Interactions between the player's windway and the air column of a musical instrument[1]

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The conversion of the energy of a wind-instrument player's steadily flowing breath into oscillatory energy in musical wind instruments has been well understood for several years. It depends on the cooperative interaction of several resonances of the instrument's air column with the flow-controlling reed. Recent work has demonstrated the importance of additional effects arising from the resonances of the player's own windway. The player can learn to control these effects and normally uses them to stabilize and refine the tone and correct the tuning. He or she may also use them to disrupt the normal processes, replacing them by oscillatory regimes made up of inharmonic partials; musicians call these sounds "multiphonics." This report outlines the way in which the instrument's air column and the player's windway jointly interact with the reed to produce these effects and presents examples of the associated phenomena. Certain medical implications are also described, in particular, chronic problems occurring in clarinet players who, because they do not exploit the resource of windway adjustability, try to improve their tone by using excessively stiff reeds and high blowing pressures.

Index terms: Acoustics • Music

Cleve Clin Q 53:27–32, Spring 1986

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This study was supported in part by grants from the *National Science Foundation.*

0009-8787/86/01/0027/06/$2.50/0

For at least two centuries, both musicians and listeners have observed that an expert woodwind-instrument player can elicit beautiful sounds from practically any instrument, even one of extremely humble pretensions. A player of limited ability, on the other hand, can achieve a much better sound when playing a fine instrument than when struggling with a poor one. This suggests that the skilled player can exploit various physiological resources to modify

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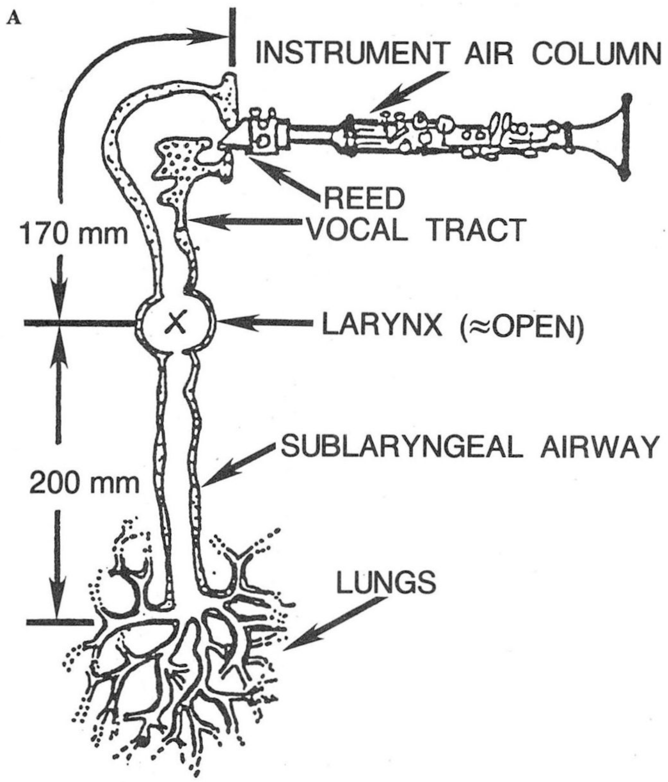

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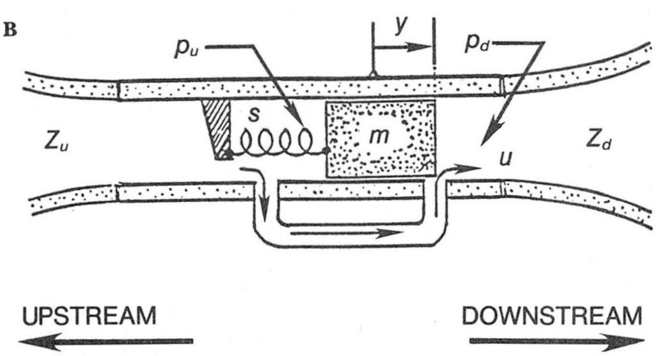

Fig. 1. **A.** The player's windway and the woodwind air column are coupled to the two sides of the reed.
B. Dynamic model of the woodwind reed-valve structure.

the playing dynamics of the instrument in ways that the less experienced player cannot.

The player plus the wind instrument constitute a four-part dynamical system of the sort illustrated (for a generic woodwind) in *Figure 1A.* One major segment is the player's own windway (PWW), extending from the lungs to the lips. Its shape can be modified by use of various throat and tongue muscles. The other major segment is the instrument's air column (IAC), whose effective length can be altered by the opening and closing of a row of toneholes distributed along its length. (In brass instruments, this effective length is changed by adding segments of tubing in the middle by means of a slide or of finger-operated valve-pistons.) Between the player and the instrument is the reed and reed cavity assembly, which compose the remaining two dynamically important segments of the system. This reed assembly provides an adjustable interface boundary between the standing waves that exist within the two air columns. The reed assembly also serves as an air-flow controller operated by the time-varying pressure difference that exists across the two sides of the reed. In the woodwinds, a piece of elastic cane is actually the reed, whereas with brass instruments, the player's lips serve as the reed. Both functions of the reed are intimately joined and are also subject to adjustment by the player: even if the lips do not move from one place to another on the reed, a mere change of lip pressure will change the top-end boundary condition via alterations in the volume of the cavity and the elasticity, inertia, and damping of the reed. Changes of lip pressure will also alter the details of the reed's nonlinear flow-control characteristic.

Formulation

Both aspects of the dynamic nature of the reed mechanism are shown in schematic form (*Fig. 1B*). This illustration also indicates that the mean position and the oscillatory motion of the reed are determined jointly by the difference between the pressures that exist in the instrument's mouthpiece cavity and in the player's mouth. In summary, a wind-instrument sound generator consists of a flow controller (the reed) coupled with the junction of a player's windway and an air column provided with a means for adjusting its effective length.

It is convenient to characterize the PWW and the IAC via their (pressure)/(volume flow) impedances as seen by the airflow controller. The impedance looking upstream into the PWW is written Z_u, while the impedance Z_d looking downstream is that of the IAC. The reed itself requires two characterizations, since it plays two roles in the complete oscillating system. Its acoustic impedance Z_r is defined in terms of its displacement volume velocity when it moves in response to a driving pressure exerted on *either one* of its surfaces (*Fig. 1B*); its flow-control characteristic then describes the flow u through the valve aperture as a nonlinear function of the pressure difference p across it as:

$$u(t) = u_o + Ap(t) + Bp^2(t) + Cp^3(t) + + + + \quad (1)$$

It may be stated that equation (1) gives the flow response of the reed valve when it is stimulated by a pressure signal provided by the composite PWW-IAC system.

The pressure response of the PWW-IAC system to a flow stimulus that comes to it through the reed-valve aperture may be given in terms of a suitably defined impedance (pressure/flow) function Z. For any Fourier component u_n of the flow stimulus, the *pressure difference* p_n across the reed is found to be related to Z_u, Z_d, and Z_r in the manner given by equation (2):

$$p_n = u_n[(Z_u)_n + (Z_d)_n](Z_r)_n/[(Z_u)_n + (Z_d)_n + (Z_r)_n] \quad (2)$$

That is to say (since Z_r is almost always very large in comparison with Z_u and Z_d), the pressure difference across the reed is essentially proportional to the *sum* of the upstream and downstream impedances.[1,2]

To summarize: equation (1) is a representation of the "active" control of net airflow by the reed in terms of a net pressure difference across it, whereas equation (2) provides us with expressions for the pressure signal arising in the airway system caused by an imposed flow; and these equations together describe a two-part (nonlinear) feedback loop, each member of which responds to a stimulus provided by the other.

Mathematical results

The essential behavior of the system is illustrated in the following equations. First, the flow $u(t)$ is written as a Fourier series:

$$u(t) = \Sigma u_n cos(n\omega_o t + \psi_n) \quad (3)$$

Here $_o$ represents the frequency of the tone being produced. Term by term, this series represents

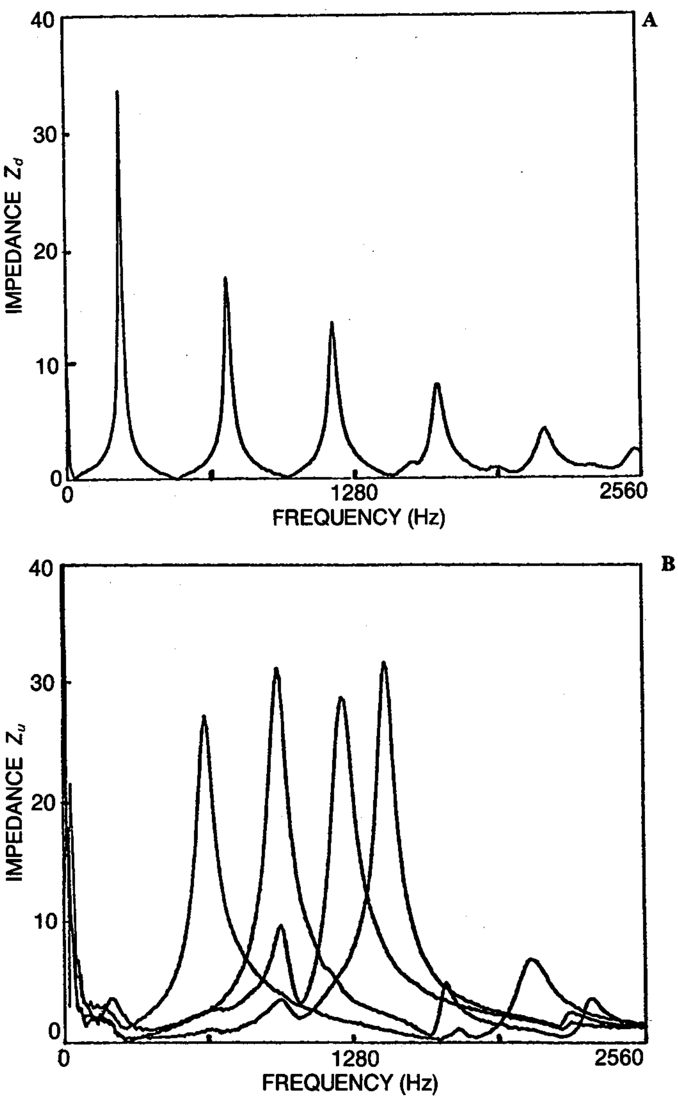

Fig. 2. A. Impedance Z_d looking downstream from the reed into a clarinet fingered to give C_4.
B. Impedance Z_u looking upstream into the player's windway for several vowel-like configurations of the mouth and throat.

the flow-excitation spectrum being applied to both parts of the (PWW + IAC + REED) system. Given the (net) impedance $Z(\omega)$ of this system, we will write Z_n for its magnitude at the frequency n $_o$ and $_n$ for its phase. The pressure signal corresponding to $u(t)$ can then be written:

$$p(t) = \Sigma Z_n u_n cos(n\omega_o t + \psi_n + \phi_n) \quad (4)$$

Equations (1), (3), and (4) can, at the expense of considerable labor, be solved simultaneously to

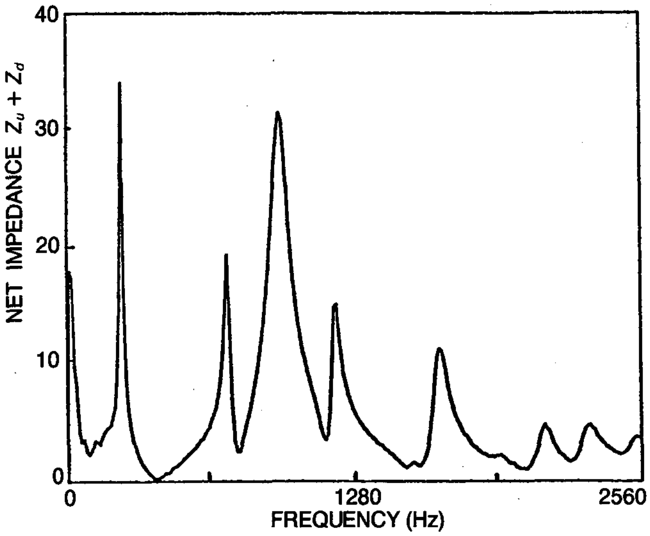

Fig. 3. An example of the composite impedance ($Z_u + Z_d$) that ultimately controls the reed.

give the pressure spectrum across the reed for a given blowing pressure, plus a great deal of information about the system, all of which has been confirmed by experimental tests.[3-5]

Equation (5) indicates the nature of the pressure spectrum as observed on the downstream side of the reed:

$$(p_d)_{n>1} = (Z_d)_n p_1^{\,n} \cdot \left\{ \frac{1 + f(\textit{powers of } p_n, \textit{etc})}{1 - Z_n[A + F(\textit{powers of } p_n, \textit{etc})]} \right\} \quad (5)$$

The analogous spectrum to be observed within the player's mouth is found by replacing the Z_d by its cognate Z_u in the numerator. Notice, however, that in the denominator, it is the *composite* Z_n [as defined in equation (2)] which appears, ensuring that both IAC and PWW have an "influence" in determining the nature of the oscillation. It is noted in passing that $(p_d)_{n=1}$ has a very similar form.

Equation (6) gives an abridged version of the major spectral implication of equation (5) and implies its upstream cognate:

$$(p_d)n = (Z_d)_n(p_1)^n \times \textit{other, slow-moving terms} \quad (6)$$

From this it can be seen that the shape of the reed-driving pressure spectrum is well caricatured by the envelope of the controlling impedance $(Z_d)_n$ and also that the nth pressure amplitude component is proportional to the nth power of the *fundamental* component amplitude (as this may be changed by alterations in the player's blowing pressure).

Changes in the positions and heights of the impedance peaks of either the PWW or the IAC are reflected directly by changes in the corresponding mouth and mouthpiece pressure-spectrum amplitudes. However, analysis and experiment reveal a further and surprising result: *changing Z on one side of the reed makes very little change in the spectrum on the other side*! Departures from this result are known, but they arise only under rather special circumstances, which are currently under detailed study.

Experimental illustrations

Since all wind instruments function in essentially the same way, most of the following discussion will be limited to only one of them, chosen to best illustrate the principles involved. *Figure 2A* shows a typical Z_d impedance curve measured for a clarinet. The played note has its fundamental component primarily fed by peak 1 of this collection, whereas the next three peaks feed harmonics 3, 5, and 7 and collaborate with peak 1 in a mutually stabilized regime of oscillation to give rise to all the other harmonics that may be present in the tone. On the best notes of fine instruments, peaks such as these have been "aligned" so that they are harmonically related to within about 0.5% (under playing conditions) in order to assure the player a clean start-up, a stable-running full tone, and controllable dynamics without pitch drift. This last statement implies almost all the structure and behavior of a fine instrument as has been discussed in detail.[6]

Figure 2B shows Z_u curves measured for various configurations of a player's windway. For each configuration, there is an impedance peak that is as tall or taller than any for the IAC. Experiments conducted by myself in conjunction with Hoekje and Jameson show (by direct measurement) that a player can position this tall peak at any desired frequency over the range 440 to 1500 Hz. If it is recalled that the reed is controlled by the *sum* of Z_u and Z_d, *Figure 3* shows such a summation for the special case in which the player has chosen to place his main PWW peak at the position of the fourth harmonic of the C_4 being played by the clarinet.

Alignment of the PWW peak causes a 40-dB (100-fold) increase of this harmonic in the player's mouth (*Fig. 4A*), along with a considerable strengthening of the nearby components as a result of heterodyne coupling between this strong component and its neighbors. The spectra measured in the mouthpiece of the clarinet (*Fig. 4B*) show, on the other hand, that alignment of the PWW resonance makes relatively little change here. The level of the fourth harmonic is raised by only 12 dB (a fourfold amplitude change).

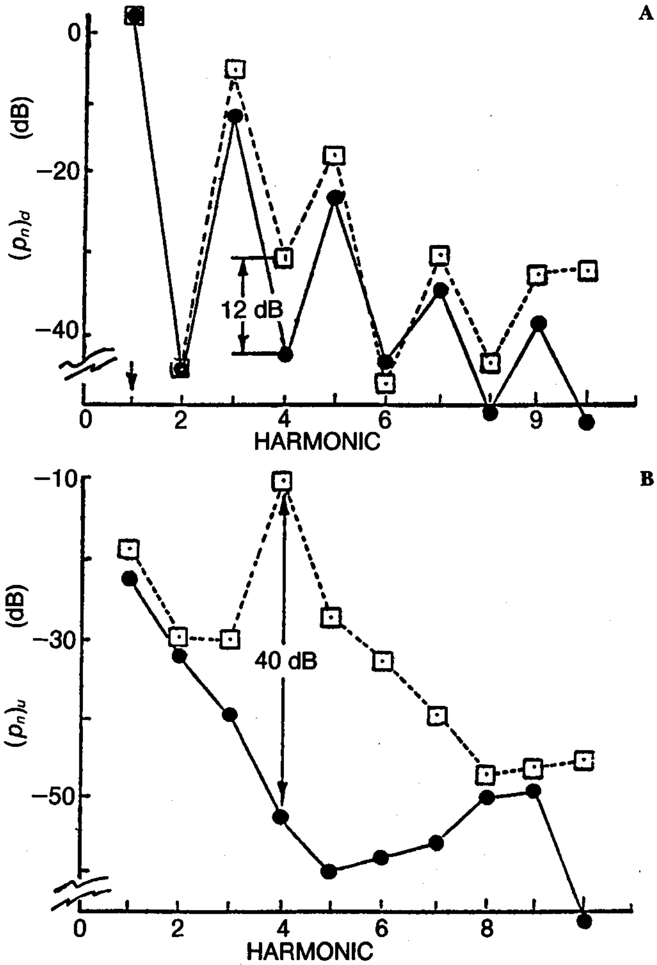

Fig. 4. **A.** Sound pressure spectra $(P_d)_n$ in the mouthpiece of a clarinet playing C_4.
B. Spectra in player's mouth. Dashed lines show spectra when PWW peak is aligned with the fourth harmonic of the tone. Solid lines give spectra when PWW peak is not aligned with any harmonic.

Musical implications

Increasingly, over the past decade and a half, I have served as a consultant to the musical industry and to individual players on problems concerning the structure of instruments and also as an adviser on problems of tone production and playing technique. This latter activity influenced the research on instrumental physics per se that called attention to the importance of physiological controls available to the player and that shaped the techniques used to study them.

The musician who has learned the automatic and quasi-unconscious placement of his PWW resonances benefits from a steadier, clearer tone that results in improved pitch stability and better control of dynamics. He or she is also better able to "fudge" a bad instrument. He or she does not, however, gain the ability to make extensive changes in the *radiated tone color*, as confirmed by Backus,[7] except in some very special circumstances as will be discussed.

Two important questions remain to be answered. First, why does the big PWW resonance fail to make its presence known in the upstream spectrum when it is *not* aligned with a playing harmonic? A partial answer is that if it did try to produce energy, the resulting inharmonic intermodulation components (away from any *Z* peaks) would result in a heavy drain on the energy reserve. However, *special* placements of a PWW peak *can* work with peaks belonging to the IAC to produce complicated inharmonic sounds known to musicians as "multiphonics." Second, is it possible to arrange a peak-free impedance curve for the IAC such that the entire burden of oscillation is laid on the adjustable peak belonging to the PWW? Such an air column has been constructed, and it behaves as expected. As an experienced professional woodwind player, George Jameson has demonstrated in tape recordings that simple tunes or even the themes of Haydn's Trumpet Concerto and the Lucia Sextette are perfectly playable on it after only a few minutes of initial practice to gain control of the PWW.

Most present-day wind players use the resonances of their PWWs to "fill out," "clarify," or "stabilize" the notes they play by providing harmonic resonances on the upstream side of the reed to supplement or to "fine tune" the IAC resonances. Although music teachers may not be very precise in explaining the physiological aspects of the use of the PWW to students, they usually manage to communicate what is needed. Most of the time it is sufficient merely to get the student to produce a certain effect. He or she can then develop the rest by thoughtful practice.

However, there are some players who have not learned to use the PWW resonances—particularly among the ranks of the clarinet players during the past 30 years. Sad to say, a kind of "feedback process" has taken place between these players and instrument manufacturers that has led them (with the best of intentions) in recent years to construct instruments that actively interfere with serious attempts to exploit the physiologically controlled resonances. Such players have thus lost control over their note-by-note tuning, and are left to strive for whatever acceptable (but unvarying) tone can be gotten from the use of peculiarly faced mouthpieces and ever-stiffer reeds. These players suffer in a personal way, because they are forced to use very stiff reeds and high blowing pressures if they are to achieve what is considered to be an acceptable tone. They are also the subject of continual complaints of conductors and the players of other instruments because they do not correct the tunings of their notes as the musical context changes and are criticized for the rigidity and the inflexibility of their tone.

Chief medical implications

From the medical point of view, the phenomena outlined in this report have two major implications. First, evidence has been presented showing that there is normally a great deal of highly coordinated activity within the wind player's vocal tract, beyond the familiar maneuvers associated with tonguing and breathing. As often happens in dealing with the professional behavior of athletes and musicians, we have added to our list of reasons for taking great care not to disrupt any subtly organized pattern of skill in the course of treating some disease or disorder. Second, among clarinet players, there is an increasing incidence of trouble arising from their relinquishment of an important resource: control of the PWW. This relinquishment, and the efforts to somehow deal with it by indirect means, often causes the player to develop a chronically lacerated area inside his lower lip, sprung mandible joints, air-leaks into the nasal passages, and a generalized feeling of tension- and discomfort-related stress that can seriously cut down his playing stamina.

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