Shock waves in trombones

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Based on physical models of musical instruments and of the human voice, a new generation of sound synthesizers is born: virtual instruments. The models used for wind instruments are simple feedback loops in which a nonlinear sound source drives a linear filter representing the pipe of the instrument. While very rewarding musical sounds have been obtained with these models, it has become obvious that some essential phenomena escape such a description. In particular the brightness of the sound generated by trombones is expected to be due to the essential nonlinearity of the wave propagation in the pipe. At fortissimo levels this leads to shock wave formation observed in our experiments both from pressure measurements and flow visualization. A modest modification of the physical model could already take this phenomenon into account. The key idea is that the nonlinear effect is essential for the transfer of sound from the source toward the listener, but can be ignored in a model of the generation of the pipe oscillations.

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Wind instruments are currently described as feedback systems in which a nonlinear amplifier, the sound source, drives a linear filter, the pipe.[1] Highly simplified physical models of the clarinet and of the violin based on the method proposed by Mc Intyre *et al.*[2] have demonstrated that musically interesting signals could be obtained by caricatures which require only a modest computational power to produce sound in real time. The first commercial ''virtual instruments'' based on this principle were welcomed last year as musically very rewarding.[3] These models are obviously also useful as design tools for the craftsmen of conventional musical instruments. Even more simplified ''source/filter'' models, in which the feedback from the filter toward the source is ignored, allow a considerable data compression of the speech signal in telecommunication. Better physical models of both wind instruments and of the human voice production would certainly be welcome for a wide range of applications.

The nonlinearity of the oscillator is a key aspect which is essential to reach steady oscillations in a feedback system and to determine the perceptive quality of the sound.[1] We focus in this paper on the hypothesis of a linear response of the pipe which has already been subject to controversy in the recent past. Backus and Hundley[4] report an essentially linear transfer function between the mouthpiece pressure fluctuations of an artificially blown trumpet and the radiated sound field at the listener position. Only a few percent second harmonic generation by nonlinear distortion were observed at the highest levels. These results were contradicted by later measurements of the amplitude dependency of the transfer function of a trombone by Beauchamp.[5,6] Beauchamp[7] had some doubt about his data, in particular the analog tape recorder which had been used.

The trombone used in our experiments is shown in Fig. 1. In particular we indicate the position of the microphones. The first microphone is placed in the mouthpiece. The second microphone is placed at the end of the cylindrical part of the pipe. The third microphone is placed at the horn exit. We used piezoelectric gauges (Kistler 603-A) with corresponding charge amplifiers (Kistler-type 5007, bandwidth 1 Hz$<f<$180 kHz) for the internal pressure measurements and a 1/8-in. BK condenser microphone with corresponding electronics outside the pipe. This in combination with modern electronic registration guarantees the linearity and the bandwidth necessary in order to observe shock waves. Our experimental results, shown in Figs. 2 and 3, confirm a violent nonlinear behavior of a trombone and provide an indication for the cause of the brightness of related brass instruments played at fortissimo levels. We observe the formation of stepwise pressure jumps. For the fortissimo level (ff) of the higher note shown in Fig. 3(b), the pressure-rise time corresponds to the travel time of the wave on the surface of the microphone.

As we will explain further on, the nonlinearity in the transfer function depends crucially on a primary nonlinearity of the source. The flow control by the lip–mouthpiece combination results in a particularly sharp pressure rise during

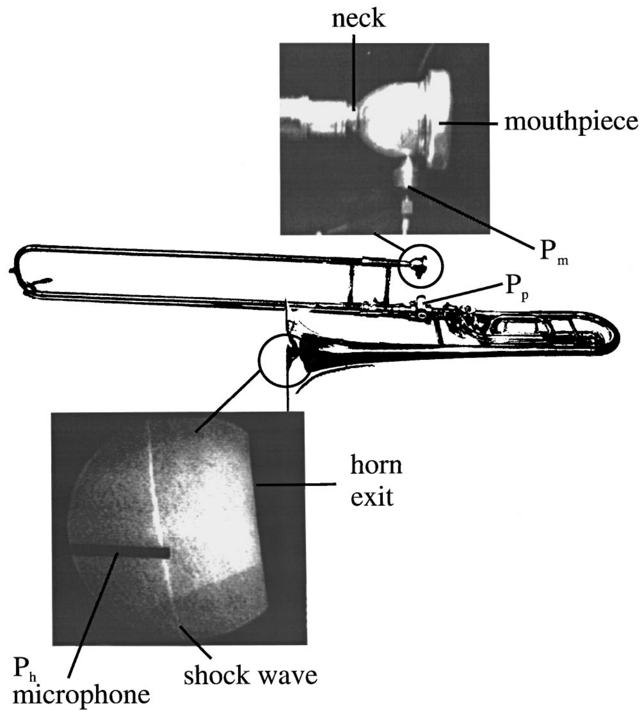


FIG. 1. A shematic representation of the trombone used in our experiments (A. Courtois trombone type 155, A. Courtois mouthpiece type 10 PM) with an indication of the position of the microphones. A typical flow visualization of a shock wave at the exit of the horn is shown. The mouthpiece geometry is specified. The pressures p_m in the mouthpiece and p_p at the end of the cylindrical pipe section have been measured by means of acceleration compensated piezoelectrical gages (Kistler 603-A) coated with a 0.1-mm silicone layer to avoid thermal effects. The bandwidth of the filters of the charge amplifiers was 1 Hz$<f<$180 kHz. An additional condensator microphone with a comparable bandwidth (BK 1/8 in.) measures the acoustical pressure p_h at 4.5 cm from the horn exit on the axis.

the oscillation. It is this compression phase which by nonlinear wave propagation generates a shock wave. We now try to understand why this occurs in a trombone while it does not occur in most instruments.

A simple explanation for the generation of this highly nonsinusoidal mouthpiece pressure p_m has been proposed for the trumpet by Backus and Hundley[4] and for the trombone by Elliot and Bowsher.[8] As shown in Fig. 2 for a low pitch, the observed mouthpiece pressure signal p_m is rather constant during much of the cycle, remaining close to the players driving pressure. This is due to the fact that the aperture between the lips is large compared to the neck of the mouthpiece shown in Fig. 1: the neck controls the flow. The pressure varies suddenly during the short time intervals in which the lips take the flow control over because they close completely. This results in the characteristic strong negative pressure pulses observed in Fig. 2. This effect becomes stronger with increasing playing level. The details of the collision of the lips at closure is certainly critical. In voiced speech production[9] or in double-reed instruments[10] most of the radiated high-frequency sound is generated in the closing phase of the ''reed'' movement. In contrast to this we will see that for the trombone the crucial phase of the cycle is the opening of the lips, corresponding to the compression phase in p_m.

It appears that Backus and Hundley's mouthpiece pressure signals are dominated by much lower frequencies than our signals. Their signals do not display such high-pressure rise rates $(\partial p_m/\partial t)_{\max}$ as the signals we have measured. The 160-dB mouth pressure amplitudes reported by Backus and Hundley in their experiments, correspond to oscillation amplitudes of about 3 kPa. This is much lower than our pressure fluctuations as shown in Figs. 2 and 3. Also Backus and Hundley report measurements on a trumpet which can have a much shorter pipe than our trombone.

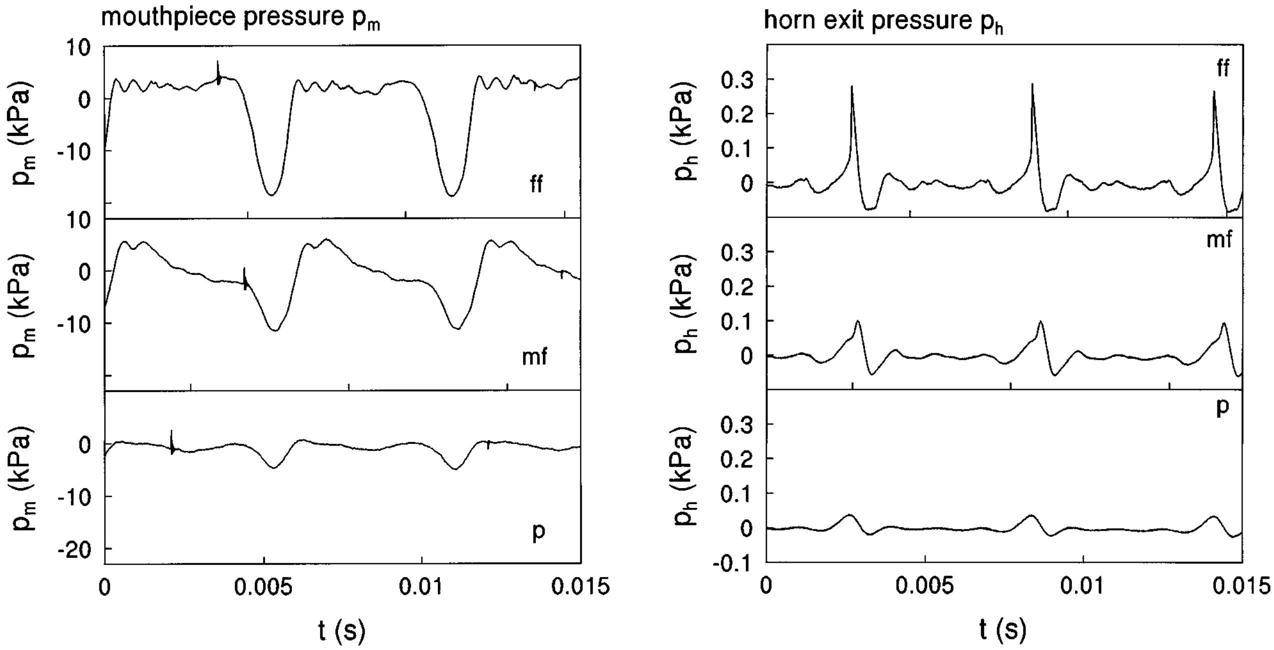
Now we can also rationalize the behavior of the pipe of the clarinet which we described earlier.[11] The reed channel of a clarinet is always much smaller than the pipe cross-sectional area. The flow therefore is always controlled by the reed movement. In addition to this, the lay of the mouthpiece of a clarinet is curved in such a way that the reed closes gradually, the flow is never interrupted abruptly. This results in a fairly sinusoidal oscillation of the pressure in the mouthpiece, even at fortissimo levels. Even though the oscillation amplitudes were comparable to those found in the trombone, we found a very reasonable prediction of a linear model for the transfer of sound from the pipe to the listener in the case of a clarinet.[11] We could not even observe the nonlinearities which certainly occur, for low pitches at fortissimo levels as a result of vortex shedding at the pipe end and tone holes.[12]

The very strong nonlinearity of the acoustical drive of the trombone already explains much of the observed difference between the sounds of the clarinet and of the trombone. Simple models as proposed by Strong[13] already generate typical brass sounds but certainly not the specific brightness of the sound at fortissimo levels. This effect is controlled by the nonlinear wave propagation in the pipe which we discuss now.

Since the most relevant high frequencies are very efficiently radiated away at the horn, we neglect reflection at the pipe termination. We therefore can assume the propagation of a simple wave into a uniform region. Starting from the measured mouthpiece pressure $p_m(t)$ and assuming a frictionless simple wave propagation along a pipe of uniform cross section, we can obtain an analytical prediction of the wave distortion. The calculation is based on the classical method of characteristics.[14] Due to the increase in speed of sound c with the temperature and the convective effects, the top of the compression side of a wave tend to catch up with the foot of the wave. It appears that the ratio of the pressure fluctuations p_m to the mean atmospheric pressure P_{at} is not the relevant parameter to judge the severity of the nonlinear steepening. Theory predicts that for distance x larger than the critical distance x_s given by

$$x_s \simeq \frac{2\gamma P_{\text{at}} c}{[(\gamma+1)(\partial p_m/\partial t)_{\max}]}, \tag{1}$$

where $\gamma=1.4$ is the Poisson constant, a shock wave is formed. The pressure profile predicted by integration along characteristics becomes multiple valued. The position and strength of this shock can be estimated from this multiple valued solution within the framework of a frictionless theory as, for example, the weak shock theory.[14,15] The shock path in a (x,t) diagram is along the bisectrix of the angle formed by two characteristics of the same family which intersect in



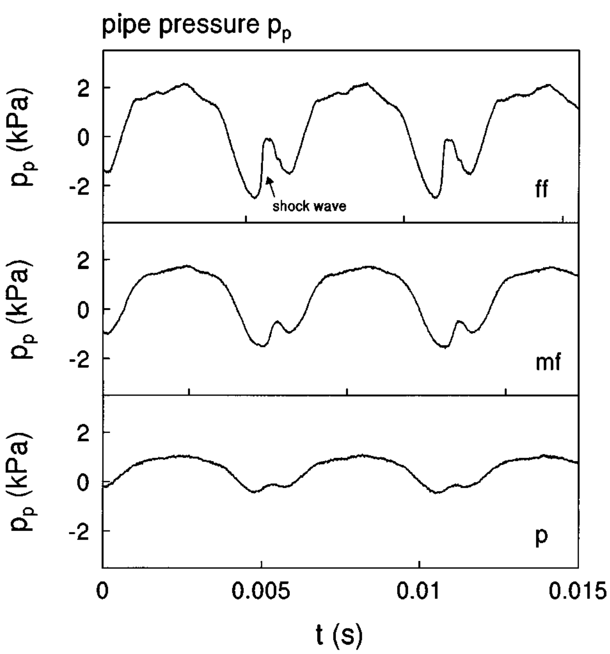


FIG. 2. Measured pressure waveforms for a low frequency. Pressure measured in the first position of a trombone at various playing levels: piano (p), mezzo-forte (mf), fortissimo (ff). We clearly observe the increased nonharmonicity of mouthpiece pressure p_m and nonlinear wave steepening in the pipe pressure p_p with increasing playing level. Comparison of p_m and p_p with the pressure p_h measured at the horn exit clearly demonstrate that the radiated sound is dominated by the high frequencies.

the region of multiple value solutions. The weak shock speed is the mean value of the speed of the two intersecting characteristics. Equation (1) gives the first point of the shock path from which the shock path can be integrated numerically.

Even for the weak shocks which we expect here, shock waves certainly correspond to a dramatic amount of high frequencies in the radiated sound: a bright "metallic" sound. As x_s is determined by $(\partial p_m/\partial t)_{\max}$ we understand the importance of the initial nonlinearity of the source which we discussed above.

Using data shown in Figs. 2 and 3 we see by using the formula for x_s that shock waves can be expected at the fortissimo level because the cylindrical pipe segment in the trombone (2 to 3 m) is longer than x_s. Indeed in Fig. 3 we see pressure discontinuities in the pressure signal measured at the end of this cylindrical pipe segment. Schlieren flow visualization obtained with a Nanolite spark discharge (80 ns) indicates again a very sharp wave front at exit of the horn (see Fig. 1). This wave of at most a millimeter thickness corresponds to the sharp pulse in the pressure signal p_h detected by the microphone (see Fig. 3). Shock waves are certainly formed in a trombone under typical playing conditions. We also expect that nonlinear wave propagation is musically relevant for the trumpet.

It is interesting to note that "bright" instruments such as the trumpet and the trombone are different from brass instruments such as Saxhorns or Flügelhorns. The bright instruments have a cylindrical pipe segment just downstream of the mouthpiece. The conical bore of the Saxhorns implies a faster decay of the wave which reduces the nonlinear wave steepening. This seems to confirm that the brightness is associated with shock wave formation.

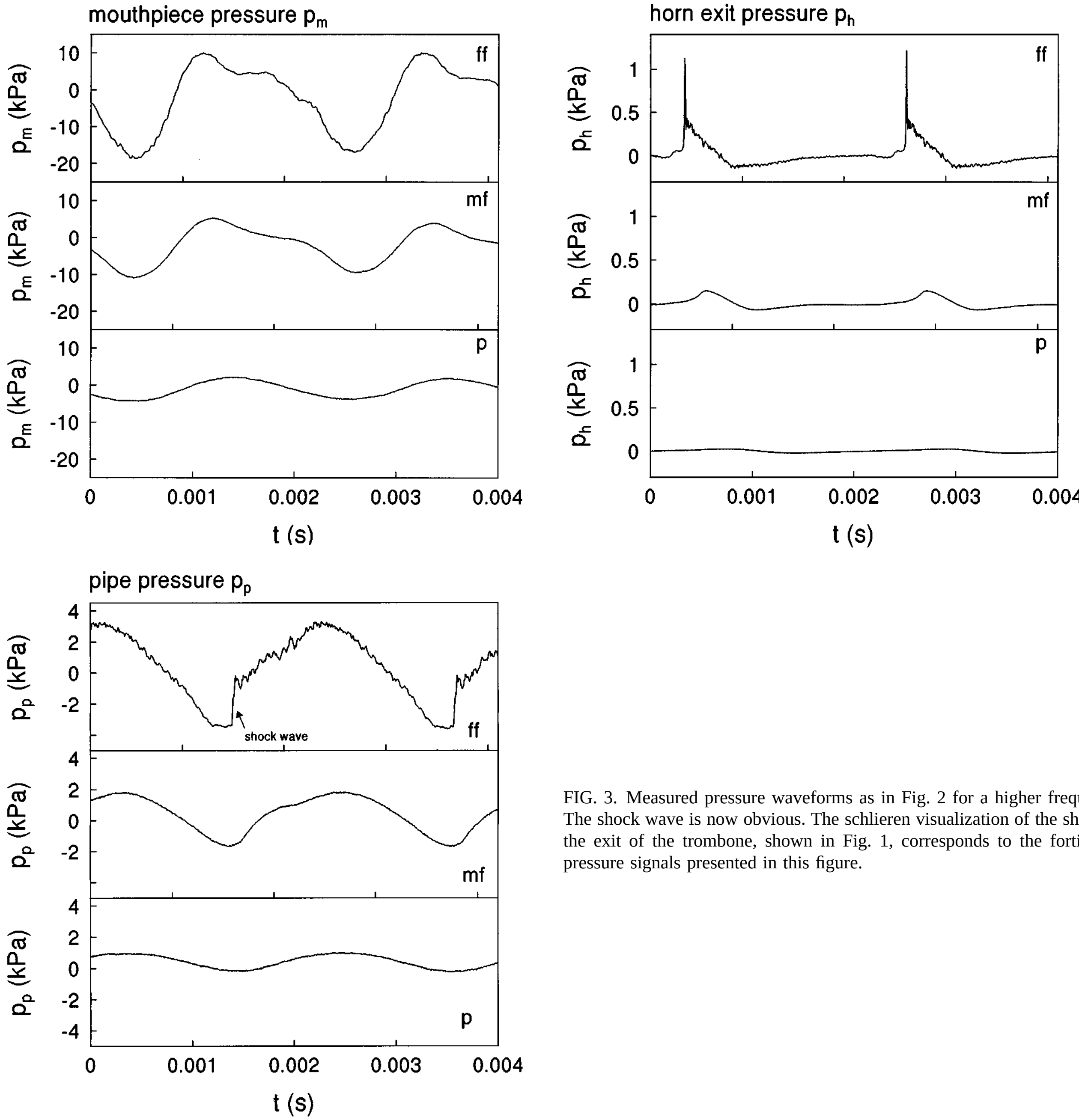


FIG. 3. Measured pressure waveforms as in Fig. 2 for a higher frequency. The shock wave is now obvious. The schlieren visualization of the shock at the exit of the trombone, shown in Fig. 1, corresponds to the fortissimo pressure signals presented in this figure.

The essential role of the cylindrical portion of the bore and the strong increase of radiation efficiency with the frequency are the important components in a simple explanation of this effect. As high frequencies are not reflected at the pipe termination they do not contribute to the regeneration of the lip oscillation. We expect that a simple linear model of the pipe taking into account at least the eight first resonances should be able to describe the lip oscillation. Once the lip movement is known, the calculated mouthpiece pressure could be used for a nonlinear propagation model. In this model the mouthpiece pressure would drive a simple wave into a cylindrical bore. Weak shock theory can be used to predict the shock wave, if relevant. The calculated pressure signal at the end of the cylindrical bore would then be radiated away by a linear model of the horn. Filtering would be used to keep the relevant audio range of frequency and to avoid numerical problems with the shock waves. This type of carricature is simple enough so that it could be implemented in a virtual instrument.

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