

## Chapter 23

# Brass Musical Instruments

The family of musical instruments known as brass instruments includes the trumpet, trombone, French horn, and tuba, among others. The ranges of these well-known orchestral instruments are given in Appendix C. If you guessed that brass instruments are made out of brass you would be right, but they are sometimes made out of other materials as well. For instance, the vuvuzela is made out of vinyl. What really characterizes the brass family, as we define it, is that the sound originates with the vibration of the player's lips in a mouthpiece. Some authors refer to brass instruments as "lip-reed" instruments. Another characteristic of the brasses is that they all have a bell, a flaring end of the horn that radiates *all* the sound.

### 23.1 Sustained-Tone Instruments

Brass instruments are sustained-tone instruments, like the bowed strings, the woodwinds, and the human singing voice. All these instruments make tones that carry melodies and can be used in close harmony. These tones are approximately periodic, though they do not have the perfect cycle-to-cycle redundancy of the periodic complex tones from an electronic function generator. They include intentional expressive variations such as glides and vibrato (frequency modulation) and tremolo (amplitude modulation), as well as unintended noise and glitches. These tones might be called "adequately periodic," in the sense that the perceived attributes of harmonic fusion and unambiguous pitch that apply to the ideal tones from precision electronic function generators also apply to them.

Sustained tones, like those from brass instruments, are close enough to periodic that the standard physical description of them begins with a perfectly periodic prototype and then deals with variations as deviations from that prototype. The prototype is not just an abstract idealization. With special care it is possible to produce a sustained tone with a brass instrument that is stable on an oscilloscope screen for many seconds. That means that the relative phases among the harmonics do not

change over the course of many seconds. That, in turn, means that the harmonic frequencies deviate from integer multiples of a fundamental frequency by much less than 1 Hz. Thus, if brass-instrument tones differ at all from perfect periodicity, it is because the performer makes it so. The basic mechanism of sound production is capable of making ideally periodic tones.

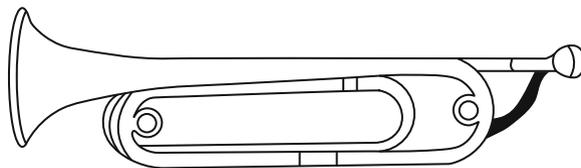
**Harmonic Partial from Inharmonic Resonances** The harmonics of a brass instrument tone (essentially perfect) should not be confused with the resonances of the instrument itself. Brass instruments are hollow tubes that have been fashioned to make air columns with modes of vibration with frequencies (resonance frequencies) that are approximately in a harmonic relationship. These modes, or resonances, are responsible for generating the harmonics of tones, but they may easily deviate from perfect harmonic by 5 or 10 %. How a musical instrument generates a tone with partials that are in a perfect harmonic relationship from resonances that are only approximately harmonic is an essential part of the nonlinear tone generation process in wind instruments.

Thus, there are two essential problems in the understanding of brass instruments. The first is to understand the resonances of the instrument. The second is to understand how these resonances can be made to produce tones with clear pitches and stable harmonic spectra. We deal with the resonance problem first.

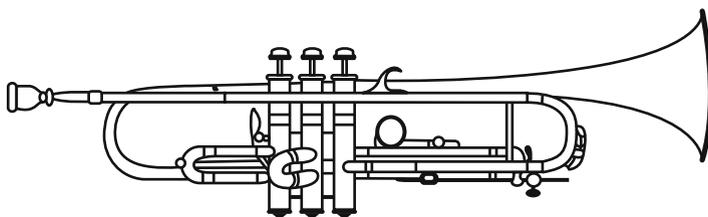
## 23.2 Evolution of the Resonances of a Trumpet

Any brass-instrument player can pick up a piece of copper pipe and play a few notes by buzzing his lips in one end of the pipe. If the pipe is 1 m long, the notes will have fundamental frequencies of about 260, 430, and 600 Hz. These frequencies fit a pattern; they are approximately  $3 \times 86$ ,  $5 \times 86$ , and  $7 \times 86$ . Returning to the study of cylindrical pipes in Chap. 8, you discover that this pattern looks like a pipe that is open at one end and closed at the other. The closed end is closed by the player's lips. You can calculate the base frequency to be  $v/4L$  or  $344/4 \cdot 1 = 86$  Hz, and that agrees with the observed result. You also expect there to be only odd resonances. It all works out, except that apparently the brass instrument player is unable to make a tone from the lowest resonance at 86 Hz. However, if a clarinet player comes along and puts her reed mouthpiece on the end of the pipe, she can play a tone corresponding to that low-frequency resonance.

**The Bugle** The first step in developing a useful instrument is to add a mouthpiece and bell to the cylindrical tube as shown in Fig. 23.1. The function of the mouthpiece is mainly to provide a comfortable and convenient place to vibrate lips. The bell has two functions. First, it helps to radiate the tone, especially the high harmonics of the tone so that the brass instrument sounds bright. Second, the bell greatly modifies the resonance frequencies of the instrument. They are no longer odd integer multiples of a base.



**Fig. 23.1** The bugle is a cylindrical pipe for most of its length. It has a mouthpiece on one end and a bell on the other. The cylindrical pipe is bent around to make the bugle easy to carry, but all those bends have little effect on the playing of the instrument. If the bends were all straightened out to make a long pipe the bugle would not sound any different

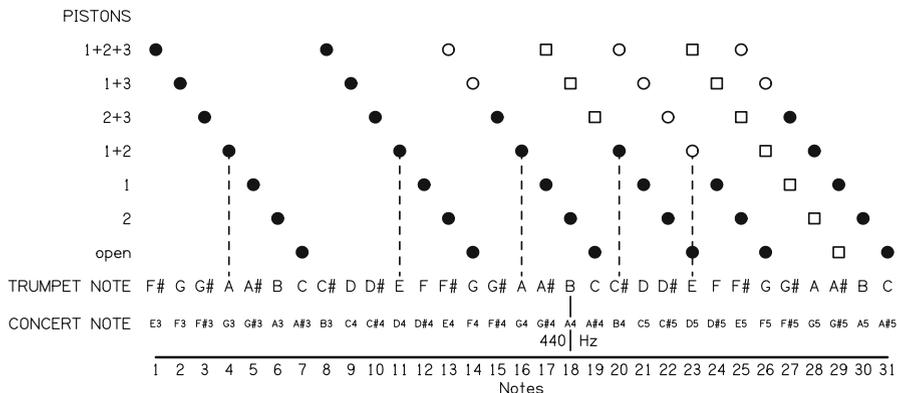


**Fig. 23.2** The trumpet has three valves. When the piston is depressed in the valve an extra length of tubing is added to the horn

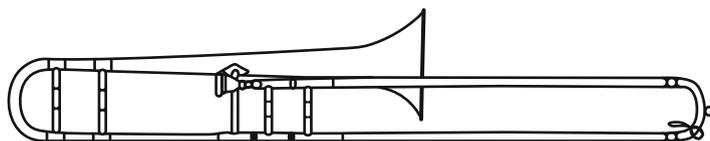
If we give the brass-instrument player a bugle, he can play many more notes than with the simple pipe. He can play notes with fundamental frequencies of approximately 196, 293, 392, 493, 587, 698, and 784 Hz. These frequencies fit the pattern  $2 \times 98$ ,  $3 \times 98$ ,  $4 \times 98$ ,  $5 \times 98$ ,  $6 \times 98$ ,  $7 \times 98$ , and  $8 \times 98$ . Appendix E shows that these fundamental frequencies correspond to the notes *G3*, *D4*, *G4*, *B4*, *D5*, *F5*, *G5*. The first five of these notes are used in traditional bugle calls, like taps or reveille. The important point is that the addition of a flaring bell to the cylindrical pipe has deformed the pattern of resonances to look like successive integers (2, 3, 4, ...) not like odd integers only. You will notice that the integer 1 is missing from the list. The lowest-frequency mode of a horn with a bell has a frequency too low to fit the pattern. It is not used musically.

**Adding the Valves** Like half a dozen other brass instruments, the trumpet (Fig. 23.2) has three valves, numbered 1, 2, and 3, with valve number 1 being closest to the player. Each valve is fitted with a piston. In normal playing, a piston is either up or down. Intermediate positions are not used. When the player depresses a piston, an extra length of cylindrical tubing is inserted into the cylindrical section of the instrument. Piston 1 inserts about 18 cm. Piston 2 inserts about 10 cm. Piston 3 inserts about 30 cm.

Figure 23.3 shows how a player uses the valves to play notes in between the standard notes of the bugle. The figure shows that the trumpet is essentially seven bugles. The first bugle is made with the open horn, and it can play the trumpet's notes *C*, *G*, *C*, *E*, *G* ... The second bugle is made by depressing piston 2, and it is tuned half a tone lower, playing *B*, *F♯*, *B*, *D♯*, *F♯* ...



**Fig. 23.3** There are seven piston configurations used in playing the trumpet, including the “open-horn” configuration—no pistons depressed. *Solid dots* on the plot show the fingering (depressed piston configuration) for 31 trumpet notes from the lowest written note to the note called “high C.” (Notes above high C are used by athletic performers.) *Open circles* show alternative fingerings, not normally used. *Open squares* show alternative fingerings that lead to notes that are badly out of tune—all flat. The five notes used in bugle calls are indicated by *dashed lines*. Labels near the bottom of the plot show the names of the musical notes. So called, “accidentals”—sharps (♯) and flats (♭)—are here indicated by sharps only. In fact, A♯ is equivalent to B♭; C♯ is equivalent to D♭, etc. The trumpet is a transposing instrument, and its nomenclature for musical notes does not agree with that for the piano or violin, the basis of “concert pitch.” Because the trumpet is a B-flat instrument, the trumpet player’s “C” corresponds to B♭ (A♯) on the piano or violin



**Fig. 23.4** The trombone has a slide that can be varied continuously, but there are seven distinct positions that correspond to notes of the scale

Other valved brass instruments, cornet, baritone horn, and tuba have very similar fingerings. Although it does not look like it, a trombone (Fig. 23.4) is essentially a trumpet, tuned an octave lower because the pipe is twice as long. Every trombone player learns seven positions for the slide—equivalent to the seven valve configurations on the trumpet.

### 23.3 Tone Production: Feedback and Nonlinearities

To a casual observer brass instruments look complicated. They look like a plumber’s nightmare of valves, slides, crooks, and tubing bent into intricate shapes. (This is especially true of the French horn (Fig. 23.5), which has a great length of tubing,

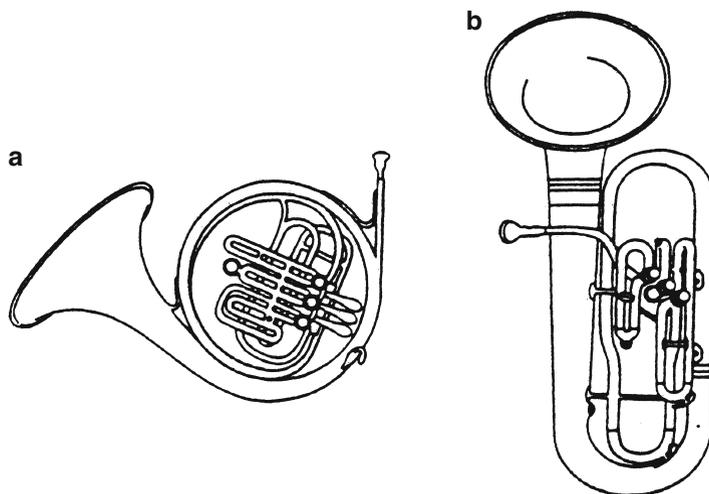


Fig. 23.5 (a) The French horn and (b) the baritone horn

all curled up into a convenient package.) But from a physical point of view, what is truly complicated about a brass instrument is the interaction of the player's lips—buzzing in the mouthpiece—and the resonances of the plumbing. This section tries to deal with that interaction.

The mouthpiece of a brass instrument can be disconnected from the rest of the instrument. If you give a bugle player the mouthpiece alone, the player can vibrate his lips without difficulty in the mouthpiece to produce a buzzy sound, rather like an obnoxious duck. While this buzzy sound continues, the rest of the instrument can be slid onto the mouthpiece to produce a normal bugle tone. What is interesting about this little experiment is the sensation experienced by the player. With the mouthpiece alone, the lip vibration feels chaotic. As the rest of the instrument is added, the lips are forced into a more orderly pattern of vibration and the player can feel this happening.

The cause of this change can be described as *feedback* from the horn to the mouthpiece, or as *reflections* of puffs of air from the horn back to the mouthpiece, or as the result of *standing waves* in the horn. The standing waves can be called “resonances” of the horn. These descriptions are essentially equivalent. Because of its strong resonances, the horn reinforces lip vibrations near its resonance frequencies. If the horn resonance frequencies are nearly in a harmonic relationship, they cause the lips to vibrate periodically and the puffs of air admitted into the horn by the lips through the mouthpiece are caused to have a well-defined shape in space and time. Well-defined pulses lead to a brassy tone with strong high harmonics. If the resonance frequencies of the horn are not well aligned in a harmonic relationship, the puffs of air are less compact in shape and the tone quality becomes duller.

The bugle player can get at least six different musical notes from the instrument. A trumpet player can get at least six for every configuration of the pistons. Of course, for each configuration the horn has only one set of resonances. Thus, it is evident that the player must be using the resonances in different ways to get all the different notes.

Figure 23.6 shows the resonances of a trumpet with no pistons depressed. You can see 14 resonant peaks there. Their frequencies are 92, 233, 364, 464, 587, 710, 819, 937, 1,065, 1,183, 1,320, 1,451, 1,579, and 1,706 Hz. These are the peaks that can be used to create tones. For example, the lowest tone of the open horn (no pistons down) has a fundamental frequency of 233 Hz. Figure 23.6 includes circles indicating the harmonics of the 233-Hz tone. Their frequencies are 233, 466, 699, 932, 1,165, 1,398, and 1,631 Hz. The first five harmonics are supported by the nearby resonances, with peaks at 233, 464, 710, 937, and 1,183.

If the musician wants to play a different note, still with no pistons depressed, the musician will tighten the lips, and perhaps blow a little harder. The result will be that the resonances are used in a different way to create a tone with a different fundamental frequency. Learning how to control the lips in such a way as to make flexible use of the resonances of the horn is the essence of learning how to play a brass instrument. The resonances that contribute to the different notes will become clear on the completion of Fig. 23.6 in Exercise 23.2.

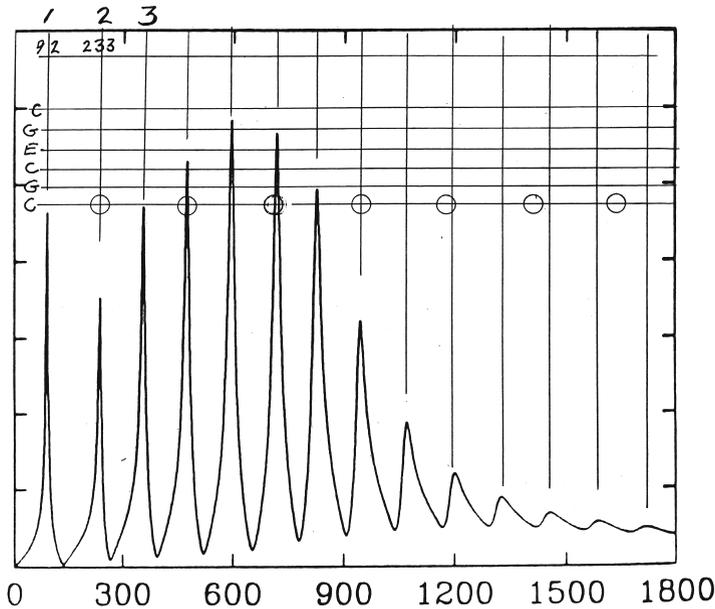
The collaboration between vibrating lips and the resonances of the horn in creating a tone has several consequences. These are described below in terms of resonances numbered 1–14 starting from the left.

### **Consequence 1: Harmonic Amplitude vs Resonance Peak Height and Tuning**

If a resonance of the horn is close in frequency to a harmonic of the tone and the resonance peak is tall, the corresponding harmonic will normally be strong in the tone. For example, in the 233-Hz trumpet tone you can expect the second and third harmonics to be strong because the 4th and 6th resonance peaks in Fig. 23.6 are tall. For the note an octave higher, with fundamental frequency 466 Hz, the fundamental should dominate because the resonance at 464 is stronger than the other contributing resonances as you will see when you do Exercise 23.2. Because these resonances are fixed in frequency, as the playing (fundamental) frequency changes, tall resonances lead to formants, characteristic of the instrument.

**Consequence 2: Harmonic Amplitude vs Intensity** If the player blows with greater force, the amplitudes of all the harmonics increase. However, the amplitudes of the higher-frequency harmonics increase more than the amplitudes of the lower-frequency harmonics. Therefore, in relative terms, the high harmonics become increasingly important, and the tone color becomes brighter.

**Consequence 3: Playing Frequency vs Intensity** Each resonance that helps to create a tone plays a role in determining the playing frequency. For example, consider the five resonances that help create the 233-Hz tone. Resonance number 2, with a peak frequency at 233 Hz, wants the playing frequency to be 233 Hz. Resonance 4, with a frequency of 464 Hz, would like to create a second harmonic of a 232-Hz tone, and therefore this resonance would like the playing frequency to be



**Fig. 23.6** The response *curve* for a trumpet indicates the amplitude of pressure variations at the mouthpiece caused by feedback from the rest of the horn. This feedback will help the player’s lips vibrate with frequencies of peaks of the response curve. Peaks are called resonances, the first three are numbered. A few of their frequencies are given too. *Circles* indicate the frequencies of harmonics of low C, with a playing frequency of 233 Hz

232 Hz. That is because  $464/2 = 232$ . Resonance 6, at 710 Hz wants to create the third harmonic of 237 Hz because  $710/3 = 237$ . Similarly resonance 8, at 937 Hz wants to create the fourth harmonic of 234 Hz, and resonance 10 at 1,183 Hz wants to create the fifth harmonic of 237 Hz.

Evidently the different resonances are voting for different playing frequencies. But the voting is not equal. The votes are weighted by the contribution to the tone. This weighting leads to small changes in frequency with increased intensity. As described in Consequence 2, the higher harmonics become relatively more important with increasing intensity. Harmonics 3, 4, and 5 would all vote for a playing frequency that is higher than 233 Hz. As they become more important with increased blowing pressure, the playing frequency of this note on this instrument will tend to rise slightly.

**Consequence 4: Bending Notes** Establishing the playing frequency of a brass instrument can be imagined in three steps. (1) First the musician tightens his lips and sets the blowing pressure to establish the general frequency range of the note to be played. (2) Then the resonances of the horn determine more precisely what the playing frequency shall be, within the range established in step (1). The resonances determine the reflections of puffs of air backwards toward the mouthpiece that

cause the musician's lips to open at the right time to admit a new puff of air. If a trumpet player is playing "high C," with a fundamental frequency of 932 Hz, then the player's lips open and close 932 times per second, admitting 932 puffs of air every second. (3) Finally, the musician can establish some micro control of the playing frequency. He can "lip" the frequency up or down. Because the playing frequency is always a compromise among the different resonances, and because the resonance peaks themselves are not infinitely sharp, a musician can tighten or relax his lips ever so slightly to cause the instrument to run a little bit sharp or flat compared to the best combination of resonances. In this way, a musician can bend notes. Bending notes can be used to play better in tune with another instrument or for expressive effect, as in jazz performance. If a trumpet player wants to bend a note by a large frequency difference, he can deliberately wreck the pattern of resonances of his instrument by closing a valve (usually the second valve) half way. When the valve is caused to be neither fully open nor fully closed, the resonances become pale shadows of what they were normally. Because the resonances are then not so strong, the musician's lips have more micro control of the playing frequency, but the tone quality becomes stuffy and not at all brassy.

## Exercises

### *Exercise 1: Trumpet tones*

With an open horn, a trumpet can play notes that the trumpet player calls  $C_4$ ,  $G_4$ ,  $C_5$ ,  $E_5$ ,  $G_5$ ,  $C_6$ . The trumpet is a "transposing" instrument, which means that the real notes (concert notes) are  $B\flat_3$ ,  $F_4$ ,  $B\flat_4$ ,  $D_5$ ,  $F_5$ ,  $B\flat_5$ . These notes have fundamental frequencies: 233, 349, 466, 587, 698, 932 Hz, respectively.

- (a) From the frequencies, show that all the notes called  $C$  are in octave relationships.
- (b) Show that the notes called  $G$  are a musical fifth above the notes called  $C$  because the frequency ratios are about  $3/2$ .

### *Exercise 2: Trumpet resonances and trumpet tones*

Refer to Fig. 23.6, the large resonance curve for the open trumpet. Do the following steps on that plot. (a) Complete the numbering of resonances, 1–14. (b) Complete the list of peak frequencies on the plot. They are: 92, 233, 364, 464, 587, 710, 819, 937, 1,065, 1,183, 1,320, 1,451, 1,579, and 1,706 Hz. (c) Use circles to indicate which resonances are used to make the six tones with the fundamental frequencies given in Exercise 1 (notes are C, G, C, E, G, C in trumpet notation). The first tone, C 233-Hz, has been done for illustration.

### *Exercise 3: Open or closed or neither?*

A bugle resembles a pipe that is open at one end (the bell) and closed at the other (the mouthpiece). However, in an important sense it better resembles a pipe that is open at both ends. In what sense is that? How do you account for this apparent paradox?

*Exercise 4: Trumpet valves and trumpet tones*

A trumpet has three valves (so do many other brass instruments). In normal playing, a valve is either open or closed. Show that the valve combinations can be represented as a 3-bit word. Therefore, show that there are eight possible combinations. Which combination is missing from Fig. 23.3?

*Exercise 5: Trombone and trumpet*

The trombone tubing is about twice as long as the trumpet. Show why you expect it to sound an octave lower.

*Exercise 6: French horn and trumpet*

The French horn tubing is about twice as long as the trumpet, but the playing frequencies are about the same as the trumpet. How can this be? [Hint: The notes that can be played in a single valve position on a French horn are much closer together than the notes that can be played on a trumpet.]

*Exercise 7: The abused bugle*

The author owns a bugle that was thoroughly dented during several years of camp. The bugle still plays the right notes (correct fundamental frequencies) but the tone color is bad. Can you explain?

*Exercise 8: Speedy!*

The text says that when a trumpet player plays “high C,” his lips open and close 932 times per second. Bozo disagrees. He says that nobody can move his muscles, even lip muscles, at such a rapid rate. Set Bozo straight on this matter.

*Exercise 9: Resonances again*

The chapter makes frequency use of the concept called “resonances.” What’s the relationship between that concept and resonance as described back in Chap. 3?

