: +33-4-7682-5946.
E-mail address: pelorson@icp.inpg.fr (X. Pelorson).

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Reynoldssche Zahlen. Der Verlustkoeffizient empirischer Last (flow coefficient), $k = 0.65$, der manchmal benutzt wird erscheint sehr diskutierbar, denn er stammt wahrscheinlich von einem experimentellen Kunstprodukt. Schließlich wird die Ausweitung dieser Ergebnisse auf den Fall eines instationären Abflusses zur Sprache gebracht.

Résumé

Depuis les travaux de Warren et DuBois (D.W. Warren, A.B. DuBois, Cleft Palate Journal 1 (1964) 52–71), la technique de "pression–débit" a été fréquemment utilisée afin d'obtenir des estimations de l'aire de constrictions du conduit vocal. Cet article tente de répondre à trois questions fondamentales concernant cette technique: (1) Quelle est la quantité mesurée (l'aire minimum, maximum ou "moyenne")? (2) Quelle est la précision que l'on peut attendre de cette technique? (3) Est-il possible de l'appliquer à des conditions d'écoulement instationnaires? Une étude théorique et expérimentale utilisant une maquette du conduit vocal pouvant présenter différentes formes de constrictions est décrite. Il est montré que la technique de pression-débit est peu sensible à la forme exacte de la constriction (circulaire, uniforme ou divergente) et il apparaît que l'aire estimée est proche de l'aire minimum de la constriction. Ce résultat peut s'expliquer théoriquement par le fait que, dans tous les cas étudiés ici, la position du point de séparation de l'écoulement est toujours proche de la constriction minimale. Par comparaison avec d'autres solutions plus complexes, un simple modèle unidimensionnel fournit déjà une estimation raisonnable des aires (à 20% près) sauf pour des nombres de Reynolds faibles. Le coefficient de perte de charge empirique (flow coefficient), $k = 0.65$, qui est parfois utilisé apparaît très discutable car il est probablement lié à un artefact expérimental. Enfin, l'extension de ces résultats au cas d'un écoulement instationnaire est abordée.

Keywords: Speech production; Speech aerodynamics; Fluid mechanics

1. Introduction

Speech production studies are conditioned by the possibility of acquiring articulatory and aerodynamic data on human subjects producing continuous speech. For a long time the pressure–flow technique has thus been used as an indirect and non-invasive way to determine constriction areas within the vocal tract: oral constriction (Hixon, 1966; Scully, 1986; Stromberg et al., 1994; Shadle and Scully, 1995), velopharyngeal opening (Warren and DuBois, 1964; Guyette and Carpenter, 1988; Zajac and Yates, 1991), or glottal area (Mair and Scully, 1996).

The pressure–flow method involves two simultaneous measurements. The pressure drop across the constriction is obtained by a pressure transducer connected to the main cavity behind the constriction by a tube inserted either through the lips or through the nose or simply estimated from the oral pressure (Mair and Scully, 1996). The air flow through the vocal tract is usually measured with a circumferentially vented pneumotachograph (Rothenberg, 1973).

Using these pressure drop and flow velocity measurements, Warren and DuBois (1964) have proposed a very simple semi-empirical formula, the Orifice equation, to estimate constriction areas within the vocal tract during speech. This Orifice equation relies on an empirical "flow coefficient", k, introduced to fit the experimental data. The accuracy and the relevance of this flow coefficient have been since then widely and controversially discussed in the literature (e.g., Warren and Devereux, 1966; Muller and Brown, 1980; Yates et al., 1990). The primary goal of this study is to determine theoretically and experimentally the relevance and the accuracy of this technique. In particular, it must be noted that the pressure–flow method has been derived and tested under a single condition: using a straight uniform tube of known area inserted inside a human vocal tract or inside a model of the vocal tract. In real life, the constrictions involved during speech production do not have such a simple shape and are instead essentially non-uniform. Under these circumstances, one can reasonably wonder what exactly is measured using the pressure–flow method.

Finally, although already used in phonetic experiments (Mair and Scully, 1996), the method has never been tested under unsteady flow conditions, the last question addressed in this paper will be: to what extent can this method be extended to unsteady flow conditions such as those existing during the production of voicing and plosive sounds?

2. Theoretical study

In this paper, a constriction is defined as being formed by an abrupt reduction of the vocal tract area, the inlet, followed by an expansion, the outlet as depicted in Fig. 1.

From a fluid mechanical point of view, the flow through such a configuration is subject to local or global variations due to pressure losses. Quite generally, these losses are a function of the flow characteristics as well as of the constriction geometry,

$$\Delta P = f(\text{flow, geometry}).$$

The idea of the pressure–flow method is to determine theoretically or empirically a general expression for f. Given f, a measure of the flow velocity, and of the pressure losses, ΔP, one can then expect to retrieve some information about the constriction area.

In the case of speech, the strongest pressure losses are due to the phenomenon of flow separation at the outlet of the constriction. This phenomenon is due to the presence of a strong adverse pressure gradient which causes the flow to decelerate so rapidly that it separates from the walls to form a free jet. Associated with flow separations, they are very strong pressure losses due to the appearance of turbulence downstream of the constriction. As a matter of fact, the pressure recovery past the flow separation point is so small that it can in general be neglected.

As the air flow velocity is much smaller than the speed of sound (low-Mach number flow) it can be assumed that the flow is incompressible. Further, in the following only steady vocal tract conditions are considered (i.e., the vocal tract walls are rigid). The principle of mass-conservation, thus yields the following relationship:

$$\Phi = v \cdot A = \text{constant}, \qquad (1)$$

where Φ is the volume flow velocity, v and A are respectively, the (local) flow velocity and vocal tract area. As both v and A are unknown, another equation, obtained from the principle of momentum conservation, is necessary.

2.1. Bernoulli solution

As the most simple approximation, all viscous effects are neglected here. However, the fact that the flow is separating is a consequence of the viscosity and has a large influence. Without separation, there would be no pressure drop across a constriction, and thus no flow control. In order to account for this effect, an ad-hoc assumption of flow separation is necessary. This leads to the well-known one-dimensional equation for the velocity at the point of separation (Blevins, 1992),

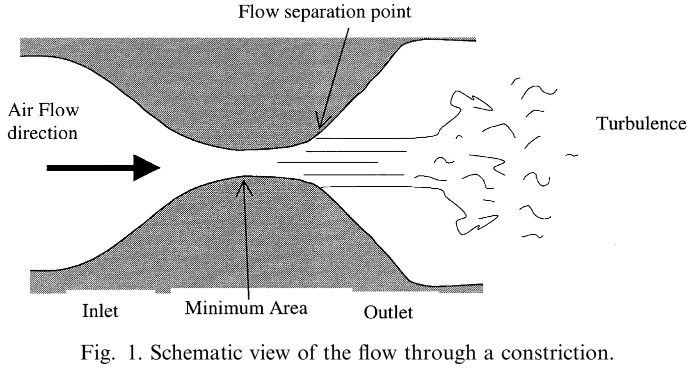


Fig. 1. Schematic view of the flow through a constriction.

$$\Delta P = \frac{1}{2}\rho v_s^2, \tag{2}$$

where ΔP is the (measured) pressure drop across the Orifice, v_s the velocity of the flow at the separation point and ρ is the (constant) air density.

In this equation, the kinetic energy behind the constriction is neglected. It is assumed in the following that the flow separates from the walls of the vocal tract at the minimum constriction point, $A = A_{min}$. Together with this ad-hoc assumption, Eqs. (1) and (2) allow a prediction of the minimum constriction area, A_{min},

$$A_{min} = \frac{\Phi}{\sqrt{(2\Delta P/\rho)}}. \tag{3}$$

2.2. Boundary-layer solution

As explained in the previous section, the flow separation point is a crucial parameter which cannot be predicted by inviscid solutions.

Based on a previous work on glottal flow modelling (Pelorson et al., 1994), an approximate but computationally efficient prediction based on boundary-layer theory is proposed. It has been shown indeed that, for Reynolds numbers $Re = v \cdot h/\nu = O(10^3)$, where h is the constriction height and ν the kinematic viscosity coefficient, this flow model was able to predict the flow separation point x_s, defined as the point for which (Pelorson et al., 1995)

$$\left(\frac{\partial v}{\partial n}\right)_{walls} = 0, \tag{4}$$

where n is the coordinate normal to the constriction walls. Given x_s, one can then determine the minimum constriction area, A_{min}, by using Eqs. (1) and (2).

2.3. Additional corrections to the Bernoulli solution

2.3.1. Poiseuille correction

At low Reynolds numbers (when the constriction is narrow and/or the flow velocity is small) the preceding solutions are not accurate, due to the presence of strong (irreversible) viscous losses within the constriction. The simplest way to account for these losses is to consider a Poiseuille term as an extra pressure drop in Eq. (2). For instance, for a straight uniform rectangular channel of width w and length L, [1] one obtains

$$\Delta P_{Poiseuille} = \frac{12\mu w^2 L}{A_{min}^3}\Phi, \tag{5}$$

where μ is the dynamic viscosity coefficient.

Together with Eqs. (1) and (2), the use of a Poiseuille correction (5) yields to a third order polynomial equation for A_{min},

$$\Delta P A_{min}^3 - \frac{1}{2}\rho\Phi^2 A_{min} - 12\mu w^2 L\Phi = 0. \tag{6}$$

Different, but still equivalent, formulations can be obtained in the case of other cross-sectional shapes. These formulations are, in general, not analytical and require a numerical integration of the momentum equation along the channel profile.

2.3.2. Unsteady Bernoulli solution

The solutions presented above are based on the assumption of a steady flow. This is obviously not the case when considering the release of a plosive or glottal areas during phonation. Unsteady flow effects can be accounted for by considering the unsteady form of the Bernoulli equation. Neglecting the effects of walls motion, this yields to the addition of a $\rho L(\mathrm{d}v/\mathrm{d}t)$ term in Eq. (2) and thus to the following solution for A_{min}:

$$A_{min} = \frac{\rho L\frac{\mathrm{d}\Phi}{\mathrm{d}t} + \sqrt{\left(\rho L\frac{\mathrm{d}\Phi}{\mathrm{d}t}\right)^2 + 2\rho\Delta P\Phi^2}}{2\Delta P}. \tag{7}$$

In practice, $(\mathrm{d}\Phi/\mathrm{d}t)$ is, in general, not measurable but can be fairly estimated by a numerical derivation of the measured flux, Φ.

2.4. Link with the Orifice equation

From empirical considerations, Warren and DuBois (1964) have proposed the following for-

[1] The width is defined here as the dimension of the constriction perpendicular to the flow direction, while the length is the dimension parallel to the flow.

mula, the Orifice equation, to predict a constriction area, A:

$$A = \frac{\Phi}{k\sqrt{2\Delta P/\rho}}, \tag{8}$$

where the flow coefficient k is an empirical constant. From their experiments Warren and DuBois found a value of k ranging from 0.59 up to 0.72 and prescribed the use of the average value $k = 0.65$.

This simple formula appears thus to correspond to the Bernoulli solution presented in Section 2.1, but assuming a considerable pressure loss within the constriction. Further, the authors did not specify explicitly what area, A, was concerned. In the following, we will assume that this Orifice equation applies for the estimation of the minimum constriction area: $A = A_{\min}$.

3. Experimental study

3.1. Steady flow measurements

3.1.1. Set-up

In order to test the above theoretical predictions, the following experimental set-up was designed. It consists of a replica of a constriction. Three constriction shapes were considered, as shown in Fig. 2:

- a uniform one, with a rounded entrance,
- a circular one,
- and a diverging one.

All constrictions have the same width $w = 3.4$ cm. For each shape, three to four apertures and thus minimum areas were considered (ranging from 0.17 to 1.02 cm^2). Apertures were measured and controlled using calibrated plates with a typical accuracy of 0.05 mm. Steady flow conditions were obtained using an air supply controlled by a valve. To avoid possible effects of turbulence generated near the valve, the air flow was carried to the constriction model using a 2 m long squared straight pipe. Downstream of the constriction, a second straight pipe (of 0.2 m) was connected to simulate the vocal tract. Both upstream and downstream pipes had a cross-section area of 3.4×3.4 cm^2. Pressures along the model were measured using an ultra low pressure transmitter (Ashcroft, XLdp) or subminiature piezo–electrical pressure transducers (Kulite, XCS 0932G). Calibration of the pressure sensors was made against a water meter, with a typical accuracy for ΔP of less than 1 Pa. Air flow velocity was measured using

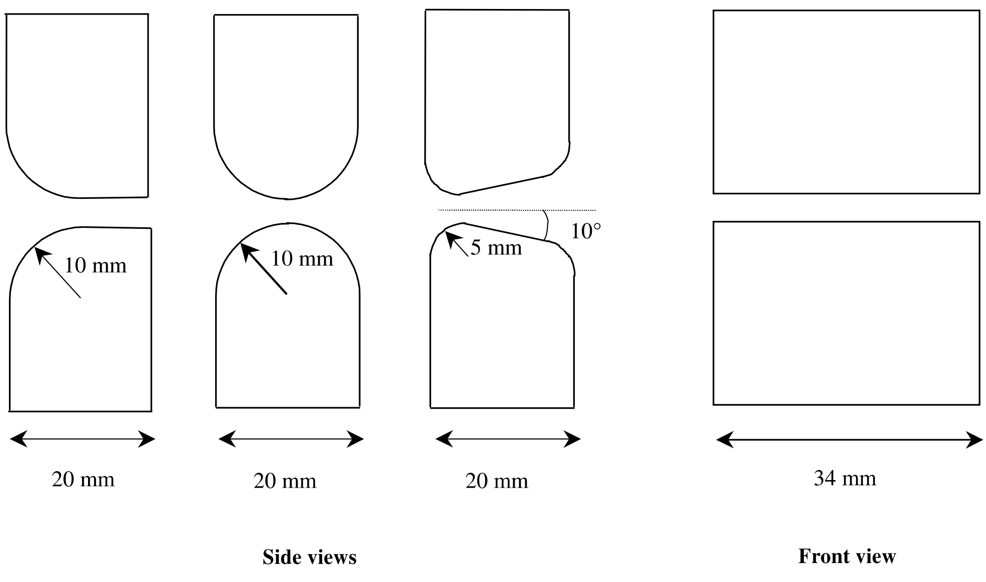


Fig. 2. Three constrictions used in this study.

either a Pitot tube or a hot-wire (Kimo TP03.0100).

In the following, we will compare different estimation methods. As a measure for the accuracy of each estimation, we use the relative error defined by

$$\text{error} = \frac{A_{\text{real}} - A_{\text{est}}}{A_{\text{real}}} \times 100,$$

where A_{real} is the real (known) constriction minimum area and A_{est} an estimation of this latter quantity using the measured pressure and flow velocity. All results will be displayed as a function of the Reynolds number, Re. For reference, typical Reynolds numbers involved during speech are estimated to reach values as high as a few thousands.

3.1.2. Uniform geometry

The uniform geometry is of particular interest here as it allows a comparison of the four predictions regardless of the position of the flow separation point (which is here always at the end of the channel). Figs. 3 and 4 present two examples of results concerning the relative error of the minimum constriction area, $A_{\min}$.

Fig. 3 displays results for low to average Reynolds number flow conditions. It can be seen that the Orifice equation overestimates by about 30% while the other three solutions are within 20% accuracy. For Reynolds numbers, Re > 1500, the Boundary-layer solution provides the best estimate for $A_{\min}$ (with an accuracy of the order of 5%), while at lower Reynolds numbers, the inclusion of a Poiseuille term leads to a more accurate estimate. This result was expected: at low Reynolds numbers, because the flow becomes fully viscous and, by definition, the Boundary-layer concept does not apply any longer (Schlichting, 1968). Fig. 4 displays results for higher Re, using a wider aperture: 2.35 mm. The simple Bernoulli solution leads again to a fair estimate: within 20%. Because the viscous losses are small in such a case, the addition of a Poiseuille term leads only to a slight im-

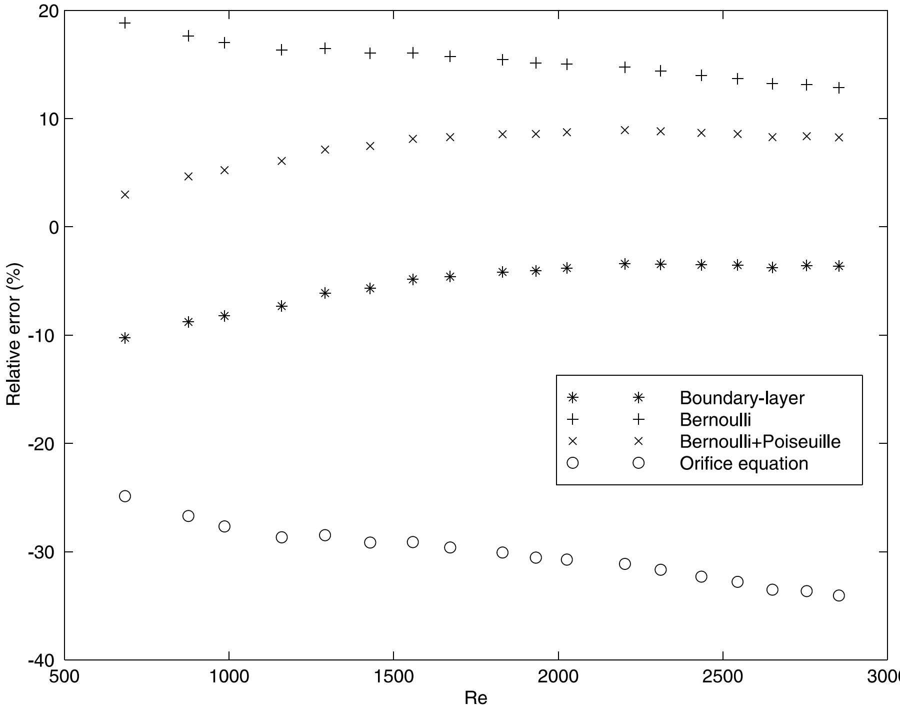


Fig. 3. Relative error for the estimation of the minimum constriction area as a function of the Reynolds number. Results for a uniform geometry at low-average Reynolds numbers. Minimum constriction height is 1 mm.

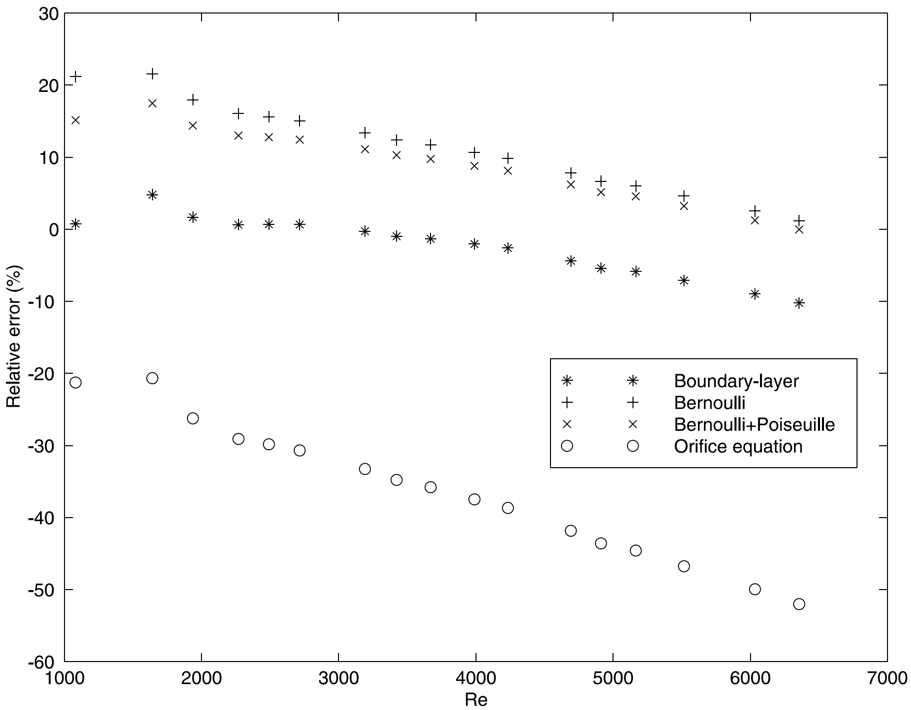


Fig. 4. Relative error for the estimation of the minimum constriction area as a function of the Reynolds number. Results for a uniform geometry at average-high Reynolds numbers. Minimum constriction height is 2.35 mm.

provement. We note that above $\mathrm{Re} = 4500$ the Boundary-layer predictions tend to diverge. This effect is likely to be related to the occurrence of turbulence within the constriction.

3.1.3. Circular geometry

An example of a typical result concerning this geometry is presented in Fig. 5.

As in the preceding section, the best results are obtained by the Boundary-layer solution while the simple Bernoulli formula remains a reasonable estimate (still within 20%). As in the case of the straight geometry, departures at high Reynolds numbers (above 4000) are also to be associated with a laminar to turbulent flow transition. Because the flow separates near the entrance of the constriction, the effective length of the model is much smaller than the one observed for the uniform one. The viscous losses, therefore, remain small and the Poiseuille correction is almost negligible. The Orifice equation here provides an overestimate varying from 60% up to 100%.

3.1.4. Diverging geometry

We now present results concerning a diverging constriction, which is another physiologically plausible configuration. An example of the results is presented in Fig. 6.

Here again, the same conclusions can be drawn: the best estimate comes from the Boundary-layer solution except for very high (and very low) Reynolds numbers. The Bernoulli solution provides an estimate within 10%, and the Orifice equation always strongly overestimates the actual areas.

3.2. Discussion

The most striking result presented here is probably the inadequacy of the albeit widely used Orifice equation to explain the measured data. More precisely, the use of a flow coefficient

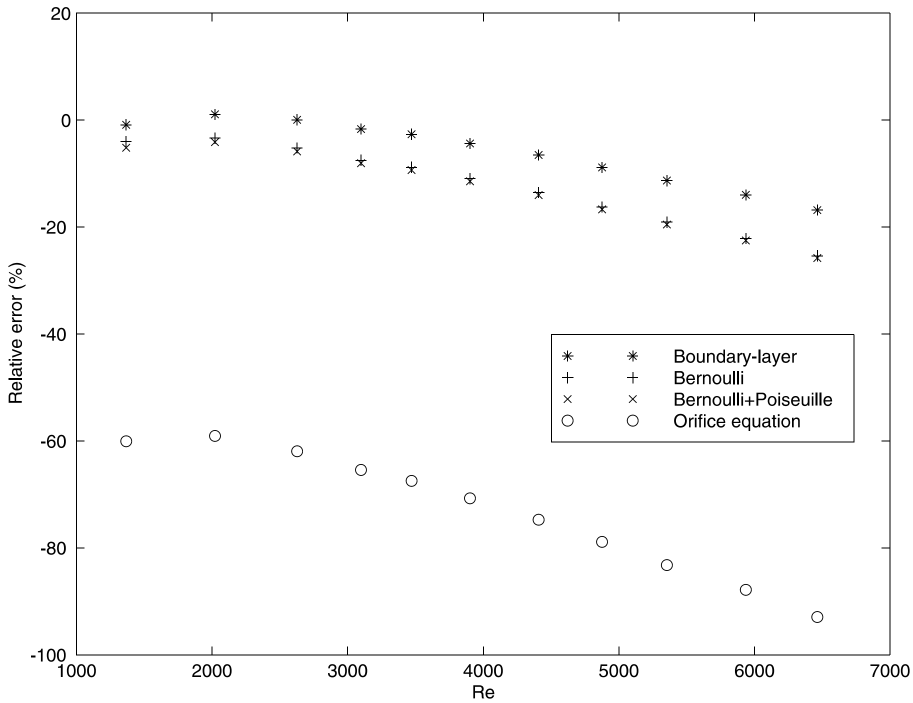


Fig. 5. Relative error for the estimation of the minimum constriction area as a function of the Reynolds number. Results for a circular geometry. Minimum constriction height is 2 mm.

($k = 0.65$) although recommended by many authors leads to a considerable overestimation of the constriction areas. A possible explanation for these discrepancies could lie in the experimental set-up used to derive this flow coefficient, which has been more or less replicated by different researchers. This set-up involves the use of an obsturator or an Orifice plate inserted inside the nasopharyngeal cavity of a human subject (Zajac and Yates, 1991) or inside a replica of the upper vocal tract (Warren and DuBois, 1964; Zajac and Yates, 1991). The major difference between these experiments and those presented here, concerns the shape of the constriction. While abrupt sharp edged constrictions were used by Warren and Dubois and followers, only well rounded constrictions, and thus more plausible anatomical geometries, are considered here.

From a fluid mechanical point of view, abrupt and sharp edged constrictions lead to important irreversible pressure losses (vena-contracta effect) and can also be responsible for triggering turbulence within the constriction. The combination of these two effects are likely to explain the need for a corrective flow coefficient. In Table 1, an attempt to analyse Zajac and Yates (1991) results is presented. In this latter experiment, three plastic tubes of length $L = 45$ mm and diameters $D = 3.2$, 4.8 and 6.4 mm were used. Reynolds numbers involved ranged, thus, from $\mathrm{Re} = 2200$ up to $\mathrm{Re} = 10800$. Using formulas and data presented by Blevins (1992), different estimates for a hypothetical flow coefficient were calculated for different flow assumptions. For comparison, similar calculations considering a rounded entrance are also displayed in Table 1.

From Table 1, it can be seen that the flow coefficient reported by Zajac and Yates (1991) ($0.65 \leqslant k \leqslant 0.73$) can only be expected by assuming a turbulent flow through a sharp edged constriction. It must be noted that, in the case of a rounded entrance, predicted k values may become significantly lower than unity. This is due to the rather large and unrealistic length of the constriction ($L = 45$ mm).

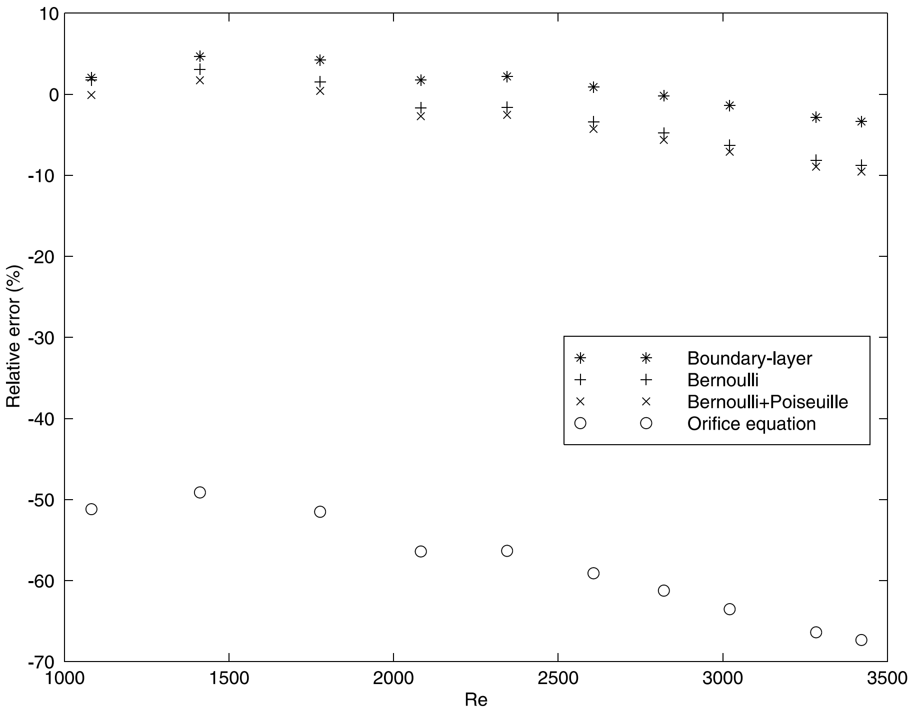


Fig. 6. Relative error for the estimation of the minimum constriction area as a function of the Reynolds number. Results for a diverging geometry. Minimum constriction height is 1 mm.

During speech, the most plausible configuration is certainly the one involving a constriction having a rounded entrance. In such a case, the use of a flow coefficient appears extremely doubtful and leads in practice to a significant overestimation of the constriction areas.

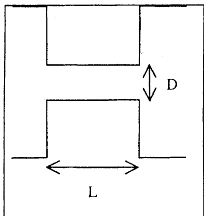
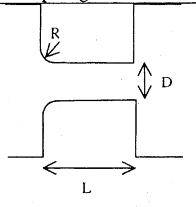
In cases where turbulence is clearly involved, such as for fricatives or whispered voice, one could however expect the need for a corrective factor to account for viscous losses. However, this raises some fundamental questions concerning the exact location of the turbulent flow (within the constriction or past it) and whether the turbulent flow is fully developed or not, questions which are far beyond the purpose of this study.

As expected, the best estimation for the minimum constriction area is obtained using the Boundary-layer solution, except for extreme Reynolds numbers. This experimentally confirms that the area which is measured by the pressure–flow method is close to the area at which the flow separates from the constriction. Although using an ad-hoc assumption about this latter quantity, a simple Bernoulli solution is found to produce fair estimates.

3.3. Unsteady-flow measurements

An extension of the above results to the case of unsteady flow conditions is now considered. Unsteady pulsatile flow conditions through the rigid constriction are obtained using a collapsible tube instead of the valve. The collapsible tube consists of a straight portion of a latex tube placed inside a compression chamber. When the pressure inside the chamber is high enough, the latex tube is subject to self-sustained oscillations providing then a pulsatile flow. More details about this experiment can be found in (Conrad, 1969; Bertram, 1986). The major advantage of this set-up is to allow the control of unsteady flow conditions which furthermore present some similarities with the glottal flow. An example of such unsteady flow characteristics is presented in Fig. 7, in the case of a uniform geometry with a minimum height of 2 mm.

Table 1
Expected flow coefficients obtained for two constriction configurations and flow regimes[a]

 sharp edged entrance	Inlet losses $k \approx 0.82$	Viscous losses (laminar flow) $0.76 \le k \le 0.81$	Viscous losses (turbulent flow) $0.69 \le k \le 0.75$
 rounded entrance	Inlet losses $k \approx 1$	Viscous losses (laminar flow) $0.90 \le k \le 0.96$	Viscous losses (turbulent flow) $0.86 \le k \le 0.88$

[a] Values are obtained using Zajac and Yates (1991) data. In the case of the rounded entrance, it is assumed that $R/D > 0.2$.

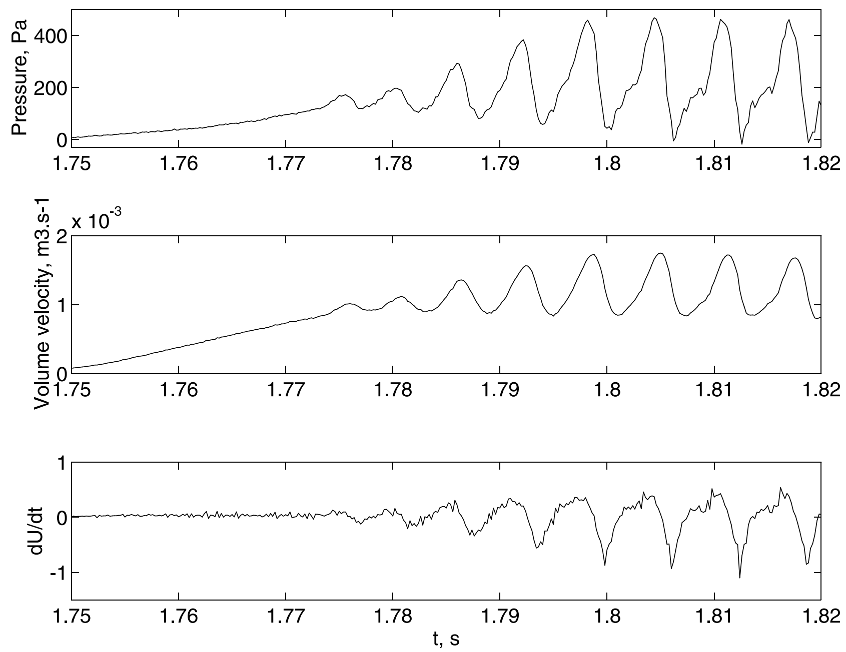


Fig. 7. Example of unsteady flow conditions imposed on the constriction model. From top to bottom: measured pressure difference across the constriction model, measured volume velocity, estimated time derivative of the volume flow velocity.

In the example shown in Fig. 7, the collapsible tube was controlled in order to obtain self-sustained oscillations at a frequency of 142 Hz which is slightly higher than the average fundamental frequency of an adult male speaker. It must be noted that the collapsible tube never closes completely, and thus the volume flow velocity never goes to zero, which is usually not the case during “normal”

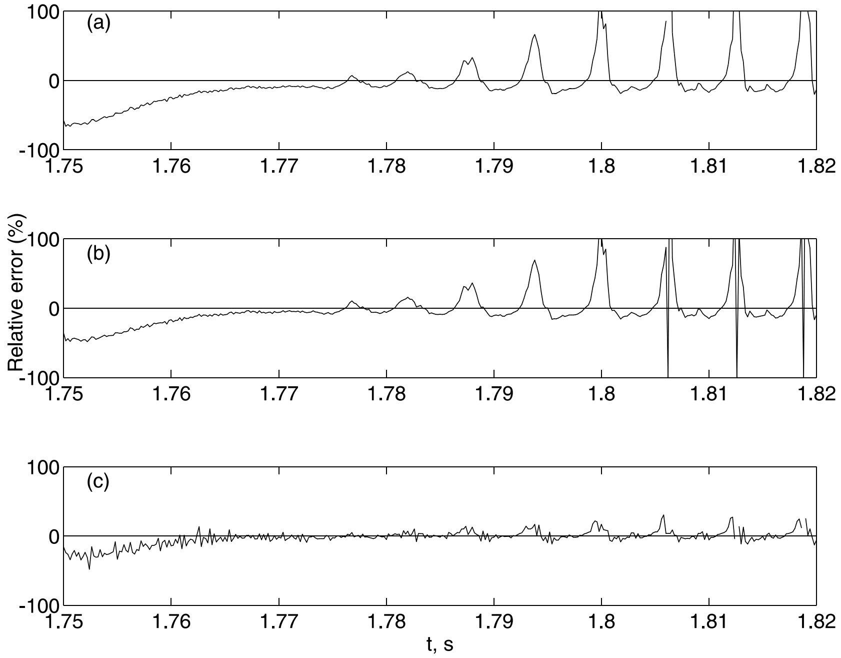


Fig. 8. Relative error corresponding to three different estimates of the minimum constriction area A_{min}. From top to bottom: (a) steady Bernoulli formula; (b) steady Bernoulli solution accounting for a Poiseuille term; (c) unsteady Bernoulli solution accounting for a Poiseuille term. Results for a uniform geometry. Minimum constriction height is 2 mm.

phonation. In Fig. 8, three different estimates for the constriction area are compared, obtained using the data presented in Fig. 7. For the sake of clarity, the boundary-layer solution is not presented here.

From the example shown in Fig. 8, it can be seen that the simple steady Bernoulli solution provides a limited overestimation of the minimum constriction area (of less than 20%) except during the closure of the collapsible tube where the estimate clearly diverges. This corresponds to periods of high negative values of $\mathrm{d}\Phi/\mathrm{d}t$; for minimum values of $\mathrm{d}\Phi/\mathrm{d}t$ (e.g. at $t = 1.807$ s in Figs. 7 and 8), the pressure–flow method fails even to provide a real solution. Although a slight improvement can be observed using a Poiseuille corrective term, this example clearly emphasise the need for an unsteady corrective term.

4. Conclusions

The major conclusions that can be drawn from this study are as follows.

(1) From a theoretical point of view, the pressure–flow method allows the estimation of the constriction dimensions at which the flow separates from the walls to form a free jet. As this position remains close to the minimum constriction, at least for moderate Reynolds numbers and for steady flows, this method therefore provides a fair estimate of this latter quantity.

(2) Concerning laminar conditions, the "flow" coefficient, although widely used, seems doubtful and could be avoided. From a theoretical analysis it has been shown that the considerable irreversible losses observed by Warren and DuBois (1964) and other researchers can only be explained by a turbulent flow through a sharp edged constriction. As noted by one of the reviewers of this manuscript, such a coefficient is, in fact, more a "shape" coefficient than a "flow" coefficient.

(3) Although the best estimates are provided by the Boundary-layer solution or using a Poiseuille correction, both of them require knowledge about the constriction (such as its length, width or geometry) which is not, in general, accessible in-vivo.

The most simple solution based on the Bernoulli formula using an ad-hoc assumption for the flow separation point appears thus to be a quite reasonable choice, allowing relative estimation errors within 20% at the most. This solution also presents the advantage of being insensitive to the constriction shape, and is thus applicable to most speech configurations. However, this solution is clearly limited theoretically and experimentally to inviscid, laminar flow conditions. The greatest care should be taken when using it for fricatives or whispered voice.

(4) When applied to unsteady flow conditions such as a pulsatile flow, the Bernoulli solution still remains reasonably accurate, except when high temporal velocity gradients are involved. This would occur during the closure of the vocal folds or during the onset of the release of a plosive. In practice, these events can easily be detected and discarded using a simple numerical differentiation of the measured flow volume velocity.

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