I’d like to thank the Musical Acoustics Technical Committee and the Session Chair for the opportunity to speak on this topic. My Ph. D. work was an effort to model the structural behavior of the lips with a finite element simulation. To characterize the instrument, I used a theoretical input impedance calculated from a series of concatenated cylinders. In a partnership with Microflown Technologies, now I have a tool to measure input impedance of brass instruments directly. I am working at Kettering University in Flint, Michigan, USA. Our primary institutional mission is undergraduate education, especially in engineering fields. Thus, most of my research is conducted with the help of students in fast-paced, ten-week terms.
Direct velocity measurement

- Acoustic input impedance: \( Z = \frac{P}{U} \)
- Microflown signal proportional to particle velocity \( u \)
- Volume velocity proportional to particle velocity \( U = uS \)
- Pressure \( p \) taken from a microphone signal
- PU sensor combines both

As a first step, I am interested in a new way to determine the input impedance experimentally. The input impedance is defined as the complex quotient of pressure over volume velocity at the plane of the rim of the mouthpiece. The pressure is taken from a small microphone, and the volume velocity is proportional to the particle velocity, which is measured by a sensor known as the “Microflown.” Packaged together with the microphone, the microflown is part of a complete probe to determine the impedance.
Various configurations of the PU probe are available. The Acoustics Lab at Kettering University has two packages. First, the 1/2-inch package shown against the red case combines a tiny precision microphone with the Microflown sensor in a pair of pillars that creates a +9dB boost by "channeling" the air flow. The mini PU probe is the size of a matchstick, shown in the inset photo. The tiny microphone is mounted underneath the Microflown in the picture. The Microflown itself is a MEMS device created by Hans-Elias deBree in the mid-1990’s. With two small, current-carrying wires, it senses a difference in temperature by variation in resistivity. The upstream wire is cooler than the downstream, so resistivity is lower. The sensor is therefore also directional (positive and negative).
Example: Radiation

- Flanged PVC pipe
  - i.d. 4.02 cm
  - flange 52 cm square
- Specific Impedance $p/u$
  - PU probe at flanged open end
  - Real part $\rho c$
- Measurements
  - general shape is good
  - poorly scaled

As a preliminary test, the first impedance task for the PU probe was to measure an experimental version of the piston in a baffle. A pipe was driven with a swept sine signal through a loudspeaker, and terminated with a square flange with sides of roughly half a meter. The PU probe was placed at the flanged termination to measure the radiation impedance. Incorporating sensitivities provided on the calibration sheets for the microphone and Microflown, and including a signal conditioner that corrects for the frequency response of the velocity sensor, the result is shown here. The real part of the specific acoustic radiation impedance is shown in blue and the imaginary reactance in green. These curves show the expected trends:

- at low frequency, the reactance is linear with frequency, and the resistance is nearly quadratic
- at high frequency, the reactance goes to zero, and the resistance approaches an asymptote
- there is a crossover point where resistance equals reactance, around $ka = 1$.

However, at high frequency, the resistance (blue curve) should go to the characteristic impedance of the gas (for air, around 415 rayls). Obviously, more care must be taken with calibration.
The application of the PU probe to measure input impedance was, as I initially thought, a matter of building a device to inject sound into the instrument, adequately re-create the boundary condition of the player’s lips, and allow the PU probe to measure pressure and velocity at the plane of the mouthpiece rim. This was accomplished using a large woofer in an enclosure, covered with the mounting apparatus. The prototype coupling element was half a racquetball, with a hole of about 1 square centimeter cut to allow sound to enter the instrument. In this hole is mounted the mini PU probe. A flange then holds the mouthpiece to the racquetball. The enclosed mount was found to cause problems loading the driver, so a modification separates the sensor and mount from the speaker, as all that is needed is some excitation source at the input.
Calibration Tube: Setup

- 1” PVC (i. d. 2.6 cm), Length 1.889 m
- Rigid termination 1/2” MDF sealed with epoxy

The calibration tube was chosen because its diameter approximates the size of a trombone mouthpiece. A fairly long tube allows many resonances for calibration via comparison with a theoretical impedance curve. The closed end is assumed to have infinite impedance (zero admittance). With this arrangement, the input impedance should be a straightforward hyperbolic cotangent with a complex wavenumber.
The calibration tube was mounted to the impedance head, and the source was swept from 30 – 2030 Hz in 2000 steps. The frequency response function of the analyzer finds the ratio of channel 2 to channel 1, proportional to pressure and particle velocity, respectively. For comparison with theoretical specific acoustic impedance (pressure over particle velocity), the frequency response was multiplied by 10 000. This plot shows the result at the lowest impedance maximum. Certainly, a more serious calibration must be performed.
Calibration Parameters

- “Complete” calibration
  - after Dalmont, 2001
  - three parameters
  - one tube
  - constant temperature
- Determined by comparison to theory: \( Z = Z_c \coth(\Gamma L) \)
- Fit as function of frequency

Following the procedure outlined in Dalmont’s “Acoustic Impedance Measurement, Part I: Review,” the three parameters delta, beta, and R were determined from a study of the measured impedance maxima and minima. The measured data is compared to the theoretical acoustic impedance (\( Z_c \) is roughly \( \rho c / S \)). The data for the real and imaginary parts of these parameters are plotted here, with quadratic fitted curves. A quick inspection shows there is not much difference between a quadratic fit and a linear fit, as borne out when the parameters are applied to the original tube data. The axes are scaled much differently; delta and R are very small (\( 10^{-7} \) and \( 10^{-6} \), respectively). Beta is large, at \( 10^4 \).
Applying Calibration Parameters

- $R$ is “first order response”
  - a scaling factor
  - includes area ($\approx 1 \text{ cm}^2$)
  - includes factor of $10^4$
- $\text{Im}(\delta), \text{Im}(\beta)$ shift frequencies,
- $\text{Re}(\delta), \text{Re}(\beta)$ affect $Q$
- $\delta$ pertains to maxima,
- $\beta$ to minima

$$Z(f) = \frac{H(f) - \beta}{R} \cdot \frac{1 - \frac{H(f)}{R}}{\delta}$$

These calibration parameters brought the original measured impedance curves into the same general range as the theoretical expectations, as shown here for magnitude and phase. However, additional work remains to refine this calibration; more confidence is needed in the calibration parameters, and the calibration tube may be less than ideal. Work continues on this, with an independent study planned in the beginning of 2006. The procedure described by Dalmont in Part II of the article (2001) uses an additional measurement with a short tube, and relies less on a constant or known temperature. This refinement may improve the results.
Calibration Check

- Apply calibration to original tube frequency response
- Still some shift in frequency and magnitude difference
- More effort required to bolster the calibration

To find out how effective the calibration parameters were, the linear, quadratic, and even zero-order (mean) fit to the parameters were applied to the raw frequency response from the calibration tube. The lower plot of phase (in radians) shows there is still shift in frequency, and a closer examination of the magnitude indicates significant discrepancies (next slide shows just the first three maxima).
Calibration Check

- Apply calibration to original tube frequency response
- Still some shift in frequency and magnitude difference
- More effort required to bolster the calibration

This is a closer look at the lowest frequency peaks in the acoustic impedance (note the calibration yields acoustic impedance, pressure over volume velocity, not specific acoustic impedance). Possible shortfalls here include more damping in the calibration tube than accounted for in the theory; Part II of Dalmont’s article (2001) addresses this—but the extended calibration procedure has not yet been implemented in this project. Nonetheless, a few preliminary projects highlight the ease of using this sensor.
Despite these calibration concerns, preliminary measurements for the sake of comparison can be made and provide interesting descriptions. For a first example, four mouthpieces are compared here. All results are calibrated using the averaged parameters, while care was taken to maintain a constant working temperature.

The transparent mouthpiece was made to observe high-speed video segments of the lips during the attack. The other three are common trombone mouthpieces; the “Other12C” is not shown in a photo, but is the same type that provided the rim and bore for the transparent mouthpiece. It is clear that the transparent mouthpiece offers much less input impedance, with a broader, lower-frequency peak.
The entire trombone was also tested. This instrument, a student model (Conn Director), shows the influence of the cutoff frequency at around 1300 Hz. Certainly, amplitude and scaling are still problematic in showing the peaks in the input impedance; these results motivate more work to calibrate the PU probe. Nonetheless, the first prominent peak at 124 is reasonable for the second peak in the input impedance; the lowest one around 45 Hz is often difficult to measure experimentally.
The student model trumpet from my childhood was also subjected to a preliminary test. This instrument, the “Al Hirt Special” model from Holton, shows the lowest peaks as very broad and low in magnitude. As this instrument has not been cleaned in years, there could be significant viscous losses at the walls.

Also, both the trombone and trumpet data are simply swept sine data that has been calibrated according to Dalmon’s “Part I.” A more careful measurement procedure may be followed when the calibration is more trustworthy.
Conclusions—Directions!

• Better calibration
• More samples, more care
  – mouthpieces
  – entire instruments
  – local repair tech. “inventions”
• Explore capabilities
  – FFT/waterfall plots
  – ??
• Students ready to lend a hand…

Much more work may be done to refine the calibration of the PU probe, and conversation with the technical staff of Microflown Technologies will continue. Once calibration issues are resolved, this PU probe is intended to provide a quick device to measure input impedance for a variety of instruments. One possible direction is to “record” the change in input impedance while a valve is operated, or the trombone slide is moved, in a waterfall plot or similar device. Another direction will involve much more careful measurement through the frequency domain.
References


