What is Acoustic Impedance and Why is it Important?

Acoustic impedance is a ratio of acoustic pressure to flow. The **specific acoustic impedance** is a ratio of acoustic pressure to specific flow, or flow per unit area, or flow velocity.

We discuss it on this music acoustics site because, for musical wind instruments, acoustic impedance has the advantage of being a physical property of the instrument alone -- it can be measured (or calculated) for the instrument without a player. It is a spectrum, because it has different values for different frequencies -- one can think of it as the acoustical response of the instrument for all possible frequencies. For instance, we measure it at the embouchure of an instrument because it tells us a lot about the way the player's lips, reed or the air jet from the mouth will interact with the instrument itself. So it tells us about the acoustical performance of the instrument, in an objective way that is independent of who might play it, and it allows us to compare subtle differences between instruments. So what is it?

An analogy. Electrical resistance is often explained by analogy with the flow of water: the hydraulic resistance would be the ratio of the pressure difference between the ends of a pipe to the flow in the pipe. Electrical resistance is the ratio of the voltage applied to the electrical current it produces. Resistance is a particular (and rather boring) example of*impedance*, which is the general term for a ratio of voltage to current. DC (direct current) means constant or slowly varying current. AC (alternating current) means any current in which the movement is alternately backwards and forwards (oscillating) with no overall motion. AC is more interesting because the impedance can vary with the frequency of oscillation of the current. (*These analogies are limited*: air is compressible so the flow does not obey Kirchoff's law about conservation of current.)

The **acoustic impedance** (**Z**) of a component is the ratio of the acoustic (or AC) pressure p across it to the flow of fluid U through it. Like electrical impedance, acoustic impedance is complicated by the fact that the current and pressure are not necessarily in phase -- the maximum voltage may be ahead of the maximum current, or vice versa. As in electricity, we use complex numbers to handle this, where the real part represents the in-phase component and the imaginary part the out-of-phase component. (The **specific acoustic impedance** is the ratio of p to the flow per unit area U/A. U/A equals the acoustic velocity: the velocity of particles in the medium due to their motion in the sound wave.

Units. The unit of pressure is the Pascal -- one Newton per square metre. A Pascal is a big unit for sound: an oscillation of one Pa is usually a very loud sound indeed. (In DC the Pa seems a small unit: atmospheric pressure is 100,000 Pa or 100 kPa.) Flow is measured in cubic metres per second. (A very gentle breeze coming in your window could be 1 m^3/s. But for 1 m^3/s to flow down a pipe, either the pipe must be big -- think ventilation ducts -- or the speed must be high.) The units for impedance are therefore $Pa.s/m^3$, which we call the acoustic ohm (Ω). For musical instruments, it is a rather small unit, so we use megohms ($MPa.s/m^3$. Finally, sound pressures have a large range. For this and other, psychophysical reasons we use logarithmic scales for sound level and impedance. For a linear quantity like sound pressure or impedance, you can convert to dB by taking the log of any ratio, then multiplying by 20.

For an infinitely long pipe, with cross sectional area S and filled with a medium of density ρ and speed of sound c, the acoustic impedance is $\rho c/S$. So, for an infinitely long pipe with diameter 10 mm filled with air, the acoustic impedance is 5 MΩ. (The quantity ρc doesn't depend on the size of the pipe: it is a property of the medium alone, called the **specific acoustic impedance**.)

Note that we have referred to an infinite pipe in the example above. In such a pipe, a varying pressure causes a wave which is a varying flow of air, and which never comes back. In a short pipe, however, the wave reflects at the far end (whether it be closed or open) and comes back, reflects again, and gives rise to standing waves or resonances (see pipes and harmonics). This causes the impedance to be much higher or lower than the value calculated above, depending on whether the pressure of the returning wave is in phase or out of phase with the driving pressure.

The acoustic impedance of musical wind instruments varies spectacularly with frequency because these instruments are designed to produce one or several frequencies only in a particular configuration. For example, the flute is played with the embouchure hole (at least partly) open to the atmosphere, so the pressure at the embouchure hole is very near to atmospheric pressure. Thus the acoustic pressure (the varying part) is nearly zero. The flow is provided by a jet of air from between the player's lips. Oscillations of air flow in the flute can cause this jet to deflect upwards (outside the flute) or downwards (inside) so that the acoustic flow (the AC component) can be large. Thus the flute operates at *minima* of Z: a small pressure and a large flow. Nearly all other wind instruments have a reed which is sealed by the player's mouth and they operate at *maxima* of Z: the varying part of the pressure is large, but the oscillating part of the air flow is small at the reed. See Flutes vs Clarinets.

In each of the impedance curves for the flute, there are at least a few rather deep, sharp minima, and the flute will usually play a note with a frequency near each of those deep minima. The ease of playing and the stability of the note depend on the depth and narrowness of the minima.

Conversely, in each of the impedance curves for the clarinet, there are at least a few rather high, sharp maxima, and the clarinet will usually play a note with a frequency near each of those high maxima. The ease of playing and the stability of the note depend on the height and narrowness of the maxima. For instance the very highest notes are hard to play, and you can see on the spectra that at high frequency the maxima and minima are weaker--they "help the player less". There is more to it than this, however. For the instrument to play properly a note with frequency f, it usually needs an extremum at f, and also extrema at 2f, 3f, 4f etc. The reason for this is that the vibration of the air jet or reed and the sound made by the flute are not simple sine waves. Their waves are periodic waves (that is they repeat in time) and they contain a fundamental and a harmonic series. It is important to the performance of wind instruments that the various minima that help produce a particular note are in the harmonic series. See "How harmonic are harmonics?" and "How do woodwind instruments work?"

For the flute, it is helpful to look at the Z curve for the lowest note C4, or middle C, for a more detailed explanation. For the clarinet, see acoustic response of the clarinet.

For more detail about acoustic impedance and its musical significance, an excellent book is

- Fletcher, NH and Rossing, TD (1998) *"The Physics of Musical Instruments"* Springer-Verlag, New York.

The acoustic impedance of the flute for any particular fingering is one of the major factors which determines the acoustic response of the flute in that fingering. It determines which notes can be played with that fingering, how stable they are and it also helps determine whether they are in tune.

The acoustic impedance also has a large influence on the sound produced. To see some examples of this, have a look at the two different fingerings for the note A#4 (the "long" fingering using the RH index finger, and the "short" fingering using only the LH thumb). Look in particular at the relative depths of the 3rd and 5th minima in the impedance spectrum, and at the strengths of the 3rd and 5th harmonics of the sound produced. Look also at the two different fingerings given for A4, the relative depths of the harmonic minima, and the effect that they have on the timbre produced. Another difference that is worth looking at is the difference made by a "split E" mechanism. Look at the different Z spectra for E6 with and without the mechanism, and compare them with that for the note A5. Then try the experiment of slurring between A5 and E6 on flutes with and without the mechanism.

Another thing which has a big influence on the sound is the player, but that is another story and it is much more complicated. Indeed a big advantage in measuring Z is that it gives us an objective measurement of the instrument alone. In that way it is in some ways more useful to scientists and to flute makers than the sound of the instrument. If you get a poor sound from a flute, it might be because the player is poor, or it might be because the instrument is poor. With our industrial collaborators, Terry McGee, Lehner Flutes Australia and The Woodwind Group, we are working to obtain objective comparisons of different flutes, to analyse the differences in their acoustical properties and to explain their different musical performance.

Source: http://www.co-bw.com/Audio_Impedance_Importance.htm