Trumpet & Sax Input Impedance

By
David Pignotti
and
Chris Van de Riet

dpignot2@uiuc.edu
chrisvan@uiuc.edu
Outline of Presentation:

• Acoustics and Saxophone Overview

• Impedance and Construction of a Trumpet

• Experimental Apparatus

• Speed of Sound Measurements

• Future Work
How Do Wind Instruments Work?

Reed or player’s lips excites air in tube

Air in tube resonates at natural frequency plus harmonics

Construction of instrument determines tuning

Impedance spectrum gives behavior of instrument
Saxophone Overview

A cane reed vibrates the air column in the instrument

Saxophone can be approximated as an open-open pipe

Produces the fundamental frequency and all the higher harmonics as overtones

What determines the vibration frequency of the reed?
Acoustical impedance is a measure of resistance to putting a pressure wave though a tube

\[ Z = \frac{\tilde{P}}{\tilde{U}} \]

At impedance mismatches (bell end of trumpet), pressure waves are reflected back to player’s lips (or the reed for woodwinds)

**Reflected waves** give player’s lips (or the reed) “information” on vibration frequency

Acoustical intensity is the product of pressure and particle velocity, \( I = PU \)
Impedance Spectra For Construction Of A Trumpet

(a) Cylindrical tubing
(b) Tubing plus trumpet bell
(c) Tubing, lead pipe, and mouthpiece
(d) Tubing, lead pipe, mouthpiece and trumpet bell
Sinusoidally excited piezoelectric driver method of impedance measurement

Piezoelectric driver frequency proportional to driving voltage

Use microphone to measure pressure

Air particle velocity is determined by the assumption that flow amplitude is known for the piezoelectric driver

Can we do better?
Our Plans To Get Impedance Spectrum

Excite the air with a piezoelectric transducer

Measure pressure using an electret microphone

Measure particle velocity using a pressure-differential microphone
Microphone is used to measure pressure

Knowles Acoustics omnidirectional condensor electret microphone is 0.1” in diameter – world’s smallest !!!

Sensitivity is flat up to 10 kHz
Pressure-differential microphone is used to measure particle velocity

Modified RadioShack condenser microphone (Part # 270-090)

Removed back of microphone to expose both sides of the pressure gradient transducer

Integrate differential-pressure signal to get value proportional to particle velocity

\[
 u = -\frac{1}{\rho_0 d} \int_{-\infty}^{t} [p_1(t') - p_2(t')] dt'
\]

Flat frequency response from 30→3000 Hz
Absolute Calibration of P & U-Mics:

• Use FG (1 KHz signal) + Amplifier + Loudspeaker + Extech 407768 SPL Meter to absolutely calibrate mics.
• Place SPL meter, P & U-mics in “far-zone” of loudspeaker along speaker axis.
• Turn up volume on amp such that achieve 94.0 dB (C-weighting) on SPL meter.
• Measured sensitivity of P & U-mics is $S_p = 280 \text{ mV/Pa}$ and $S_u = 140 \text{ mV/Pa}^*$, respectively. (1 Pa* = 2.5 mm/s), with ~ 10% uncertainties.
Both instruments were playing concert-pitch Ab (103.83 Hz for the sax, and 207.66 Hz for the trumpet)

Discrepancies at higher frequencies could be due to the nature of the instruments (with the trumpet, the higher frequencies are intended to be excited by the player, while with the sax, they merely “color” the sound)
Saxophone $|P|, |U|$ Data:

1/f ventilation noise dominates the data at low frequencies.

Particle velocity graph shows consistent shape of peaks.
1/f ventilation noise is still an issue in these plots.

Impedance graph shows symmetry about peaks.

Impedance graph also shows the fundamental is not the easiest note to play using this key configuration.
Standing Wave Tube

Has very well-known resonances

Originally constructed to calibrate phase response of pressure and particle velocity sensors
Standing Wave Tube $|P|$, $|U|$ Data:

These plots extend to 4kHz, and it should be noted that the SWT has a higher-order transverse vibrational mode which begins at ~3.3 kHz.

This higher-order transverse mode is evident in the pressure graph, but not as evident in the (longitudinal) particle velocity graph.

1/f noise is also less of an issue in these plots than with the sax, as the SWT is sealed, whereas the sax has an open bell.
Standing Wave Tube $|Z|$, $<|I|>$ Data:

Impedance peaks are sharp, but the presence of 1/f ventilation noise (in the U-data) is an issue…

The lack of numerous impedance peaks explains why the SWT is a rather uninteresting musical instrument.

The onset of the higher-order mode of the SWT is clearly visible in the both graphs.

Note: The intensity graph’s vertical axis is displayed on a logarithmic scale.
A measurement of the speed of sound was desired for calibration of the standing wave tube.

Used a small piezoelectric speaker driven by 1-100 µs pulses from a function generator to excite sound waves in free air.

Pressure microphone was placed a known distance from the speaker.

Both the pulsed signal from the function generator and output of the microphone were observed on a Tektronix 3052B oscilloscope.

Measured time of propagation from the speaker to the microphone over a range of distances up to 50 cm.
Speed of sound in free air closely matches accepted value:

Measurement in free air gave \( v_{\text{meas}} = 345.8 \pm 1.0 \text{ m/s} \)

At \( T=21.5^\circ\text{C} \) and 60% relative humidity, \( v_{\text{pred}} = 345.07 \text{ m/s} \)

Accuracy is limited by the time difference LSB resolution of the Tektronix TDS 3052B oscilloscope.
Variations in the speed of sound with resonance frequency were observed in the standing wave tube ($v_{\text{air}} = 342.4 \text{ m/s measured, vs. } v_{\text{air}} = 345.8 \text{ m/s that we measured in free air}$). See graph on next page…

Analogous to EM waves propagating inside waveguides!
n.b. Direct measurement of speed of sound in SWT using 10 $\mu$S pulses gave:

$$V_{\text{air}} = 341.0 \pm 0.5 \text{ m/s}$$
SWT Speed of Sound

The Helmholtz-Kirchhoff equation for air travelling in a tube states that $1/v$ should scale linearly with $1/\sqrt{f}$ for dry air:

$$v = v_0 \left(1 - \frac{K}{D \sqrt{2\pi f}}\right)$$

As shown by the top right graph, we did not observe this linear relationship.

The Helmholtz-Kirchhoff equation implicitly assumes that the boundary layer of air is rigidly coupled to the inner wall of the SWT.

Due to high humidity (60-70%), a thin monolayer of water coats the inside of the SWT, preventing this rigid coupling from occurring, thus changing the dependence to $1/f^{3/2}$!
Long-term Plans:

• Collect more data (and buy more lock-ins… 😊)

• Construction of three-dimensional air particle velocity sensor

• “Universal” apparatus: can be used for measuring complex $Z = p/u$ and $I = pu$ for any wind instrument, as well as for arbitrary sound fields!

Questions?
Email- dpignot2@uiuc.edu
chrisvan@uiuc.edu

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