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TRACKING VORTEX DIPOLAR STRUCTURES IN A LARYNGEAL-LIKE JET

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Abstract. A vortex dipole is a couple of two closely-packed counter-rotating circulations which is usually observed in geophysical flows, in tidal channels and in laboratory flows using stratifed fluids, shallow water, soap films or slitted nozzles. The glottis, defined by the aperture between the vocal folds, takes the shape of a size-varying slit during voice production. The vocal folds configure the first of two constrictions encountered by the flow through the human larynx. If the so-called false vocal folds are sufficiently adducted, a second slit is present. These geometrical conditions favor the roll-up of vortex dipolar structures as the laryngeal jet is formed at the slits. In this work, we present direct numerical simulations and laboratory experiments for simple (static and rigid) and complex (dynamic and elastic) models of the vocal folds. The simple model is used to do the register of the possible types of vortex dipoles which form and evolve during a fluid transient compatible with vocal fold opening. Vortex dipolar structures are then tracked in flow visualizations for models of increasing complexity. Three-dimensional numerical simulations appear as necessary to gain further insight on the mechanisms in play.

1 INTRODUCTION

The larynx has two sets of interior folds: the vocal folds, which vibrate during voice production, and the false vocal folds that, in the absence of vocal effort, form a non-vibrating slitted orifice constricting the laryngeal channel. The glottis is the space between the true vocal folds. Because the contraction ratio of the glottis is of order 10^{-2}, laryngeal flow is often considered planar or quasi two-dimensional.

However, the planarity of larynx-like flow applies to conditions which are not necessarily holding during real vocal fold oscillation. On the one hand, when the vocal folds start opening/closing, a transverse view of the larynx shows that the folds do not form a slit of a fixed aspect ratio. On the other hand, and however planar the jet is at its formation, contamination by three-dimensional effects is likely within the time scales of a vocal fold cycle. Studying the flow through complex models of the larynx obliges the researcher to account for the relevance of these effects.

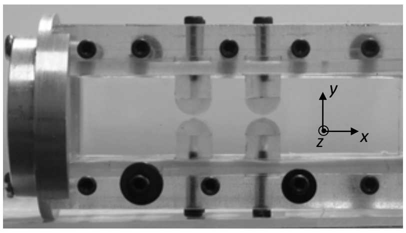

Figure 1: Rigid model roughly representing a larynx-shaped channel with true vocal folds (first constriction) and unmountable false vocal folds (second constriction).

Simple models with fixed aspect-ratio slits are the starting point of most experiments designed to gain some insight into the fluid mechanics of voice production. The larynx-like flow inspected in these models is still akin to a quasi-2D description. Laboratory and numerical experiments presented in Chisari et al. (2010) show that the salient feature of a starting flow through a pair of subsequent slits is a structure often termed *vortex dipole*.

A vortex dipole is a plane analog of the vortex ring – see for instance Lamb (1932). Wells and van Heijst (2003) maintain that vortex dipole formation has been shown to be relevant in the mechanism operating during breathing. In fact, planar jets and vortex dipoles are united by the same mechanism of generation: the action of a localized source of momentum in a viscous fluid. Attention to the formation of this kind of patterns in a single-slit configuration had been drawn by Hofmans (1998). On the basis of flow visualization experiments, Hofmans conjectured that a significant part of broad-band noise in voiced speech could be due to quasi-periodic two-dimensional flow instabilities rather than to three-dimensional turbulence.

In this work, we compare the vortex dipolar structures found in a simple double-slit configuration with the flow features displayed by more realistic models. The simple model of Fig. 1 has the geometry of the larynx-shaped channel considered in Chisari et al. (2010), while the more complex cases are those studied in Krebs (2010). This thesis includes consideration of driven flow pulsations through static models as well as the flow dynamics of a self-oscillating valve with water-filled folds made of latex (Fig. 2).

Even if this study is essentially motivated by a description of the fluid dynamics in the context of voice production, our results are applicable to all engineering, biological or geophysical flows with a similar physics. It is a noticeable fact that vortex dipoles are the predominant fluid structure when the laryngeal system is simplified. It is therefore worth considering what changes vortex dipolar structures undergo when the complexity of the model is gradually increased.

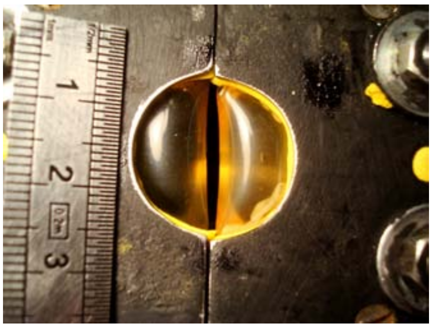

Figure 2: Self-oscillating valve representing the vibrating vocal folds.

2 THE NUMERICAL MODEL

A two-dimensional CFD method is proposed to simulate airflow within a two-dimensional larynx-like channel. The code allows for simulations with fixed/moving boundaries. The fluid-structure interaction is not modelled. The governing equations are:

$$\frac{\partial V}{\partial t} + (V.\nabla)V = \frac{1}{Re}\nabla^2 V - \nabla P \tag{1}$$

$$\nabla.V = 0 \tag{2}$$

where $V = (U, W)$ is the velocity of the flow in the channel (associated to a mid-coronal view of the laryngeal system). The Reynolds number Re is built on the channel's maximum height H (corresponding to the tracheal diameter) and the incoming axial velocity U_0.

$$Re = Re_H = \frac{U_0 H}{\nu} \tag{3}$$

When the boundaries are set to move, a synchronization is necessary between the inlet condition and forced wall motion. In this case, an input parameter is defined to turn on/off the synchronization option. On the solid walls (channel and constriction), we impose the classical no-slip and no-injection condition. At the inlet, we impose an advective-type boundary condition:

$$\frac{\partial V(\Gamma, z, t)}{\partial t} + \frac{\partial V(\Gamma, z, t)}{\partial x} = 0 \tag{4}$$

which reduces to a homogeneous Neuman condition if the flow reaches a steady state. No symmetry condition is forced for the flow along the channel axis.

The equations are integrated in unsteady form. The time marching algorithm is based on a prediction projection method which consists in computing an intermediate velocity field V^* assuming a known pressure field.

$$\frac{3U^* - 4U^n + U^{n-1}}{2\delta t} + [2(V^n.\nabla)U^n - (V^{n-1}.\nabla)U^{n-1}] = -\frac{\partial P^n}{\partial x} + \frac{1}{Re}\nabla^2 U^* \tag{5}$$

A similar equation is used for W^* with respect to the z coordinate. This scheme leads to independent Helmholtz problems for each component U^* and W^*. Up to this step, the velocity field V^* is not divergence free. Projection onto the space of divergence free vector fields is performed through a scalar variable Φ which can be seen as a pressure correction, such that:

$$V^{n+1} - V^* = \delta t \nabla \Phi \tag{6}$$

To compute Φ, we take the divergence of equation (1), so that, for $\nabla.V^{n+1} = 0$:

$$\nabla^2\Phi = -(\nabla.V^*)/\delta t \tag{7}$$

associated with the boundary condition $\partial\Phi/\partial n = 0$. This equation is solved with a multigrid algorithm. In the last step:

$$V^{n+1} = V^* + \delta t \nabla\Phi \tag{8}$$

$$P^{n+1} = P^n + \frac{3}{2}\Phi \tag{9}$$

For the spatial discretization we use the classical staggered grid arrangement, where the viscous and convective terms are treated by finite centered differences.

The overall domain has N_x x N_z rectangular cells. The grid can be refined in the places of interest. The time step is adjusted so that the CFL is of order 10^{-2}. The boundaries are taken into account through a phase function equal to 0 or 1 for fluid or structure cells respectively, and velocities are implicitely set to zero in the structure cells. This phase function is rendered time-dependent to admit boundary motion.

In the numerical results presented herein, the code settings are adapted to the laboratory experiments. Spatial resolution was of 1024 x 512 cells in the simulations and refinement implemented in the constricted zones of the channel. A subroutine is coded to track the vortex dipoles as they move along the channel. Vortex dipole tracking is achieved through a systematic monitoring of local maxima and minima in speed and pressure. A vortex dipole is located where the pressure field and the streamwise component of the velocity field have a local maximum surrounded by two local minima. Further details can be found in Sciamarella and Le Quéré (2008).

3 THE STATIC MODEL

Let us introduce the simple model in order to do the register of the possible types of vortex dipoles forming spontaneoulsy in a geometry sketching the shape of the laryngeal channel. For flow onset, two-dimensional direct numerical simulations, shown in Fig. 3, account for the spontaneous generation of starting vortex dipoles and smaller-sized trailing vortex dipoles. These starting vortex dipoles present a behavior that compares well with Afanasyev (2006). Boundary vortex dipoles are also generated when the mentioned structures interact with the solid boundaries of the false vocal folds. A complete survey and tracking of vortex dipoles in a larynx-shaped channel using numerical and laboratory experiments can be found in Chisari et al. (2010).

The question that follows is if such two-dimensional vortex dipolar structures remain predominant beyond flow onset. To answer this question we consider an experiment in which a motor valve is used to modulate the flow at about 100 Hz through a single lip-like constriction defining a 1.5 mm $\times$ 20 mm slit. Particle Image Velocimetry (PIV) images of the pulsating jet are used to visualize the flow patterns. The images are acquired with a pulsed laser which limits the exposure time to nanoseconds.

Flow fields produced with the motor valve are quite repetitive. Fig. 4 and Fig. 5 show coronal (x-y) and sagittal (y-z) views of the flow at two different instants of a single cycle. Slides (a) correspond to the formation of the front of coronal starting vortex dipoles (*i.e.* the front of a planar vortex ring), while slides (b) show the evolution of the jet flow a few miliseconds later,

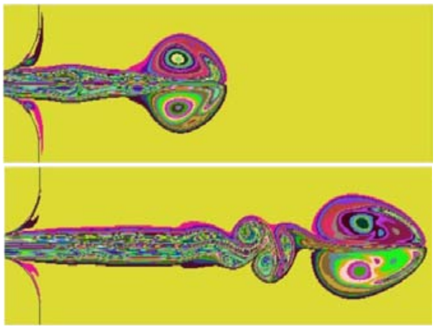

Figure 3: Starting and trailing vortex dipoles from two-dimensional direct numerical simulations at different stages of the flow through a single slit larynx-shaped channel.

with trailing vortex dipoles forming in the coronal plane as a result of instabilities in the shear layer of the trailing jet – see Fig. 4(b).

The vortex dipolar structures of the two-dimensional numerical simulations can be tracked without major difficulties in the mid-coronal views of the flow. However, this does not mean that the flow remains two-dimensional. A rupture of the planar symmetry of the flow is clearly visible in the sagittal view of the same frame – see Fig. 5(b). Contamination of three-dimensional effects in this configuration seems to develop a few milimeters downstream of the glottis. Notice that in the same frame, sagittal vortex structures are created in the vicinity of the channel wall, so that the front of vortex dipoles loses coherence apart from contracting in the y-z direction.

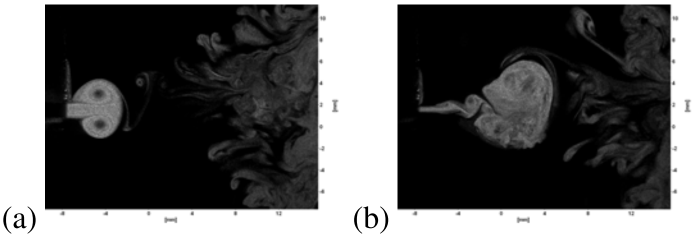

Figure 4: Coronal $(x - z)$ view of the formation and evolution of a front of vortex dipoles when the flow is pulsed with a motor valve at 171.5 Hz.

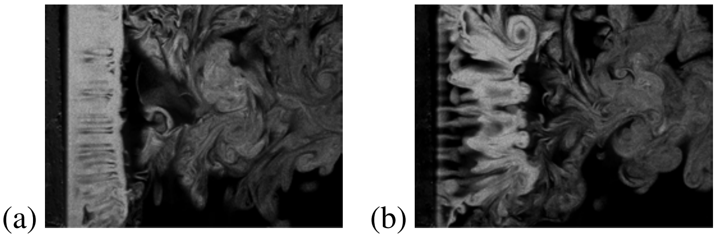

Figure 5: Sagittal $(x - z)$ view of the front of vortex dipoles corresponding to Fig. 4(a) and (b).

4 THE SELF-OSCILLATING MODEL

The model can be further complexified if the flow is modulated by a moving structure. For real voice production, vocal-fold vibration is not driven but self-sustained via fluid-structure interaction. Let us consider the flow created by a self-oscillating valve inspired in Ruty et al.

(2007, 2008). This valve is as complex as a vocal fold model can be. It consists of a pair of water-filled folds, whose natural frequency depends on adjustable water pressure. The model is thus not only self-oscillating but tunable. However, this complexity is attained at the expense of a loss of experimental repeatability.

The complexity of the model does not prevent flow visualization of the formation and evolution of dipole-like vortex structures throughout an oscillation cycle. Fig. 6 shows a mid-coronal view of the flow in the vicinity of the folds of the model for a free jet configuration (without a channel downstream of the vocal valve).

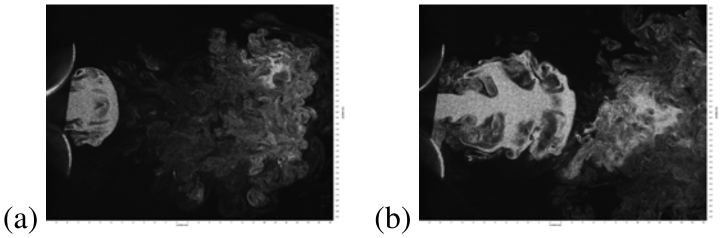

Figure 6: Flow visualization of two instants withing a single cycle of a self-oscillating valve vibrating at 160 Hz.

The flow structures observed in this case can still be qualitatively associated with the front of coronal vortex dipoles observed in the case of the driven flow. The head of the dipole is however subject to instabilities which seem to create spatially successive flow fronts in a single instant, as shown in Fig. 6(b). The smaller-sized trailing vortex dipoles observed in the case of the motor valve are also visible upstream of these fronts. Flow evolution in the spanwise direction also presents the trends observed in Fig. 5.

5 CONCLUSIONS

In this work we present some considerations on the fluid dynamics of the airflow through progressively complex vocal fold models. In the simplest case, the model is a channel with a single or a couple of slitted constrictions.

In a recent paper we show that, in this configuration, there is one vortex structure that prevails in the coronal plane: the vortex dipole. Flow visualization is used to track this kind of structure when the flow is modulated through a slitted aperture with an external motor valve, and when the flow is generated by the self-sustained oscillations of a pair of water-filled latex folds.

Numerical and laboratory experiments presented herein show that mid-coronal vortex dipolar structures are still traceable in the more complex cases, even if the coherence of the flow in the mid-sagittal plane is increasingly lost as the flow develops.

Using three-dimensional direct numerical simulations to seize the dynamics of the full process makes part of the work in progress.

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