Aeroacoustics of Musical Instruments

Benoit Fabre,[1] Joël Gilbert,[2] Avraham Hirschberg,[3] and Xavier Pelorson[4]

[1]LAM (Lutheries–Acoustique–Musique), UPMC Université Paris 06, UMR 7190, Institut Jean Le Rond d'Alembert, 75005 Paris, France; email: benoit.fabre@upmc.fr

[2]Laboratoire d'Acoustique, UMR 6613 CNRS/Université du Maine, 72000 Le Mans, France; email: joel.gilbert@univ-lemans.fr

[3]Department of Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands; email: A.Hirschberg@tue.nl

[4]Gipsa Lab Departement PC, UMR 5216 CNRS/Université de Grenoble, Domaine Universitaire, F-38402 Saint Martin d'Hères, France;
email: Xavier.Pelorson@gipsa-lab.grenoble-inp.fr

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Abstract

We are interested in the quality of sound produced by musical instruments and their playability. In wind instruments, a hydrodynamic source of sound is coupled to an acoustic resonator. Linear acoustics can predict the pitch of an instrument. This can significantly reduce the trial-and-error process in the design of a new instrument. We consider deviations from the linear acoustic behavior and the fluid mechanics of the sound production. Real-time numerical solution of the nonlinear physical models is used for sound synthesis in so-called virtual instruments. Although reasonable analytical models are available for reeds, lips, and vocal folds, the complex behavior of flue instruments escapes a simple universal description. Furthermore, to predict the playability of real instruments and help phoneticians or surgeons analyze voice quality, we need more complex models.

1. INTRODUCTION

Singing and musical performances are basic human social activities. Although singing is certainly older, wind instruments appeared at least 20,000 years ago (Baines 1967, Dauvois et al. 1998). These instruments produce a self-sustained oscillation driven by an almost constant blowing pressure. As for any stable limit-cycle oscillation, a nonlinear saturation mechanism limits the amplitude. This implies that the radiated sound is dominated by pure tones at multiples of the fundamental oscillation frequency, harmonics. For such general aspects of musical acoustics, we refer readers to excellent textbooks (Benade 1976, Backus 1977, Campbell & Greated 1994, Fletcher & Rossing 1998, Nederveen 1998, Henrique 2007, Chaigne & Kergomard 2008). Perceptually, these harmonics make the sound bright and pleasant. Our hearing is furthermore very sensitive to temporal changes. A perfectly stable oscillation sounds unnatural. Psycho-acoustic tests reveal that a sound produced by a wind instrument or human voice that has been stripped from the attack transient can be confusing (Rossing et al. 2002). Slow modulation, vibrato in music, and prosody in singing are also important. More minute effects such as a broadband noise related to turbulence appear to be musically important. Our ears are sophisticated instruments with a superior dynamical range, from 20 μPa to 20 Pa. We can discriminate pitch changes of less than 1% within one-tenth of a second, and a semitone corresponds to a 6% change in frequency. This implies that we are able to probe and analyze sounds produced by details that, although perceptually essential, escape current physical modeling. The finishing touch of an instrument maker involves adjustments to the mouthpiece of the order of hundredths of a millimeter. We can only hope that physical models will provide us with a global understanding. This can allow us to more rapidly design new instruments. In some cases, a real-time solution of a physical model can become an interesting musical instrument on its own, so-called virtual instruments. An interesting idea is to use physical models to explore the parameters that determine the playability of an instrument (Woodhouse 1995). Physical models can be used to understand voice pathologies (Herzel et al. 1994). In this review we start our discussion by a short classification of wind instruments (Section 2) and a history of physical modeling of wind instruments (Section 3). Section 4 is dedicated to the nonlinear response of acoustic resonators. In Sections 5–7, we discuss the fluid dynamics aspects of instruments on the basis of the classification of Section 2. Section 8 is dedicated to some perspectives. The present article complements earlier reviews provided by Fletcher (1979), Hirschberg et al. (1995), Fletcher & Rossing (1998), Howe (1998), Fabre & Hirschberg (2000), Campbell (2004), and Kob (2004).

2. A CLASSIFICATION OF WIND INSTRUMENTS

From a fluid dynamics point of view, we distinguish two families of wind instruments: the reed instruments and the flue instruments. A reed is a flexible element, a valve, that oscillates as a result of flow-induced vibration (flutter). This results in a modulation of the flow and sound generation. Prototypes of such instruments are the clarinet, oboe, harmonica, trombone, and human voice. Helmholtz (1885) distinguished between outward-striking (opening) and inward-striking (closing) valves. An outward-striking reed opens upon increasing blowing pressure. An inward-striking reed has the opposite behavior. Using a mechanical model with a single degree of freedom for the reed, Helmholtz (1885) predicted that closing reeds coupled to a pipe will oscillate at a frequency below the acoustic pipe resonance frequency. The opposite is predicted for outward-striking reeds. Although some reeds can certainly be described as closing, the commonly accepted prototype of opening reeds, the lips of a brass player, appears to display both behaviors (Cullen et al. 2000). One also distinguishes between beating reeds, which can close completely (clarinet, bassoon), and so-called free reeds, as found in the harmonica and the accordion. Apart from the vibration of the reed, wall vibrations are negligible in first approximation.

Flue instruments are wind instruments in which sound is produced by flow instability without significant wall vibration, not even from a reed. Examples of such instruments are the flute, recorder, flue organ pipe, and human whistling. In these flue instruments, a jet or shear-layer instability couples to an acoustic standing wave in an adjacent resonator. Some sounds can be produced for which the feedback from the acoustic resonator is not essential: broadband turbulence noise and so-called edge tones.

In most instruments, there is a significant effect of the presence of a pipe or cavity on the radiated sound. For some, the coupling between the pipe and the sound source is so strong that the oscillation frequency is dictated by the acoustic resonance of the pipe. In other cases, the resonator is only improving the radiation of acoustic energy in certain frequency bands, so-called formants. Actually, in many instruments, the fundamental frequency is not radiated efficiently (Fletcher 1979). These acoustic waves are kept by reflection inside the instrument and drive the oscillation. The higher frequencies are radiated quite efficiently. These higher frequencies reach our ears and dominate the musical sound. This implies that the global dynamical response of the instrument can be described by a simplified model involving the fundamental oscillation frequency and a few higher harmonics. The musical sound, however, depends on details of the oscillation process involving short timescales. Obviously, the closing of a reed has a huge impact on the sound quality as it generates most of the higher harmonics (Pelorson et al. 1994, Hirschberg et al. 1995).

3. EVOLUTION OF MUSICAL ACOUSTICS

Early physical models aimed at predicting the resonance frequency of the resonator and identifying this with the oscillation frequency (Bernoulli 1764, Rayleigh 1896, Nederveen 1998). Considering a pipe terminated by nonradiating (open or closed) ends and neglecting visco-thermal losses, one finds stationary solutions of the Helmholtz wave equation, which are called modes. These modes form a set of functions, which can be used to approximate the actual oscillation behavior of the system (Chaigne & Kergomard 2008). Assuming plane-wave propagation, Bernoulli (1764) observed that the model would explain experiments if the model pipe were assumed to be slightly longer than the actual pipe. This so-called end correction takes into account the inertia of the oscillating acoustic flow outside the open end of the pipe. Similar corrections were later applied to tone holes and various discontinuities in the pipe (Nederveen 1998, Chaigne & Kergomard 2008). Such models predicting pitch reduce considerably the trial-and-error phase in the design of a new wind instrument. The acoustic coupling with the mouth of the player has often been ignored. However, this coupling is the subject of current research (Guillemain 2007, Chen et al. 2008, Scavone et al. 2008).

Starting around 1960, lumped-element models have been developed to take into account the acoustic feedback on the sound source. The essential nonlinearity of such feedback oscillators was understood. This called for the first quantitative models for the flow described by Fletcher (1979). In the early 1980s, the first time-domain simulations were obtained based on wave-guide models coupled to the source models (Mc Intyre et al. 1983, Smith 2004, Valimaki 2005). The sounds were not judged as realistic. In the past few decades, the focus has shifted toward detailed numerical simulations and visualizations of the flow in wind instruments, on one side, and toward a better understanding of a player's control with application to the virtual instruments, on the other.

A crucial problem in the physical modeling of wind instruments is the separation of the instrument's properties from the aspects related to the player. This is now possible thanks to artificial blowing devices and scale models. There has been a significant effort in this area for single reeds (Backus 1963, Wilson & Beavers 1974, Idogawa et al. 1993), double reeds (Almeida et al. 2007b, Grothe et al. 2009), brass (Backus & Hundley 1971, Gilbert et al. 1998), free reeds (St. Hilaire et al. 1971, Banhson & Antaki 1998, Millot et al. 2001), flue instruments (Coltman 1968, Fletcher 1979, Verge et al. 1994, Yoshikawa 1998, Dequand et al. 2003, Bamberger 2004, Ferrand et al. 2010), and the human voice (Pelorson et al. 1994, Barney et al. 1999, Hofmans et al. 2003, Vilain et al. 2004, Zhang et al. 2006, Becker et al. 2009, Erath & Plesniak 2010, Triep & Brucker 2010). Artificial blowing devices are also useful to obtain objective information about the quality of an instrument (industrial quality control) and to simulate the playing of historical instruments, which one is not allowed to play otherwise. In parallel, there is an increasing effort to understand the player control of wind instruments (Fuks 1998, De la Cuadra 2005, Scavone et al. 2008, Cossette et al. 2010, Guillemain et al. 2010).

4. NONLINEARITIES IN RESONATORS

4.1. Nonlinear Wave Propagation

Acoustic pressure waves propagate with a speed c with respect to the air and with a speed $u + c$ with respect to the laboratory, where u is the local flow velocity in the direction of wave propagation. We consider plane-wave propagation in which the flow is directed along the pipe axis. For an ideal gas, the speed of sound is given by

$$c = \sqrt{\gamma R T}, \tag{1}$$

where T is the absolute temperature, R is the specific gas constant, and γ is the Poisson ratio of specific heats at constant pressure and volume. As $\gamma > 1$, the temperature increases upon adiabatic compression, increasing the speed of sound. The combined amplitude-dependent sound speed and convective velocity result in wave distortion. A simple wave propagating in the positive x direction with pressure $p_i'(t)$ at $x = 0$ will become infinitely steep after propagating a distance x_s. Beyond this distance, a shock wave will form, that is, a discontinuous jump in pressure. Neglecting friction, for an ideal gas with constant specific heat, we have

$$x_s = \frac{2\gamma p c}{(\gamma + 1)(\partial p_i'/\partial t)_{\max}}, \tag{2}$$

where p is the atmospheric pressure (Hirschberg et al. 1996). Backus & Hundley (1971) erroneously estimated the time derivative assuming a harmonic oscillation: $|\partial p_i'/\partial t|_{\max} = \omega |p_i'|$, with ω the angular frequency corresponding to the pitch of the note played. They concluded that nonlinear distortion is negligible in a trumpet. Because of the strongly nonlinear relationship between flow and pressure through the lip/mouthpiece combination, the time derivative $|\partial p_i'/\partial t|_{\max}$ appears to be much larger. Beauchamp (1980) clearly demonstrated the nonlinear character of the transfer function between p_i' at the pipe inlet and the acoustic pressure p' for the listener of a trombone.

Hirschberg et al. (1996) observed shock-wave formation in a trombone. The phenomenon was confirmed (**Figure 1*a***) for the trumpet by Pandya et al. (2003), for example. Gilbert et al. (2008) and Norman et al. (2010) studied nonlinear wave propagation including viscous effects before shock formation to asses its significance in various instruments. The sound of a brass instrument becomes gradually more enriched in upper harmonics during a crescendo. At fortissimo levels, the timbre becomes brassy, physically corresponding to the formation of shock waves. The potential for nonlinear wave distortion depends on the bore profile. Gilbert et al. (2007) introduced a

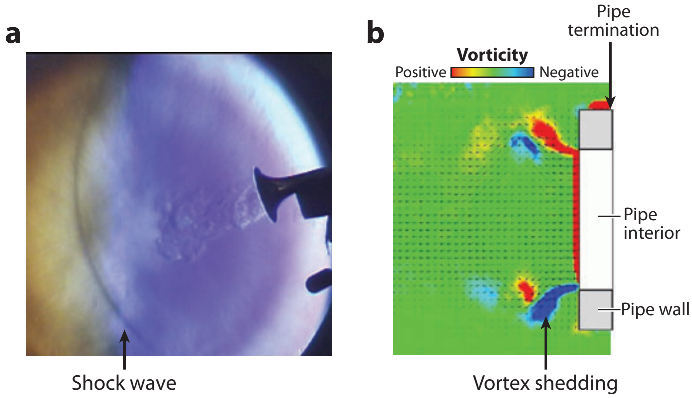

Figure 1

Nonlinearities: (*a*) schlieren visualization of a spherical shock wave radiated by a trumpet (Pandya et al. 2003) and (*b*) particle image velocimetry measurement of vortex shedding at the open end (*right*) of a resonating pipe (Buick et al. 2011).

brassiness parameter B defined by

$$B = \frac{1}{L_{ecl}} \int_0^L \frac{D(0)}{D(x)} dx,$$

where $D(x)$ is the bore diameter. The integral is carried out over the full pipe length L, and L_{ecl} is the length of a cone (pipe) with the same fundamental resonance frequency as the instrument. The resonance frequency of the cone is independent of the base diameter. Myers et al. (2007) proposed a classification of brass instruments based on the parameter B and the inlet bore diameter $D(0)$. Brassy sounds are also produced by elephants (Gilbert et al. 2010), which clearly confirms that the sound quality is not related to the material used to build the instrument.

4.2. Acoustic Streaming

High-amplitude acoustic waves induce vortex shedding at open pipe terminations (see **Figure 1*b***) and tone holes (Bouasse 1936, Ingard & Ising 1967). Jet flows driven by this vortex shedding are now called synthetic jets and can be used to cool electronic components (Kooijman & Ouweltjes 2009). This phenomenon, called streaming, has been studied for an open pipe termination (Disselhorst & van Wijngaarden 1980, Peters & Hirschberg 1993, Atig et al. 2004, da Silva et al. 2010). The vortex shedding induces energy losses that scale roughly with the third power of the acoustic amplitude. The exact shape of the edges of the pipe termination and the wall thickness have a strong influence on this phenomenon (Buick et al. 2011). In some cases, different vortex shedding modes are observed depending on the history of the flow (Disselhorst & van Wijngaarden 1980). One expects similar effects to play an important role at the mouth of flue instruments. Coltman (1968) showed that, at oscillation amplitudes typical for playing conditions, the acoustic impedance of the flute mouth, seen from the pipe, is amplitude dependent (nonlinear). This idea was confirmed by Fabre et al. (1996), Verge et al. (1997a,b), and Dequand et al. (2003), showing that modeling these nonlinear losses is necessary for the prediction of the oscillation amplitude of a flue instrument.

The nonlinear response of the tone holes of a clarinet has been demonstrated by Keefe (1983) who built two acoustically equivalent clarinet pipes with a series of open tone holes. The first pipe had thick walls, as found in clarinets, and the second had thin walls. To achieve the same acoustic flow inertia, holes in a thin wall pipe have to be narrower, resulting in a higher acoustic velocity through them and more losses. As a consequence, when attached to a clarinet mouthpiece, the thin-walled instrument could not be played, whereas the thick-walled instrument oscillated. A quasi-static nonlinear model proposed by Ingard & Ising (1967) explains this difference (Nederveen 1998). In addition to those involved in the response of the pipe termination (wall thickness, edge shape, pipe diameter, acoustic amplitude, frequency, initial conditions), parameters describing a tone hole include the ratio of the pipe-to-hole diameters and the ratio of grazing-to-bias flow. The grazing flow is directed along the pipe axis, whereas the bias flow passes through the hole. The grazing flow is determined by the position of the hole along the pipe. Although the effect of bias flow has been studied, the effect of a grazing flow on the nonlinear response of a tone hole is an unexplored aspect of the problem.

5. REEDS

5.1. Valve Instability

Reeds, lips, and vocal folds act as valves. Oscillation of the valve inlet gap height h induces a modulation of the volume flow Q_v entering the instrument, which is a source of sound. The narrow channel with a height of the order of h is referred to as the channel. It has a length L and a width W. Similar phenomena are observed in river gates and industrial valves (Kolkman 1976, Ferreira et al. 1989, Antunes & Piteau 2010). In first approximation, a valve can be described as a mass spring system with a single degree of freedom. When the hydrodynamic force F_h acting on the valve has an oscillating component in phase with the valve velocity dh/dt, a net transfer of energy can occur from the flow to the oscillation of the valve. This can lead to a self-sustained oscillation if the time average of the power $F_h dh/dt$ is sufficient to compensate the damping. Obviously, a quasi-steady flow model, for which $F_h = f(h)$, cannot predict the oscillation of a valve with a single degree of freedom because the net work over an oscillation cycle vanishes when the force depends only on h, $\oint f(h)dh = 0$. For flutter to occur, the hydrodynamic force must depend not only on the opening h, but also on the valve velocity dh/dt; hence $F_h = f(h, dh/dt)$. For example, if the shape of the valve changes depending on the sign of the velocity dh/dt, then flutter can occur. This corresponds to the simplest model of vocal folds oscillation, in which one assumes that the valve has two mechanical degrees of freedom, allowing a change in the shape of the valve depending on the sign of dh/dt. Another possibility is that the flow within the valve has a memory time of the order of magnitude of the oscillation period. Such a memory effect usually corresponds to the traveling time of the vortices along the valve. This is analogous to the stall flutter of an airfoil. Alternatively, the pressure difference across the valve can be modulated by the acoustic response of an adjacent resonator. This is the simplest model for a clarinet or oboe, in which the acoustic coupling is so strong that the oscillation frequency corresponds to an acoustic pipe mode rather than the valve mechanical resonance frequency.

We now give an example demonstrating the complexity of the problem. Hirschberg et al. (1994) built a single-degree-of-freedom valve and placed it in a wall between two large rooms to minimize acoustic feedback. Although oscillation was not observed for a uniform channel height, oscillation did occur at $Sr_L = \omega L(hW/Q_v) = O(10^{-3})$, with ω the oscillation frequency, for a fully chamfered (diverging) channel. This indicates that the assumption of a uniform reed channel height used in most existing models is not always good.

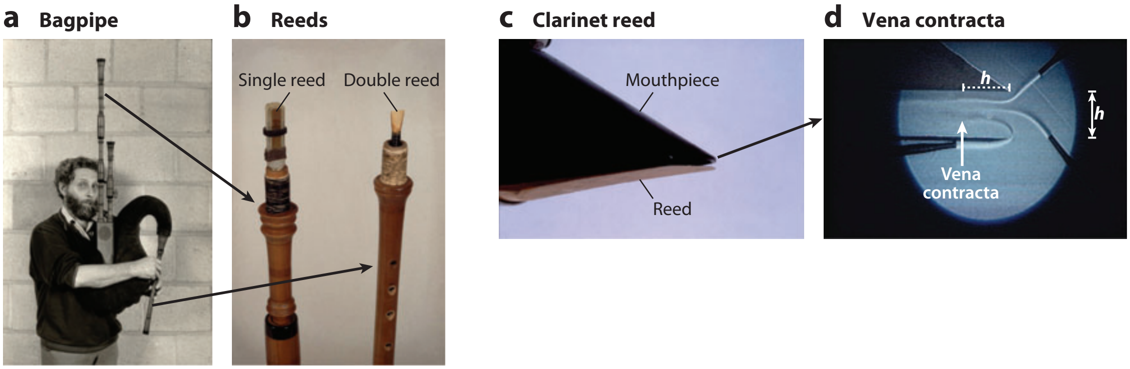

Figure 2

Single- and double-reed instruments. (*a*) Bram Wijnands playing a Flemish bagpipe with (*b*) a double reed of the conical melody pipe (*right*) and a single reed of the cylindrical drone pipe (*left*). (*c*) Tip of the mouthpiece (*black*) of a clarinet with a single reed (*below*). (*d*) Schlieren visualization of the vena contracta (flow pattern in the middle of the channel at a distance h from the inlet) of an upscaled (factor of 10) static 2D model of the mouthpiece of a clarinet. Needles were used to inject CO_2 as a tracer. h is the height of the channel. Visualization provided by A.P.J. Wijnands.

5.2. Single Reeds

A single reed is a thin flexible rod (plate) that is clamped at one end and free at the other end (see **Figure 2**). The reed is placed over the opening of the mouthpiece. In its resting position, it leaves a thin slit-like opening: the reed channel. Upon an increase in blowing pressure, the reed channel height h decreases until a critical threshold blowing pressure is reached, at which point the reed starts oscillating. Although torsional vibration can occur (Backus 1977), the normal motion corresponds to the first bending mode of the reed.

For a clarinet and a saxophone, the reed is commonly made of reed cane. It is flat and has a wedge shape with a sharp edge at its free end. The free end is pressed by the player's lip against the side walls of the mouthpiece opening, referred to as the lay. For a clarinet, contact with the lips provides damping, avoiding oscillation of the reed at its natural frequency, which corresponds to unpleasant squeaks and squeals (Rossing et al. 2002). The contact of the reed with the lay is an essential nonlinearity, which largely controls the sound quality.

In reed organ pipes, the reed is commonly a metal plate that is curved by the instrument maker. The lay is almost flat. The reed has a low damping. Hence, in contrast with the clarinet, the instrument oscillates at a frequency close to the natural frequency of the reed. The reed is tuned by shifting a clamp.

The simplest fluid dynamic model for the flow in the reed channel assumes an incompressible, frictionless, and quasi-steady flow. The flow separates at the channel exit, resulting in the formation of a free jet of height h within the mouthpiece. The kinetic energy of the jet is dissipated by turbulence with negligible pressure recovery. This leads to the relationship between the volume flow Q_v, entering the pipe through the reed channel, and the pressure difference $(p_0 - p)$ across the reed:

$$Q_v = hW\sqrt{\frac{2|p_0 - p|}{\rho}} \quad sign(p_0 - p), \tag{3}$$

where W is the reed channel width, p_0 is the mouth pressure, p is the pressure at the pipe inlet, and ρ is the air density. Backus (1963) proposed an empirical modification of this formula. The formula is based only on limited experimental data, however, and has not been confirmed by further research. Hirschberg et al. (1990) attempted to improve this formula by allowing flow separation at the sharp edges of the reed channel inlet (**Figure 2**). For short channels, $h/L > 0.5$, this results in a decrease of Q_v by the vena contracta factor $\alpha \approx 0.5$. We note that an inlet edge radius of curvature of 10% of the channel height is sufficient to make this phenomenon negligible (Blevins 1992). The vena contracta effect has been observed in static models (van Zon et al. 1990) and two-dimensional (2D) lattice–Boltzmann numerical simulations (da Silva et al. 2007, Bader 2008). Steady flow measurements on actual clarinet mouthpieces have not confirmed this (Dalmont et al. 2003). This may partially result from the difficulty in the definition of the reed channel opening Wh as a result of the essentially 3D geometry, with inflow from the sides. The effect is therefore not established for the clarinet and saxophone. It does certainly occur in reed organ pipes (Hirschberg et al. 1990) and in experiments such as those presented by Wilson & Beavers (1974). Recent particle image velocimetry (PIV) measurements confirm the existence of the vena contracta $\alpha \approx 0.5$ locally at a distance $x \approx h$ from the inlet of the reed channel of a saxophone mouthpiece under playing conditions (V. Lorenzoni & D. Ragni, unpublished data).

Van Zon et al. (1990) proposed an analytical model taking into account friction for a uniform reed channel height [corrections of typing errors in this paper are provided by da Silva et al. (2007)]. The model is an extension of Ishizaka & Matsudaira's (1972) model, based on the von Kármán integral equations (Blevins 1992). Experiment and numerical simulation confirm the validity of the model. The effect of friction is controlled by the product of the Reynolds number $[Q_v/(W\nu)]$ (based on the kinematic viscosity ν) and on the aspect ratio h/L, of channel height h and length L. When a reed is beating (closing completely), the model predicts strong viscous effects. It is not obvious, however, that deviation from the basic model equation (Equation 3) is dominated by viscosity. Indeed as the channel height is reduced, the volume flow driven by the unsteady movement of the reed can become dominant. In experiments with a mechanically driven channel height, Deverge et al. (2003) found that, for a uniform channel height, the unsteady flow phenomena dominated on impact when the reed closed completely. When the channel height was nonuniform, as for lips, the viscous effects appeared to be dominant. Deverge et al. (2003) proposed simplified analytical models to describe the flow in both cases.

When the reed channel–length surface area WL is small compared with the moving surface area of the reed, the unsteady displacement flow can be neglected within the reed channel, although it is still significant for the acoustic response of the instrument. In a first linear approximation, the displacement flux results in an end correction for the pipe length (Dalmont et al. 1995, Fletcher & Rossing 1998, Nederveen 1998, Chaigne & Kergomard 2008).

In the simplified model, which is successful for virtual instruments, the exact geometry of the mouthpiece does not seem to be relevant, except for the shape of the lay. Experiments indicate, however, that a small modification of the inner geometry of the mouthpiece can have a significant impact on the playability of the instrument (Hirschberg et al. 1994).

5.3. Double Reeds

The double reed of an oboe or bassoon consists of two reed-cane wedges, fixed to a metal pipe segment (staple for the oboe or bocal for the bassoon; see **Figure 2**). The sharp free ends, pressed against each other, form the inlet of a narrow channel. Paradoxically, Gokhshtein (1981) has shown that in a bassoon, cutting these edges (rounding them off) enhances the playability of the instrument. In an attempt to obtain a simplified model, Hirschberg et al. (1995) assumed that the staple or bocal had significant flow resistances. Applying Equation 3 to the reed followed by a static nonlinear flow resistance, one observes a steepening of the volume flow characteristic as a function of the pressure in the range in which oscillations occur. This would explain the fast closing of the reed. Antique double reeds do have a neck (Baines 1967). Measurement of the geometry of a bassoon reed indicates such a neck (Gokhshtein 1981). Although the model of Hirschberg et al. (1995) is attractive because of its simplicity, it is contradicted by the experiments of Almeida et al. (2007b) on oboe double reeds. An additional problem is that the reed displacement flux in the reed channel is expected to be more important for a double reed than for a single reed, so the flow might be essentially unsteady.

Modern double-reed instruments have a conical pipe. It appears that this is more important in explaining their particular dynamic response than the exact behavior of the double reed (Gokhshtein 1979, Grand et al. 1997, Chaigne & Kergomard 2008). Owing to the conical shape of the pipe, the reed closes for only a short fraction of the oscillation period. Apparently, double reeds are designed to close rapidly and completely (Gokhshtein 1979, Almeida et al. 2007a), but mouthpieces with single reeds have been made that can be used to play an oboe or a bassoon. This example indicates that plausible wrong explanations exist for the complex phenomena we are considering.

Extensive measurements have been carried out by Grothe et al. (2009) on the bassoon to explore the role of the bocal. Vibration of the bocal is reported to influence the high frequencies in the radiated sound.

5.4. Free Reeds

Harmonica reeds are rectangular, thin metal strips. Each reed is fixed at one end to the side of a rectangular hole in a plate. The hole is such that the strip can move through it without colliding with the plate. The reed starts oscillating above a critical pressure threshold, applied across the plate. The reed oscillates close to the natural frequency of its first bending mode. In a first modeling approach, acoustical coupling with the acoustic field is assumed to be a secondary effect. St. Hilaire et al. (1971), Tarnopolsky et al. (2000), and Ricot et al. (2005) argued furthermore that the oscillation of the reed does not rely on the breakdown of the jet downstream of the reed into discrete vortices. This excludes stall flutter. It is assumed that the reed oscillation is a consequence of the local flow inertia.

St. Hilaire et al.'s (1971) model for this phenomenon is based on a matching between a 2D unsteady incompressible potential flow through the slit between the reed and the plate and a 3D incompressible point-source potential flow. The matching between such a 2D flow and a 3D flow depends on the distance at which the matching occurs. The difficulty results from the logarithmic divergence of the 2D flow potential $\Phi(R) - \Phi(R_0) \to (Q_v/2\pi)\ln(R/R_0)$, where R is the distance and Q_v is the sum of the volume flux through the reed channel and the reed-displacement flux. An extension of the 2D theory to infinity would imply an infinitely large inertia of the flow so that the flux Q_v should be independent of time. St. Hilaire et al. (1971) chose the matching distance to be equal to half the reed length. Ricot et al. (2005) encountered a similar matching problem. By comparison with a 3D potential, van Hassel & Hirschberg (1995) showed that the arbitrary choice made by St. Hilaire et al. (1971) is physically reasonable. An integral formulation based on the 3D Green's function for an incompressible flow seems to be the most logical next step.

Interestingly, the simple quasi-steady reed flow model proposed by Tarnopolsky et al. (2000) and Millot et al. (2001, 2007) does predict the behavior of a free reed when taking into account the acoustic response of the upstream cavity (i.e., the player's mouth). This contradicts the assumption that the acoustical feedback is negligible. We note that if the acoustical response of the blowing pressure supply is the key effect for free reeds, there is no essential difference between these reeds and the reed organ oscillating without the downstream resonator (the pipe), as studied by Miklos et al. (2003). One expects, therefore, that for reed-organ pipes the acoustic coupling of the reed with the pressure supply (the foot) may also be important.

6. VOCAL FOLDS AND LIPS

6.1. Two-Mass Model

The vocal folds are lip-like structures that mainly serve to completely close the lower airways, preventing the intrusion of food or liquids into our lungs. The flow channel between the folds is called the glottis. Forcing airflow through the glottis can induce a self-sustained oscillation of the vocal folds. This produces so-called voiced sounds. The pitch is determined mainly by the tension of the vocal folds. The spectrum of the radiated sound is dominated by lines corresponding to harmonics of the fundamental oscillation frequency. The spectral envelope formed by the tops of these lines presents peaks, which are called formants. They correspond to the resonances of the vocal tract (Benade 1976, Rossing et al. 2002). Modulation of the radiated spectra by changing the formants of the vocal tract yields various vowels or voiced consonants and allows modification of the sound color.

The first models of vocal-fold oscillation assumed that the vocal folds were a simple outward-striking reed coupled to vocal-duct acoustical resonance. Obviously, this does not explain why we are able to pronounce the same vowel at different pitches and different levels. Ishizaka & Matsudaira's (1972) model, assuming that the vocal folds are a mechanical system with two degrees of freedom, solved this problem. The model assumes two successive valves, each represented by a couple of mass spring systems. The upstream and downstream valves are elastically coupled by springs. In their original model, the masses are sharp-edged rectangular rods, forming two successive uniform flow channels. Singular pressure losses were assumed due to flow separation at each sharp edge. Pelorson et al. (1994) proposed a smoothly shaped two-mass model with flow separation only at the downstream side of the glottis. The flow-separation point was predicted by means of a boundary-layer theory. A more robust boundary-layer theory has been applied by Vilain et al. (2004). A drawback of the classical two-mass models is that they do not account for acoustical feedback from the vocal tract and lower airways. A model has been proposed by Lous et al. (1998) in which the fluid dynamics is simplified, but acoustical feedback is modeled. This effect appears to be significant in speech (Titze 1988, Lucero et al. 2009, Tokuda et al. 2010), and in singing at very high pitches, it can become dominant (Joliveau et al. 2004).

The robust boundary-layer theory of Thwaites (Blevins 1992) obviously fails when the glottis is almost closed (Decker & Thomson 2007) but is otherwise quite reasonable (Van Hirtum et al. 2009). The lubrication approximation of Reynolds proposed by Deverge et al. (2003) seems to be most adequate when the glottis is almost closed. A smooth transition between the boundary-layer model and the lubrication theory is obtained by using the quasi-parallel flow approximation proposed by Lagrée et al. (2005). A global discussion of flow unsteadiness is provided by Krane & Wei (2006). It is obvious that accounting for the unsteadiness should not be limited to the momentum equation (unsteady Bernoulli). The displacement flux due to the movement of the vocal folds becomes essential during impact (Vilain et al. 2004).

A point of discussion in the literature is the relevance of the Coanda effect, which appears in numerical simulations and experiments. This spontaneous flow asymmetry (**Figure 3**) needs some time to establish itself (Hofmans et al. 2003) and is less pronounced in practical 3D situations than in 2D models. We do not know to what extent the Coanda effect has an impact on the folds' vibration and sound production (Erath & Plesniak 2010).

The collision of vocal folds is commonly described in the two-mass models by a change in stiffness and damping of the mechanical model. In the simple model, the instant of mechanical contact coincides with the interruption of the flow. As vocal folds are complex 3D structures, one can expect a gradual increase in mechanical contact before the interruption of the flow.

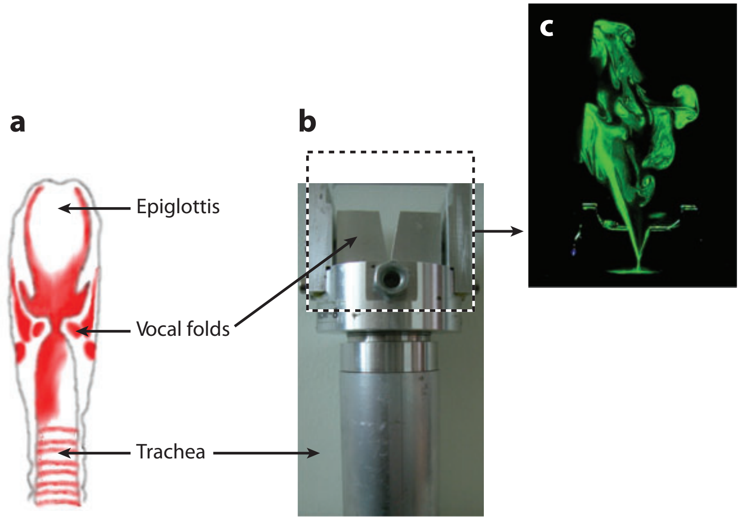

Figure 3

(*a*) Schematic view and (*b*) mechanical replica of the human larynx. (*c*) Visualization of the Coanda effect in an upscaled (factor of three) static 2D model of vocal folds. The jet created by the flow separation downstream of the channel throat flows along the left side of the diverging part of the glottis. Figure courtesy of A. van Hirtum.

This idea was implemented by Pelorson et al. (1994). It improved significantly the prediction of the sound source by avoiding the metallic sound due to abrupt closing. Improving the fluid dynamics without accounting for such aspects could actually deteriorate the prediction as errors in a model can compensate for each other. Hence improvements are meaningful only when they coherently increase the accuracy of all aspects of a model. When considering the flow upon collision, as discussed above, we ignored the presence of a layer of mucus (liquid) on the vocal folds (Murugappan 2010) and elastic deformation. This can lead to inconsistent modeling. Along these lines, we expect that a perfect 2D model including fluid-structure interaction will produce less realistic voiced sounds than a classical quasi-1D two-mass model optimized to produce realistic sounds.

During collision, elastic waves are generated, which we feel along our throat. Modeling of this radiation damping has not received much attention. Mechanical models often consider the vocal folds as mechanically elastic structures with either free or rigid boundary conditions. This leads to higher structural modes, elastic standing waves, with low damping. The two-mass model actually is a two-mode approximation. One could alternatively describe the oscillation by considering a single mode combined with elastic traveling surface waves (Tsai et al. 2008).

6.2. False Folds

Downstream of the glottis, past the flow-separation point, it is generally assumed that all the kinetic energy of the jet is dissipated by turbulence. Although this assumption is reasonable for normal voicing, sound can also be produced by interaction of the jet with the ventricular folds. These so-called false folds are located downstream of the glottis. Their involvement during voiced sound production has been reported during singing, e.g., Mongolian kargyraa throat singing or Sardinian A tenor bassu singing. Typical voice production is characterized by a period-doubling

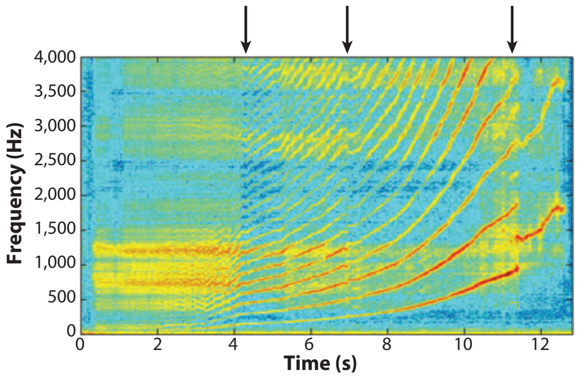

Figure 4

Spectrogram of a glissando (continuous pitch increase) performed by a soprano singer. The abrupt variation at each change of the voice mechanism is indicated by arrows. Figure courtesy of N. Henrich.

phenomenon, an octave jump below the original tone. Based on in vivo exploration and in vitro experimental studies, Bailly et al. (2008) showed that a plausible explanation for this effect could be an interaction of the glottal jet with the ventricular folds. Numerical simulations tend to confirm this assumption.

6.3. Voice Registers

Voice registers are generally, but sometimes ambiguously, defined on the basis of perceptual consequences. Physically, they refer to different modes of vibration of the vocal folds (Henrich 2006). The transition between the different registers can be perceptually subtle but is clearly observed in spectrograms (**Figure 4**). During speech, one commonly uses the vocal fry, chest, and falsetto registers. The transition between the chest and the falsetto register is often explained by a sudden change in the internal stiffness of the vocal folds, the contraction of the vocalis muscle. However, Lucero (1996) showed that similar jumps could be explained by a bifurcation phenomenon of a nonlinear dynamical system, without the need for a sudden mechanical change. Tokuda et al. (2010) studied the effect of acoustical coupling on register transitions. In singing, a fourth register is often mentioned as the whistle register. A well-known example is provided by the famous Queen of the Night aria by W.A. Mozart. The underlying mechanism is still controversial. To some authors (e.g., Zemlin 1997), the vocal folds are not oscillating, and the nature of the source is comparable to whistling (Wilson et al. 1971). Others have recorded measurable wall vibrations (Sakakibara 2003, Tsai et al. 2008). The origin of these vibrations, however, could be a response of the wall to forcing by the acoustic field.

6.4. Acoustic Coupling of Lips with Brass Instruments

Since Helmholtz (1885), lips on brass instruments have been modeled as outward-striking reeds with a single mechanical degree of freedom coupled to the resonating air column in the pipe. This simple model yields surprisingly realistic sounds under normal playing conditions (Vergez & Rodet 2000).

In general, the musician will select a mechanical mode of the lips close to the selected acoustic mode. There is one exception: the very high notes played by expert musicians. The term very high note here means that the playing frequency is higher than any of the instrument resonances. In

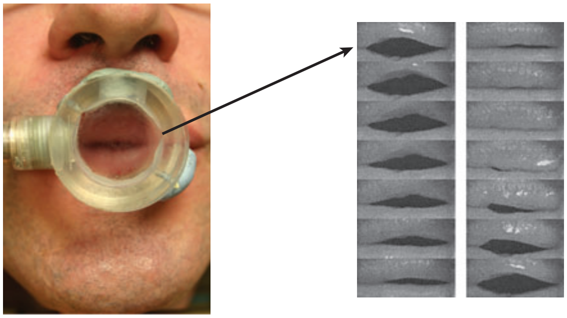

Figure 5

Oscillation of the lips of a brass player playing a Bd pedal note (58 Hz) at the ff level on a trombone: (*a*) a transparent mouthpiece and (*b*) a period of oscillation of the lips. There is a gradually increasing mechanical contact between the lips in the closing phase. Figure courtesy of M. Campbell.

the absence of acoustical feedback, a two-mass model must be invoked to explain the oscillation. Furthermore, brass players are able to obtain self-sustained oscillation of the lips (buzzing) without any brass instrument. The parallel between the lips and vocal folds becomes attractive (Elliot & Bowsher 1982). Observation of elastic surface waves on the lips of brass players provides an additional argument (Copley & Strong 1996, Yoshikawa & Muto 2003).

Artificial lip excitation systems based on a pair of water-filled latex tubes have been developed by Cullen et al. (2000). With this device, both inward- and outward-striking behaviors have been observed near the oscillation thresholds and at the transition between the pipe modes. This also justifies the use of lip models with at least two mechanical degrees of freedom.

6.5. Role of the Mouthpiece in Brass Instruments

The choice of the mouthpiece is crucial for brass players. In addition to comfort, the mouthpiece provides an enhancement of the sound radiation around the mouthpiece formant, its Helmholtz resonance frequency (Benade 1976, Kergomard & Caussé 1986). It also corrects for the nonharmonicity of resonances (Campbell & Greated 1994). The combination of the lips and mouthpiece can also explain the generation of higher harmonics for low pitches at fortissimo levels at the inlet of the pipe (Backus & Hundley 1971, Elliot & Bowsher 1982). Under such circumstances, the maximum lip opening is much larger than the neck of the mouthpiece. During large parts of the oscillation period, the flow is controlled by the flow separation downstream of the neck, and the pressure in the mouthpiece is close to the mouth pressure. As the lips close, there is a critical aperture below which the flow separation at the lips will take over the flow control (see **Figure 5**). As this occurs just before complete closure, the flow is interrupted abruptly, generating higher harmonics.

7. FLUE INSTRUMENTS

7.1. Lumped Models for Recorder Flutes, Organ Pipes, and Flutes

In most flue instruments, a thin air jet (thickness h) is formed by blowing through a flue channel or a slit formed by the musician's lips. The jet flows across an opening in the resonator, called

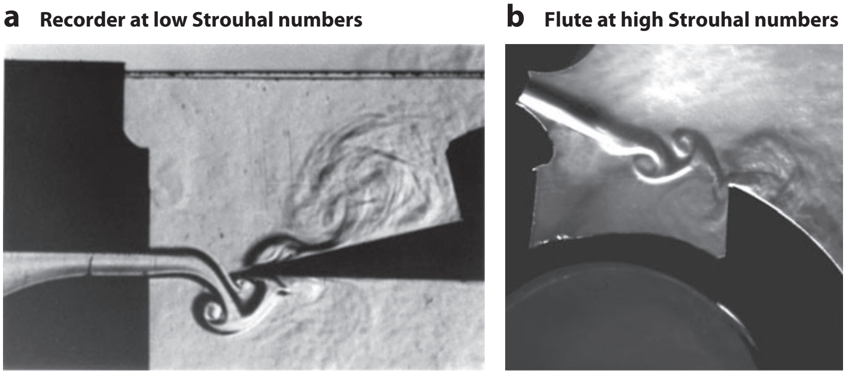

Figure 6

Schlieren visualizations. (*a*) Jet oscillation at low Strouhal numbers in a recorder-like flue instrument. The vortex sheds at the edge of the labium. Visualization provided by A.P.J. Wijnands. (*b*) High-order hydrodynamic mode at high Strouhal numbers of a jet blown across the mouth of a modern Boehm flute at high Strouhal numbers. The jet breaks down into a discrete vortex street.

the mouth. The jet is directed toward a sharp edge, called the labium (**Figure 6**). During steady oscillation, the acoustic standing wave in the resonator drives an air flux through the mouth of the instrument, normal to the jet. The acoustic velocity perturbations at the flue exit induce a modulation of the vorticity in the shear layers delimiting the jet. The vorticity perturbation is amplified by hydrodynamic instability as it is convected toward the labium. The oscillation of the jet around the labium induces an unsteady aerodynamic force. The reaction force of the labium on the air is the source of sound driving the acoustic resonator oscillation. This feedback loop can be described qualitatively in terms of semiempirical lumped models. A review of these models is provided by Fabre & Hirschberg (2000).

In view of the small width of the mouth [$W = 5$ mm compared with the acoustic wavelength $Wf/c = O(10^{-2})$], the low Mach number $U_{jet}/c = O(5 \times 10^{-2})$, and moderately high Reynolds number $U_{jet}h/\nu = O(10^3)$, an incompressible frictionless flow with singular vortical structures, such as vortex sheets or point vortices, is a good approximation. Assuming infinitely thin shear layers, various authors have proposed formal models for the linear stability of such flows (Crighton 1992, Elder 1992, Howe 1998). Howe (1975) and Holger et al. (1980) proposed discrete vortex models. Although they have little predictive value, these models are conceptually important. In particular, Howe (1975, 1984) provided a useful definition of the acoustic field by using a Helmholtz decomposition of the velocity field. The acoustic field is defined as the unsteady scalar potential component of the velocity field. He used this to define a low-frequency Green's function by matching a plane-wave acoustic model in the pipe to a locally incompressible irrotational flow in the mouth of the instrument. As the acoustic velocity is by definition singular at a sharp edge, and vortex shedding occurs at the sharp edges because of viscosity, the model clarifies the importance of the shape of the labium in sound production. One should note that vortices shed at the labium (**Figure 6*a***) actually correspond to nonlinear energy losses, as predicted by Coltman (1968), rather than a driving force for the fundamental harmonic.

Using the formal Green's function proposed by Howe (1975), Verge et al. (1994, 1997a,b) and Fabre et al. (1996) proposed a lumped model for a recorder flute with $W/h \approx 4$. In this model, the laminar jet oscillation is described by a semiempirical model inspired by Cremer & Ising (1967/1968) and Fletcher (1979). The interaction of the jet with the labium is inspired by the idea

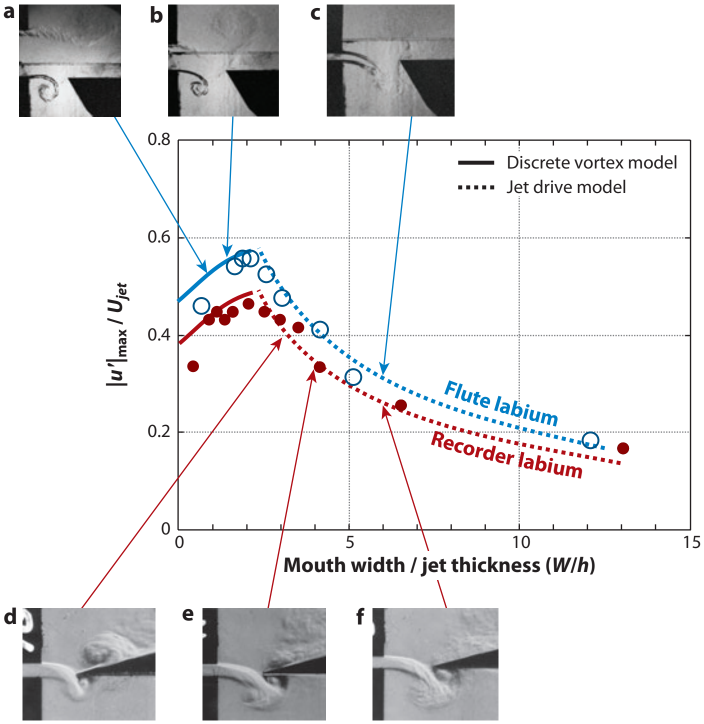

Figure 7

Ratio $|u'|_{\max}/U_{jet}$ of the acoustic velocity through the mouth of a flue instrument and the jet velocity as a function of the ratio W/h of the mouth width and jet height: the jet drive theory (*dotted line*) for $W/h > 2$ (Fabre et al. 1996) and the discrete vortex model (*solid line*) for $W/h < 2$ (Dequand et al. 2003). Visualizations of the flow around the flute labium are shown for W/h equal to (*a*) 0.8, (*b*) 1.7, and (*c*) 6. The flow around the recorder labium is shown for W/h equal to (*d*) 3, (*e*) 4, and (*f*) 6. Visualizations provided by J.F.H. Willems and A.P.J. Wijnands.

of Coltman (1968, 1969, 1976) and Elder (1973) of the separation of the jet flow into a flux Q_{in} entering the pipe and a flux Q_{out} leaving the pipe. On the basis of an order-of-magnitude estimate, Fabre et al. (1996) represented the interaction with the labium as a localized injection of a point source Q_{in} below the labium at a distance h from the edge and a complementary point source Q_{out} above the labium at a distance h from the edge. The pressure difference across the mouth of the instrument due to these oscillating sources drives the acoustic oscillation of the pipe. The potential flow model is furthermore used to calculate a hydrodynamic feedback at the flue exit, allowing the prediction of edge-tone oscillation (Powell 1961, Castellengo 1976, Segoufin et al. 2004, Paal & Vaik 2007, Ausserlechner et al. 2009). Complemented by a quasi-static flow-separation model describing the nonlinear losses by vortex shedding at the labium, the model predicts surprisingly accurately (see **Figure 7**) the limit-cycle oscillation amplitude for steady blowing at low Strouhal numbers $Wf/U_{jet} < 0.3$ for thin jets $W/h < 2$ (Verge et al. 1997a,b; Dequand et al. 2003). In this model for a sharp labium, as found in a recorder flute, a vena contracta factor $\alpha = 0.6$ is assumed. For a thick labium, as found in flutes and pan flutes, one should assume $\alpha = 0.6$ during acoustic inflow and $\alpha = 1$ during outflow. The success of the proposed model in predicting the limit-cycle amplitude should be considered as a lucky strike. Different errors in this simplified model probably compensate each other.

A model is needed to describe the formation of the jet during the attack transient, before it reaches the labium. Such a model has been proposed by Verge at al. (1994). Verge et al.'s (1997b) recorder flute model does produce interesting sounds. At high Strouhal numbers, the jet tends to break down into discrete vortices (**Figure 6*b***), and the jet drive model becomes inaccurate.

For organ pipes with $W/h \gg 4$, the jet is often turbulent. Measurements from Bechert (1976) and Thwaites & Fletcher (1980) can be used to obtain a jet model. The large value of W/h implies that higher hydrodynamic modes will be promoted in such instruments at low velocities. This is observed during the attack transient. The instrument often starts oscillating at a higher pitch (second or third acoustic mode) before recovering the fundamental as the oscillation saturates. This is predicted by the lumped model because the linear amplification of transverse jet perturbations is roughly proportional to $\exp(2\pi Wf/U_{jet})$ for thin jets. Linear behavior promoting higher hydrodynamic modes is expected to prevail in the initial phase of the attack. These modes also dominate the steady oscillation of a flue organ pipe at low blowing pressures, when $Wf/U_{jet} > 0.5$. They appear as a succession of oscillation bursts of decreasing amplitude, after stopping the electrical fan if the key is kept down. Fletcher's (1979) model severely exaggerates these modes because it ignores the breakdown of the jet into discrete vortices for $Wf/U_{jet} > 0.5$ (**Figure 6*b***). Using the sound source model of Holger et al. (1980), Dequand et al. (2003) were able to predict the oscillation amplitude of flue instruments for these higher-order modes. Their discrete vortex model also appeared to be reasonable for very thick jets $W/h < 2$ (**Figure 7**). A unified model integrating the jet drive model (Coltman 1968, Fletcher 1979, Fabre et al. 1996) with the discrete vortex source model of Holger et al. (1980) is a challenge for future research. Without this, we will not be able to provide realistic sound synthesis for organs and flutes. Although such lumped models can be used to create virtual instruments, they cannot explain the importance of the geometric details of the mouth for the playability and sound quality of musical instruments.

7.2. Receptivity of the Jet

Considerable attention is given by the recorder maker to the shape of the flue channel and in particular to the chamfers at the end of the channel. The shape of the flue channel determines the velocity profile of the jet, which determines the jet amplification of the initial vortical perturbations at the flue exit (Nolle 1998, Segoufin et al. 2000). These vortical perturbations are generated by the acoustic flow normal to the jet. In the limit of vanishing boundary-layer thickness and for sharp edges, this jet receptivity for acoustical forcing is described by the Kutta condition applied at the edges (Crighton 1992, Howe 1998). To understand the effect of the details of the flue exit's shape, we need a more accurate model. This is typically a problem that can be approached by the use of a 2D numerical model, which calls for further research (Blanc 2008).

7.3. Unconventional Whistles

The configuration of a jet impinging on a sharp edge is not the only one able to produce musically interesting whistles, demonstrated, for example, by the virtuoso melodic whistler T. Desgagné and others at the International Whistlers Convention. As shown by Wilson et al. (1971), the instability of the jet formed downstream of our lips can couple with the acoustic resonance of the mouth to produce whistling tones. A qualitative explanation of this in terms of vortex sound theory is provided by Hirschberg et al. (1989) and Howe (1998). A striking point here is that the vortex rings formed at the lips do not impact any walls. This clearly demonstrates the superiority of vortex sound theory (Howe 1975, 1998; Hirschberg et al. 1995) compared to intuitive models describing whistling as a result of an impact of an oscillating jet or shear layer on a sharp edge.

An intermediate situation is found in pan flutes. A pan flute is a set of bamboo pipes closed at the bottom. When the player blows with a thin jet directed toward the labium, a pure sound is obtained. By blowing into the open ends using a rather broad jet, the player obtains an easy oscillation without having to direct the jet accurately to the downstream edge of the opening. This allows a very rapid change of the pipe necessary for rapid playing, at the cost of a considerable increase in broadband noise (Fletcher 2005). One can expect that the flow of the jet into the closed pipe generates a static overpressure, which deflects the jet, forcing it to pass along the downstream edge. As explained by Fletcher (2005), the jet will furthermore entrain air by momentum transfer to its surroundings. This will also affect the flow but is not expected to be a major effect. As discussed above, hitting the edge is certainly not necessary for sound production. In the limit of a very thick jet ($W/h > 1$), one can expect that the vortices formed in the lower shear layer will dominate the sound production. This corresponds to the discrete vortex model of Hirschberg et al. (1995) and Howe (1998) for deep-cavity whistling.

Similarly, vortex sound theory provides a model for the sound production in musical toys called the hummer or voice of the dragon (Tonon et al. 2010, Nakiboglu et al. 2011). This is a flexible corrugated open tube approximately 80 cm in length and 3 cm in diameter. By holding the pipe by one end and swinging the tube above the head, one can produce a musically interesting sound. The sound is characterized by a vibrato due to the rotation of the interference pattern produced by the radiation from both ends and the Doppler frequency modulation of the sound from the rotating end.

8. PERSPECTIVES

8.1. Numerical Simulations

Unsteady 2D incompressible flow simulations for geometries with rigid walls can be carried out using commercial codes. A powerful personal computer provides results for Reynolds numbers (5×10^3) relevant in the source region of wind instruments within a few hours. The main problem is to define questions that can be answered quantitatively. Nakiboglu et al.'s (2011) study on the effect of the mean flow profile on the whistling Strouhal number of a corrugated pipe is an example of an interesting result. The sound production of the bullroarer has been studied by Roger & Aubert (2006) using a 2D locally incompressible flow model. The effect of the flue geometry on the jet's receptivity to acoustic forcing in flue instruments is another example of a well-defined problem that can be studied using a 2D incompressible flow model (Blanc 2008). The simulations become much more complex when coupling with wall vibration is involved, such as for reeds (da Silva et al. 2010). In particular, the collision in beating reeds or vocal folds is a problem numerically.

It is important to note that compressible 2D simulations focusing on the source region are extremely difficult. Spurious acoustic reflections and numerical sound generation by vortices at the boundaries of the numerical domain are not easy to avoid. A full 2D simulation of the entire instrument involves radiation. A 2D acoustical radiation at a pipe termination or tone hole is dramatically different from a 3D radiation (Lesser & Lewis 1972). Mathematically matching a 2D inner field to a 3D radiation field is problematic.

It seems more logical to focus on 3D flow simulations allowing the description of the transition from laminar to turbulent flow, which occurs in most musical instruments. Such simulations are currently possible for research purposes. The correct description is essential for the accurate prediction of flow separation from smooth surfaces (vocal folds) and the Coanda effect. Large-eddy simulations (Wagner et al. 2007) or unsteady Reynolds averaged Navier-Stokes models can be meaningful only in the case of fully turbulent flow, as encountered in large flue organ pipes. For other instruments, the lattice Boltzmann method seems most promising (Skordos & Sussman 1995; Kühnlet 2007; da Silva et al. 2007, 2010). This method is quite suitable for parallel computing, and anechoic boundary conditions are relatively easily implemented (Kam et al. 2007).

8.2. Experimental Methods and Analytical Models

Digital signal analysis and image processing have become versatile and cheap. Applications to the study of reed or lip movements are obvious (Almeida et al. 2007a, Guillemain 2007). Numerical schlieren visualization by subtraction of a reference image is another example. The automatic detection of jet oscillation from a flow visualization has been used by De la Cuadra (2005). The laser Doppler anemometer can provide time-resolved velocity data at a point (Paal & Angster 2006). PIV provides global information (Bamberger 2004). It is important to realize that both the laser Doppler anemometer and PIV are difficult to implement in air and are actually not noninvasive. Such measurement can be carried out only in combination with artificial blowing. The injection of fluid particles affects the acoustics of the instrument. Flow measurements on a model using water as the fluid are therefore attractive (Triep & Brucker 2010).

A danger of numerical simulations and sophisticated experimental methods such as PIV is that they generate a huge amount of data that are useless if they are not summarized. One can ask critical questions of the actual impact of the flow details on the radiated sound (Zhang & Neubauer 2010). As stated by Pedley (1980) regarding collapsible tubes, "it is not enough to demonstrate that a particular mechanism can cause oscillations in some experiments." We should aim at quantitative results. A dimensionless representation of the data is a first step toward the quantification of ideas (**Figure 7**). Comparison with simplified analytical models is a further step. Such models are needed to develop musically interesting sound synthesizers, which remains a fascinating goal. Very simple models appear to be suitable in the case of reed and brass instruments. In view of the increasing computer power, one may be tempted to use more complex models. Before making this investment, it is crucial to identify the key effects that are worth modeling. Furthermore, it is crucial to keep the level of accuracy in the model coherent. It might, for example, be useless to improve further the flow model if the mechanical models for the reeds, lips, and vocal folds remain primitive. Moreover, a perfect 2D model can be a poor description of reality. It is often more important to improve the player's control of the virtual instrument than to improve the fluid dynamics model. This allows musical phrasing by the musician.

When considering the use of physical models to assess the playability of wind instruments or as a diagnostic support for phoneticians or surgeons, one needs more sophisticated models, which are not available.

SUMMARY POINTS

1. Artificial blowing is an essential research and development tool in musical acoustics.
2. The nonlinear acoustical response of the pipe, involving wave steepening and vortex shedding, is musically relevant.
3. 2D modeling can display dramatically unrealistic behavior and in practice can be less relevant than quasi-1D models.
4. A player's control of the virtual wind instrument, allowing musical phrasing, is more important than the accuracy of the physical model used in sound synthesis.

5. The typical behavior of modern double-reed instruments (oboe, bassoon, saxophone) results mainly from the conical shape of the pipes.
6. A brass player's lips can commonly be described as outward-striking simple reeds, but they have more complex behaviors around the thresholds and for the transitions between notes.
7. Simple models of flow in wind instruments are efficient in sound synthesis but do not clarify the impact of geometric details on the playability of the instrument.
8. Detailed experimental measurements such as PIV or direct numerical simulations are valuable only when confronted with simplified models.

FUTURE ISSUES

1. The lattice Boltzmann method is a promising numerical method allowing 3D simulations of the flow in the source region.
2. Studies of a musician's control and of the playability of wind instruments are key issues.
3. Flow models for the glottal flow should not be improved before more sophisticated models are available for the mechanical response of the vocal folds, including the effect of mucus (moisture).
4. The impact of the Coanda effect on vocal-fold oscillation and sound production should be determined quantitatively.
5. Although lumped models of flue instruments perform well for laminar jets at low Strouhal numbers, new models are needed for turbulent jets and for high Strouhal numbers.
6. The jet flow directed at a large angle into closed flue instruments, such as the pan flute, deserves further research.
7. The role of the acoustic coupling with the pressure supply should be clarified for free reeds.
8. The effect of combined bias and grazing flow on the nonlinear response of tone holes should be studied.

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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