BRASS ACOUSTICS—IS PROPAGATION LINEAR OR NONLINEAR?

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> *"Higher intensity tones appeared to contain stronger upper harmonics than would be predicted by a filter computed at lower intensities."*

Since the beginning of the twentieth century, the acoustics of brass instruments has been and continues to be a popular topic in musical acoustics. Of approximately 200 musical acousticians listed on the current Technical Committee on Musical Acoustics website, about 12% list brass as one of their specific interests. Actually, "brass" is not the defining term, as instruments constructed of brass may be considered woodwinds (e.g., the saxophone), and instruments constructed with other materials can be classified as "brass" (e.g., the baroque cornett). What brass instruments have in common is that they are excited by a vibrating lip. Based on Martin's seminal work on lip vibrations[1], Backus and Hundley developed a trumpet model that employed a sinusoidally changing lip opening and a nonlinear slit resistance to generate harmonically rich mouthpiece pressure waveforms[2]. More recently, Yoshikawa showed that lips under different conditions may exhibit either "swinging door" or "sliding door" motion[3]. Adachi and Sato formulated a two-dimensional lip model that simulated these motions[4]. Meanwhile, Copley and Strong made a detailed stroboscopic study of trombone lip vibrations[5], and Dean Ayers has demonstrated lip motion in real time with a stroboscope and video camera at several ASA meetings (e.g., McLaughlin *et al.*), concluding that lips exhibit Rayleigh wave motion[6].

While lips act as the source (or excitation) of a brass instrument, its pipe (or horn) acts as its filter. In the late 1960s I became intrigued with the possibility of synthesizing brass sounds using a source-filter model, a model whose validity has been a prevalent assumption for acoustic signal production since the early days of acoustics. This model certainly has been much used for synthesis of speech sounds, and it was quite successfully used in early analog electronic music synthesizers. Analysis by Luce and Clark showed that brass spectra follow a basic low-pass filter characteristic whose "roll off rate" varies with performance dynamic[7]. Thus, more intense tones are perceptually brighter while less intense tones sound darker. I also became acquainted with a Ph.D. dissertation (Univ. of Illinois, 1941) written by Daniel Martin (ASA editor-in-chief, 1985-99) which not only showed that more intense tones were brighter but also included measurements of mouthpiece-to-output transmission response and radiation patterns from the bell[8]. The latter two measurements were done with swept sine wave input. However, it seemed that simultaneous measurements of mouthpiece and output pressure waveforms, resulting from actual performance, could be used to derive a source-filter model. To do this, I arranged for four different trombonists at the University of Illinois to play a series of tones at different pitches and dynamics on the same trombone in an anechoic chamber. The mouthpiece and output pressure signals were recorded on two tracks of a tape recorder. The mouthpiece pressures were unexpectedly high—between 150 and 170 dBC SPL, whereas output pressures varied from 67 to 100 dBC. An analog wave analyzer and, later, computer Fourier analysis were used to compute input and output spectra, and then a filter function was computed from their ratio[9-12]. Surprisingly, the filter was not fixed but appeared to vary with dynamic or intensity. Higher intensity tones produced stronger upper harmonics than would be predicted by a filter computed at lower intensities. Thus, it appeared that the trombone's transmission response had to be nonlinear.

In 1973, I visited Arthur Benade, who was posthumously awarded the Society's Gold Medal in 1988, at his lab at Case Western Reserve University. During my visit, he made simultaneous swept-sine-wave graphs of input impedance and transmission response for my cornet. (Up until that time several researchers had published plots of input impedance response, but the only transmission response curves I had seen were Martin's.) What was interesting about the two curves was that while they both exhibited a series of approximately harmonic-spaced resonances, the maxima of the input impedance corresponded to the minima of the transmission response, both corresponding to the playing frequencies of the instrument. This phenomenon is easily explained in terms of wave reflection: When a wave reflects back from the horn opening to reinforce lip motion, a maximum of pressure occurs at the lips (thus, an impedance maximum), but very little energy escapes from the horn (thus, a transmission minimum). However, in between these frequencies, energy radiates relatively efficiently from the bell, and very little reflects back, giving rise to pressure minima at the lips. This is at least what happens when wave lengths are longer than the bell diameter. When they are shorter, reflections become weaker and weaker, transmission flattens off, and input impedance falls to a low value. The frequency above which reflective behavior changes to non-reflective behavior is called the "cutoff frequency." Benade soon published some mouthpiece and output trumpet spectra and a rough high-pass-filter-shaped transmission response[13]. Back at the University of Illinois, I made more swept sine wave transmission response measurements, this time again on a trombone. The resulting transmission curve minima lined up well with values taken from the filter response previously calculated from the trombone tone spectral analysis. But while agreement was good for frequencies below cutoff, it was not for frequencies above cutoff. Again, the nonlinear effect seemed obvious. However, I had doubts about my performance-condition measurements because (a) computing the ratio with weak mouthpiece harmonics above cutoff is tricky, and (b) some prominent musical acoustics researchers (e.g., Backus and Hundley and Elliott *et al.*) had predicted that significant nonlinearity was unlikely[14-15]. Nevertheless, in 1995 Hirschberg and colleagues finally verified the nonlinearity effect—due to shock waves[16]. A thorough predictive analysis was later done by Thompson and Strong[17]. It turns out that high-amplitude traveling waves "steepen" as they move down the pipe, thus increasing the upper harmonic content. Synthesis methods based on this idea have been devised by Vergez and Rodet, Msallam *et al.*, and others at IRCAM in Paris[18-19]. In the meantime, Andrew Horner and I devised a filter-like multiple-wavetable brass synthesis model based on a variable spectral envelope[20]. The increased speed and memory of computers that transpired between the 1960s and the 1990s had made a strictly linear source-filter model, which proved to be incorrect, unnecessary.**AT**

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