PITCH BENDING AND ANOMALOUS BEHAVIOR IN A FREE REED COUPLED TO A PIPE RESONATOR

James P. Cottingham
Phys. Dept., Coe College, Cedar Rapids, IA 52402 USA, jcotting@coe.edu

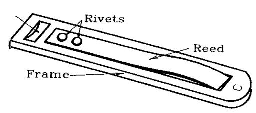
Abstract

The reed-pipe system studied consists of a reed from an American reed organ coupled to a cylindrical pipe resonator. Over a wide range of pipe lengths and playing pressures, the sounding frequency of the reed-pipe combination is slightly below a pipe resonance frequency and can be pulled considerably below the natural frequency of the reed. This is in agreement with the results of investigations of free reed organ pipes by Braasch and co-workers. [J. Braasch and C. Ahrens, Acustica 86, 662 (2000)] Additional measurements of reed vibration for low frequency free reeds in narrow pipes show that, as the playing pressure is increased, there can be a sudden transition to period doubling or, in some cases, tripling or quadrupling. Some pressure intervals exist in which apparently chaotic reed vibration occurs, or in which the reed will not vibrate at all. Period doubling was found to occur over varied values of pipe length, pipe diameter, and for different reeds with matching resonance frequencies. General trends in the onset and steady-states of period doubling are described using measured waveforms and spectra of both reed motion and radiated sound pressure. [Work supported by National Science Foundation REU Grant No. 0354058.]

INTRODUCTION

The free reed instruments consist mainly of two families. One family includes instruments such as the harmonium, reed organ, harmonica, and the accordion-concertina family. These originated in Europe about 200 years ago. These instruments employ "offset" reeds in which the tongue is mounted outside the reed frame in such a way that sounding is normally possible only on one direction of airflow. Under normal operating conditions these behave as "blown-closed" or (-,+) reeds in the classification of Fletcher.[1] This kind of reed, illustrated in Figure 1, sounds easily without the aid of a pipe resonator. The sounding frequency of the blown reed is below the natural vibrating frequency of the reed tongue.

The second principal family of free reed instruments consists of the Asian free reed mouth organs, including the *sheng* of China, the *sho* of Japan, and the Laotian *khaen*. They employ symmetric free reeds that are usually operated on both directions of airflow. An example is the sheng reed shown in Figure 1. These reeds are cut from a single sheet of metal resulting in their approximate symmetry with respect to direction of airflow. The structure of these reeds necessitates coupling the reed to a pipe resonator. It has been shown that, in this configuration, the free reed normally functions as a "blown-open" or (+,-) reed, with the sounding frequency of the reed-pipe combination above both the natural frequency of the reed and the resonance frequency of the pipe. In these instruments it is possible in some cases for the reed-pipe combination to sound nearly an octave above the natural frequency of the reed. [3]



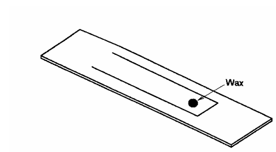


Figure 1: A free reed from an American reed organ (left) and a sheng reed (right) from Gellerman [2].

The reed-pipe system considered in this paper represents a kind of hybrid constructed from a reed from an American reed organ coupled to a pipe resonator constructed of PVC pipe of 1.58 cm inside diameter. The only occurrence of this kind of reed-pipe combination in standard instruments is the free-reed organ pipe, which is used in some organ stops. The acoustics of free-reed organ pipes has been studied recently by Braasch and co-workers.[4] Free reed organ pipes are generally constructed in a manner very similar to the more common reed pipes that employ beating reeds, making them similar to but not identical to the reed-pipe combinations used in the work reported here. (It might be noted, however, that Braasch recently reported the discovery of some free reed stops in German organs that appear to have been constructed in the same manner as the pipes discussed here, in which reed pipes are constructed by simply attaching American organ reeds to the pipe. [5])

Some of the results involving the dependence of sounding frequency on pipe length reported here are similar to, and in agreement with, measurements made on free reed organ pipes by Braasch, et al.[4] This investigation of free reed organ pipes, however, was confined to moderate blowing pressures close to normal playing pressure, and pipes with resonance frequencies relatively close to the reed frequencies. Some of the more unusual effects reported below involve either high blowing pressure, unusual pipe length, or both. Some of the results in this paper have been presented earlier in preliminary reports by the author and students Justin Vines, Ammon Paquette, and Evan Goetzmann.[6,7]

EXPERIMENTAL PROCEDURE

For the measurements of reed vibration, an airtight "boot" was constructed from wood and Plexiglas for the reed-pipe, with interfaces for a manometer, a variable impedance transducer (VIT) proximity sensor, and an air pressure source. A second boot was constructed with a transparent window instead of the VIT interface so that measurements of reed vibration could be made with a laser vibrometer. The length of the pipe was varied in small increments. For each length of pipe, a set of different blowing pressures was applied, and for each pressure the sounding frequency of the reed-pipe combination was measured along with the frequency spectrum and a sample waveform of reed vibration. Because of range limitations, the VIT sensor was mounted close to the fixed end of the reed.

Reeds of various frequencies were mounted in pipes of a wide range of lengths, and a wide range of blowing pressure was explored, often ranging from 0.4-4.0 kPa, with even higher pressures used in some cases. All the results reported here are for pipes with inside diameter 1.58 cm, although some experiments with larger diameter pipes were also done.

Figure 2: Free reeds mounted in PVC pipe.

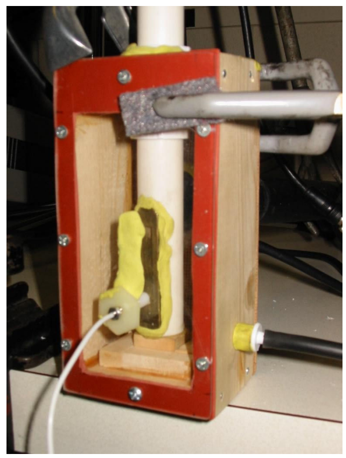


Figure 3: Reed pipe in the boot with VIT sensor attached.

SOUNDING FREQUENCY OF THE REED-PIPE COMBINATION

Blown-closed vs. blown-open reed

The first example to be considered is that of a 615 Hz reed mounted in a pipe of length 62 cm. The first three measured resonance frequencies of the pipe are 139 Hz, 416 Hz and 694 Hz. Figure 4 shows the amplitude of oscillation of the point on the reed directly below the VIT sensor as the blowing pressure is gradually increased. The upper and lower curves represent the maximum and minimum distances of excursion of this point from the initial equilibrium position at zero. The middle grey curve represents the shift in equilibrium position as the blowing pressure is increased.

For pressures less than or equal to 3.4 kPa the reed sounds at approximately 607 Hz, which is somewhat below its natural frequency and also below the pipe resonance at 695 Hz. This is the behavior expected of a blown-closed (-,+) reed. At around 3.5 kPa the equilibrium position of the reed is so far depressed that the reed does not sound. At pressures above 3.8 kPa however, the reed again sounds, this time at 707 Hz. This is above the reed frequency and the 695 HZ pipe resonance. The reed is now behaving as a blown-open reed.

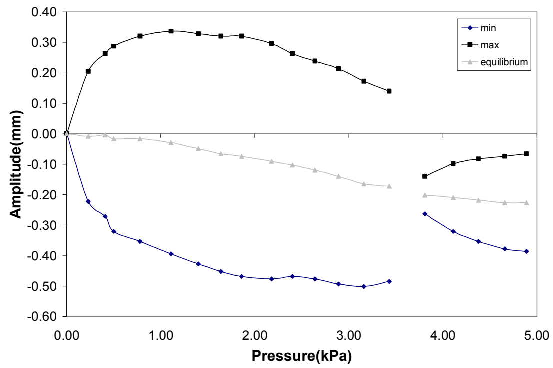


Figure 4: Amplitude of reed oscillation as a function of pressure for the 615 Hz reed in a 62 cm pipe.

Second transverse mode

For the same reed with certain shorter pipe lengths some unusual results have been observed. In particular there are pipe lengths for which there is no pipe frequency close enough to the reed frequency to permit sounding the reed in the fundamental mode at normal blowing pressure. In some of these cases the reed-pipe combination will sound with the reed vibrating in the second transverse mode at 2080 Hz. An example of this is the case of a 28.5 cm pipe. In this case the pipe sounds at 2080 Hz for blowing pressures around 3.0 kPa. In some cases Modes 1 and 2 (615 Hz, 2080 Hz) are both clearly audible and clearly detectable. Figure 5 shows this, along with some harmonics as well as sum and difference frequencies.

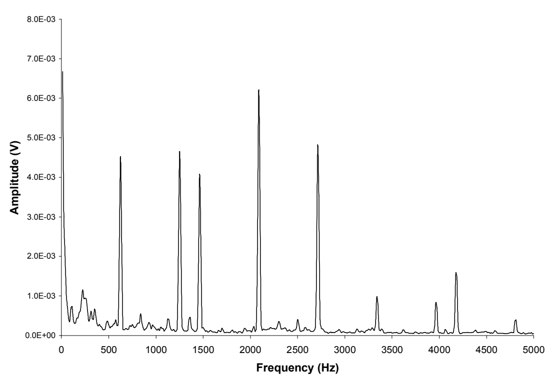


Figure 5: Spectrum of reed vibration measured with a VIT sensor at 3.2 kPa for 615 Hz reed mounted in a 28.5 cm pipe.

It should be noted that hysteresis effects are important in these cases. For the example just given, it is much easier to obtain Mode 2 vibration when the pressure is lowered from above. In this higher pressure region the reed does not sound at all. It was also observed that this same reed-pipe combination sounds strongly at 925 Hz, near the third pipe resonance at very high blowing pressures around 5.8 kPa.

Blown-closed behavior for a reed over a wide range of pipe length

The sounding frequencies of reed-pipes using a 235 Hz reed were measured over a very wide range of pipe lengths (0.15-2.0 m) and over a wide range of blowing pressures. The data for these reed-pipe combinations is shown in Figure 6. Over the entire range shown the sounding frequency is somewhat below the natural frequency of the reed and also below one of the pipe resonance frequencies. In some cases it is the second or third pipe resonance that determines the sounding frequency. This pitch variation of approximately one octave is the behavior normally expected of a blown-closed (-,+) reed and is consistent with the results for free reed organ pipes. (The data sets shown in Figures 6 and 7 are both from an earlier study.[6])

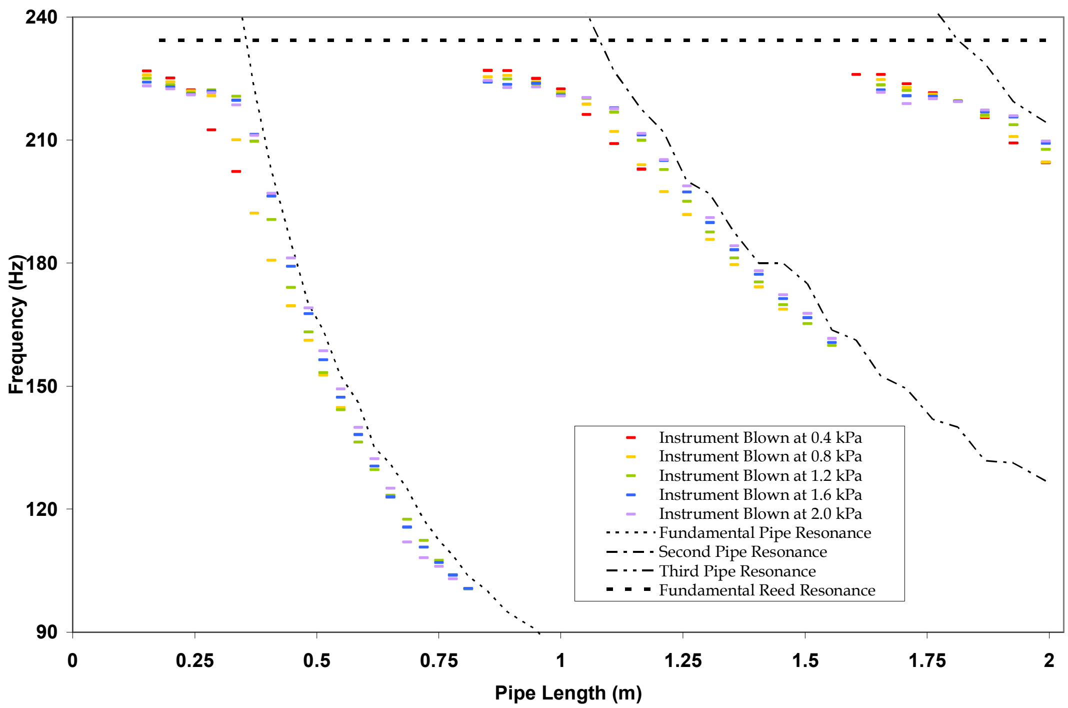


Figure 6: Sounding frequency as a function of pipe length for a 235 Hz reed. The dashed horizontal line is the reed resonance. The dotted curves represent the measured pipe resonances.

Anomalous behavior for a low frequency reed in long pipes

Figure 7 shows the sounding frequency of a 48 Hz bass reed mounted in various lengths of 1.58 cm diameter pipe. Where the pipe resonance and the reed resonance are close together the behavior is what would be predicted for a blown-closed reed. That is, the reed-pipe combination sounds below the reed frequency and somewhat below the pipe frequency for all blowing pressures if the pipe resonance is below the reed frequency. If the pipe resonance is above the reed frequency, the sounding frequency is above the pipe resonance for high blowing pressure, as would be expected for a blown-open reed. This reed-pipe does not sound at pressures below 1.6 kPa.

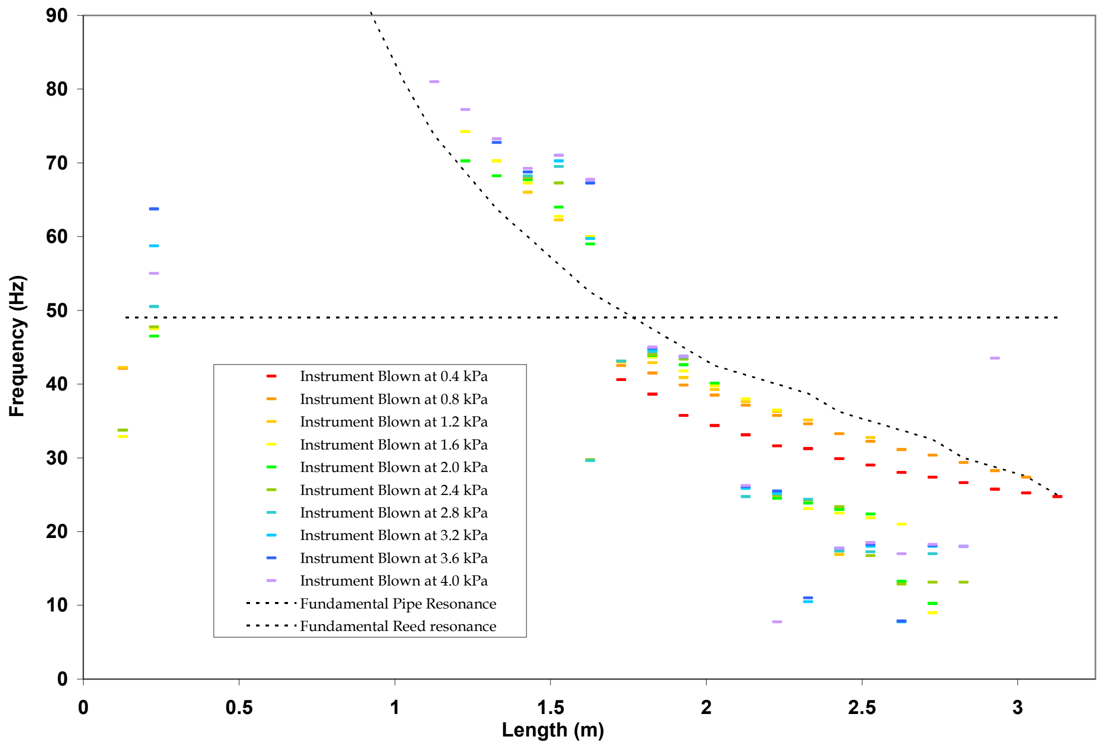


Figure 7: Sounding frequency as a function of pipe length for a 48 Hz reed. The dashed horizontal line is the reed resonance. The dotted curve represents the fundamental pipe resonance.

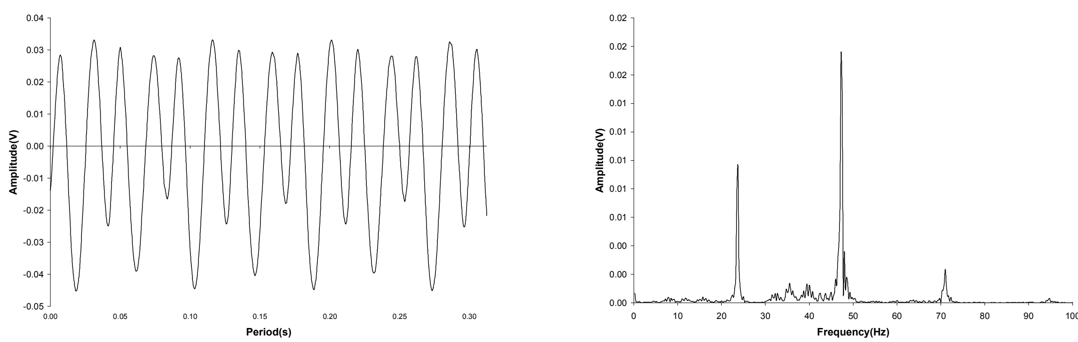


Figure 8: Waveform and spectrum of reed motion for a 48 Hz reed in a 2.07 m pipe at 0.96 kPa.

Some anomalous effects, including period doubling or tripling, can occur for this reed with pipe lengths greater than 2.0 m. This is illustrated in the waveforms and spectra shown in Figures 8 and 9. For a pipe length of 2.07 m at 0.96 kPa, period doubling is clearly observed as shown in Figure 8. The waveform and spectrum in Figure 9 show period tripling occurring at 2.96 kPa.

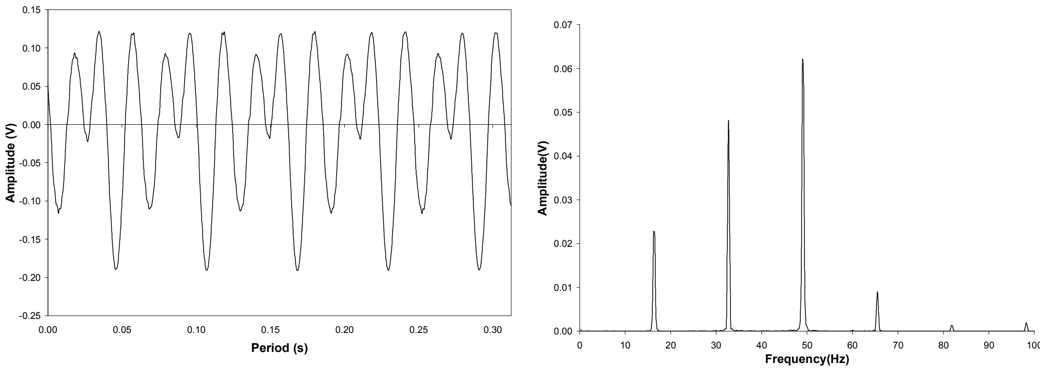


Figure 9: Waveform and spectrum of reed motion for a 48 Hz reed in a 2.07 m pipe at 2.96 kPa.

Figure 10 illustrates several of the possibilities.[7] It shows a spectrogram of reed motion for a 48 Hz reed mounted in a pipe of length 2.36 m and diameter 1.58 cm. In pressure Region 1 the behavior is normal, in that the reed vibrates below its natural frequency and near the pipe resonance frequency (36 Hz). Region 2 is a pressure range over which reed oscillation does not occur. Region 3 is a transition to period doubling. Region 4 shows a drop in frequency, which precedes period doubling in Region 5 at pressures beginning around 1.5 kPa. At pressures above 2.7 kPa the reed oscillation becomes complex and possibly chaotic.

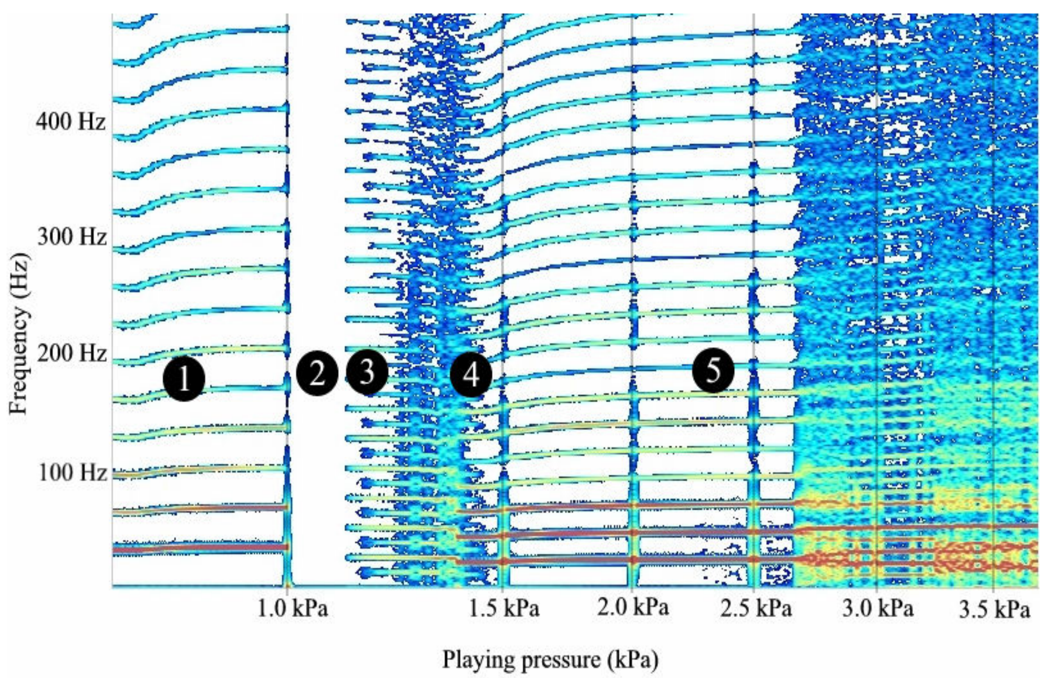


Figure 10: Spectrogram of a 48 Hz reed in a 2.36 m pipe.

SUMMARY

Reed-pipe systems consisting of a free reed from an American reed organ coupled to a cylindrical pipe resonator have been studied over a wide range of pipe lengths and playing pressures. At low to moderate blowing pressures, the sounding frequency of the reed-pipe is slightly below a pipe resonance frequency and can be pulled considerably below the natural frequency of the reed. This behavior is consistent with expectations for a blown-closed reed coupled to a pipe. At higher blowing pressures the equilibrium position of the reed can be so far displaced that the reed will not vibrate at all or, in some cases, the reed-pipe vibrates above the reed frequency as expected for a blown-open reed. In a few cases vibration of the reed in the second transverse mode is possible. Measurements of reed vibration for low-frequency free reeds in long pipes with resonance frequencies below the reed frequency show that, as the playing pressure is increased, there can be a sudden transition to period doubling or tripling. Some pressure intervals exist in which apparently chaotic reed vibration occurs, or in which the reed will not vibrate at all.

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