bowed string appears the same as the shape of a plucked string; however, looks are deceiving. If we study the bowed string with photographic techniques so that the vibrating string can be observed in slow motion, we find that the string has an angular shape formed by two straight-line segments. The junction point of the two line segments propagates along the string and is reflected at the end supports.

The salient features of the bowed string's motion can be represented in a diagram (Figure 9.13). Point P, the discontinuity, races around a parabolic path (dotted line) once during each cycle. For the open A string on a violin, the period $T = 1/440$ s; therefore, the discontinuity makes 440 round trips every second.

The discontinuity passes under the bow twice—once while moving to the right and once while moving to the left—during each round trip. Each time the discontinuity passes under the bow the status quo is disturbed: If the string is sticking to the bow, it will be knocked loose by the passing discontinuity. If, on the other hand, the string is slipping along the bow, the passing discontinuity enables the bow to once again grab hold of the string. The revolving discontinuity is the clockwork mechanism that provides the precise alternation (referred to earlier) between sticking and sliding.

The overall motion of a bowed string is different from that of a plucked string. Likewise, the specific points along a bowed string move differently than they would if the string were plucked. The points along a plucked string spend only a fraction of each period in motion. This is not true for a bowed string. Let Q be a point on the string that is a distance D from the bridge. If the length of the string is L, the point Q divides the string into two segments having lengths D and $L-D$. For a string bowed in the "up-bow" direction, the time that point Q spends slipping (falling) is proportional to D. The time that point Q spends sticking (rising) is proportional to $L-D$. If T_F = the time spent falling (slipping) and T_R = the time spent rising (sticking), we can write

$$\frac{T_F}{T_R} = \frac{D}{L - D}$$

or

$$T_F = \left(\frac{D}{L - D}\right) T_R$$

If

$$D = \frac{1}{20} L = 0.05L$$

then

$$\frac{0.05L}{L - 0.05L}\, T_R = \frac{0.05}{0.95}\, T_R = 0.053\, T_R$$

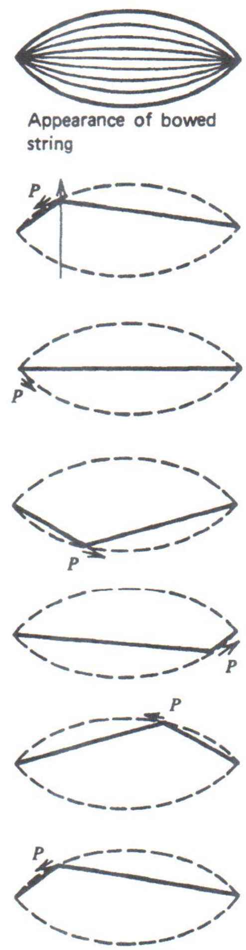

Figure 9.13 The shape of a bowed string through one cycle for the case of up-bowing.

However, since $T_R + T_F = T$, we can write

$$T_R + 0.053T_R = T$$
$$1.053T_R = T$$
$$T_R = 0.95T$$

FFT 7 This result indicates that 95 percent of each period the string is rising. The other 5 percent of the period it is falling.

These results are shown in diagrammatic form in Figure 9.14. Three points Q, R, and S are identified on the string. The motion of each point

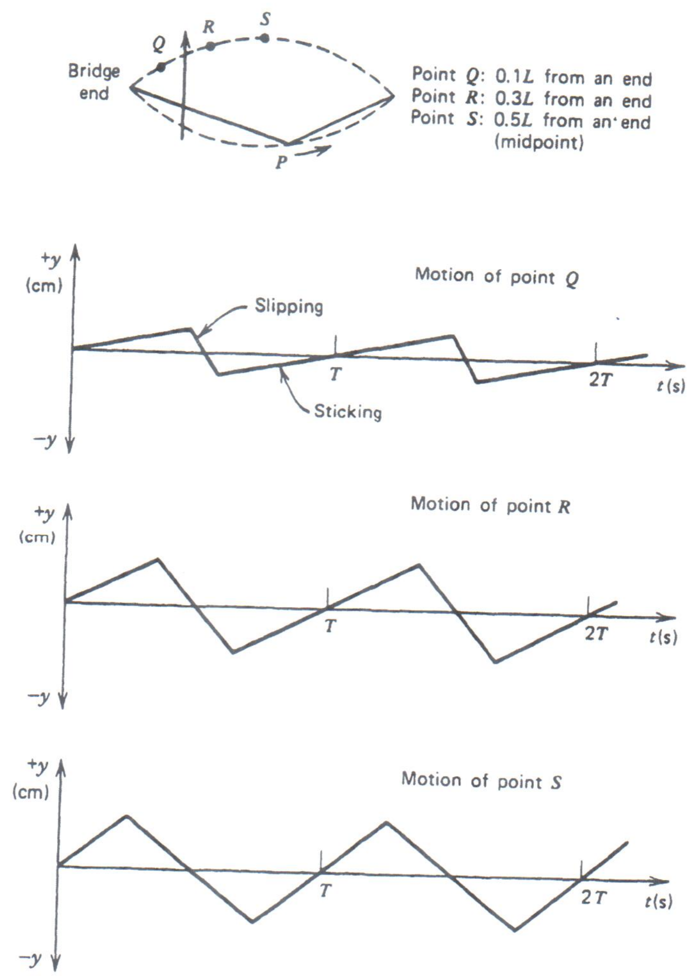

Figure 9.14
Motion of specific points along a string bowed in the "up-bow" direction.

graphed separately. From both the results above and the succeeding graphs it is apparent that all points along a bowed string are moving at all times.

A string bowed in the up-bow direction initiates a discontinuity that revolves around a parabolic path in a counterclockwise sense. When the string is bowed in the down-bow direction, the discontinuity revolves in a clockwise sense. As Figure 9.15 shows, the ratio of times spent sticking and slipping is independent of the bowing direction.

The harmonics present in a string vibration depend on its shape. Since the shape of a bowed string is different from that of a plucked

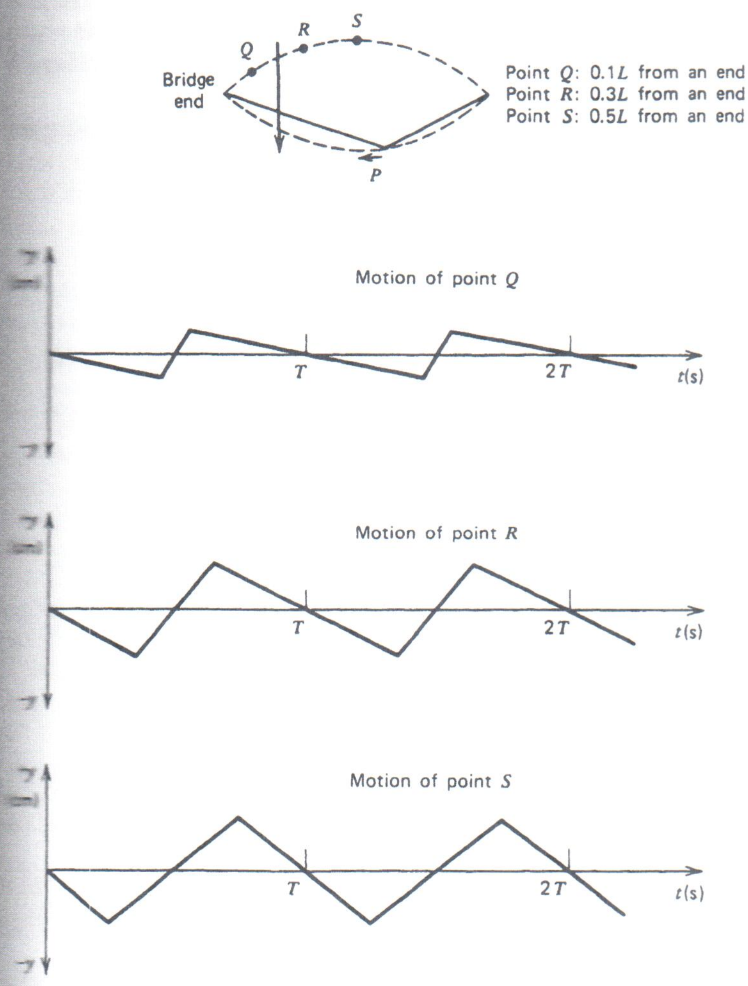

Figure 9.15
Motion of specific points along a string bowed in the "down-bow" direction.

string, we would expect a difference in their timbre. The triangular form of the bowed string makes possible a sound spectrum that is very rich in harmonics. Both even and odd harmonics are present and their intensities decrease much more slowly than do the harmonic intensities of a plucked string. For the bowed string, the intensity of the nth harmonic is, as with the struck string, $1/n$ times the intensity of the fundamental. For the plucked string, as we have seen, the intensities of harmonics decrease in proportion to $1/n^2$. The rich harmonic content of the bowed string is of utmost significance in the production of sound in the string instruments.

FFT 8

In summary, when the bow is placed on the string and drawn steadily across it in the up-bow direction, the string alternately sticks to and slips against the bow. There is an initial period of instability before the standing waves get established on the string and the precise alteration begins. The bowing process is represented in Figure 9.16.

The shapes and motions of the bowed string and plucked string are

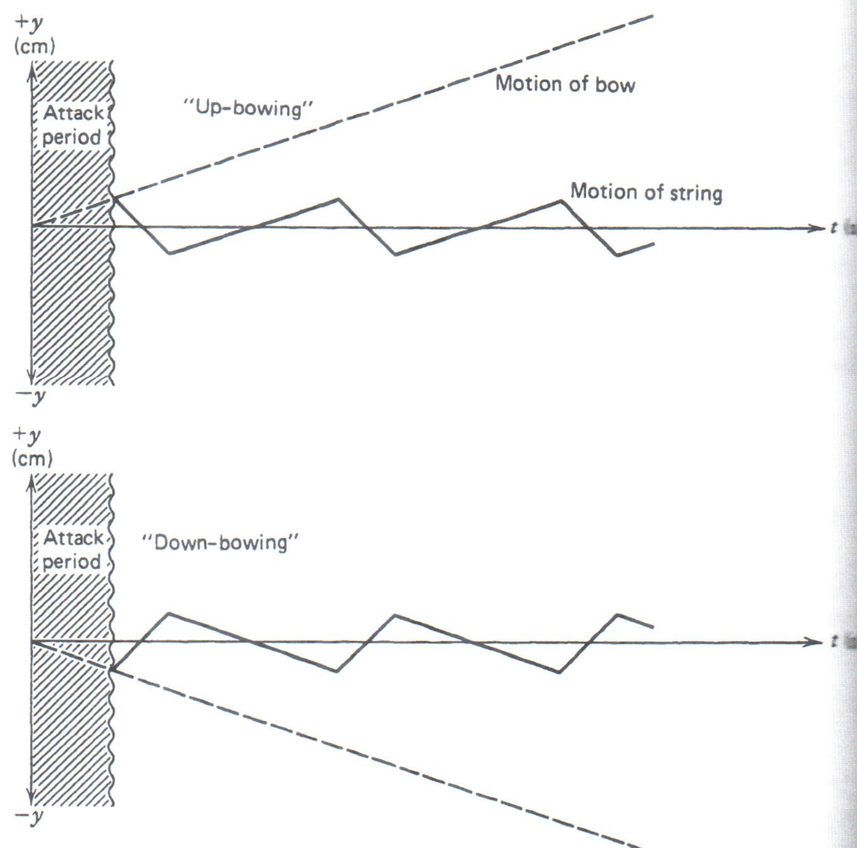

Figure 9.16
Motions of both bow and string for up-bowing and down-bowing.

different. For this reason, the quality of sound of a string excited by these two techniques is quite different.

THE GENERATION OF COMPLEX VIBRATIONS IN AN AIR COLUMN

Anyone who has ever blown across the top of a soda bottle has probably been able to excite the enclosed air into vibration. If you can recall such an experience, you may remember that the instant you stopped blowing, the bottle stopped "singing." This suggests that the enclosed air vibrates only so long as you help it to do so. When the outside assistance ceases, the air vibrations decay immediately. In this regard, an air column behaves differently than a stretched string: A string's vibrations decay slowly, whereas those of an air column decay immediately. Impulsive excitations, therefore, will not suffice for the air column; rather, energy must be supplied continuously if oscillations are to be sustained.

Edge Tones

Imagine a chamber containing air at a pressure higher than that of the outside air. If a narrow slit is opened in a wall of the chamber, a jet of air will stream from the slit into the outside air. Near the exit slit, the stream can have a reasonably well-defined ribbonlike form. Further from the exit slit, the ribbonlike form is lost as the stream pushes and drags against the static ambient air. The edges of the stream, in more direct contact with the ambient air, are peeled back and small whirlpoollike vortices are formed. The rotational motion of the vortices exerts a sideways (or transverse) influence upon the faster-moving interior of the jet stream. There is a hissing sound associated with the jet stream, a sound resulting from the superposition of many, many frequencies. There are many familiar phenomena that have as their origin the movement of air through a narrow orifice: a person whistling, the whistling of the wind through a crack around a door or through a slightly opened car window, and the spooky sound of the wind around the eaves of a house or through the rigging of a ship.

The energy of the jet stream can be effectively transformed into sound (acoustic energy) of one or more frequencies by directing the jet stream against an edge as illustrated in Figure 9.17. The perceived pitch

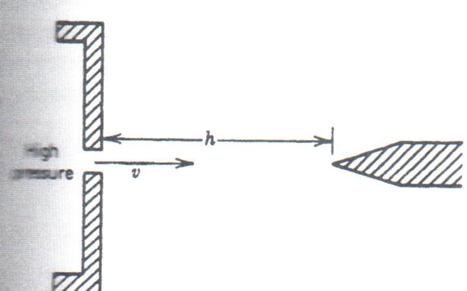

Figure 9.17
The jet–edge system.

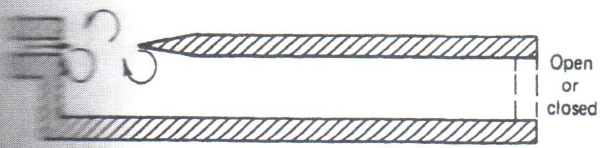

Figure 9.18
The jet–edge system as an integral part of an air column.

So far we have focused on the experimental features of the edge tone—features on which everyone agrees. It is in the context of explanation that differences exist. There are those who explain the edge tone frequency in terms of the vortices formed in the jet stream; others maintain that the vortices are formed too far downstream and have little influence (see references at the end of the chapter).

The differences among the experts on the edge tone are of secondary significance for our purposes because we are not concerned with the jet–edge system per se. Our ultimate interest is the way air columns are set into oscillation. In other words, the jet–edge system is, for our purposes, coupled with an air column, and it is how this jet–edge system excites an air column that is our concern.

When the jet–edge system is an integral part of an air column, as illustrated in Figure 9.18, there is a give-and-take between the jet–edge system and the air column with each affecting the other. In musical instruments such as the flute, the orifice of the jet stream (performer's lips) and the edge are close enough together that the jet stream still retains its ribbonlike form at the site of the edge. The jet stream itself is sinuous enough that small pressure differences above or below the stream can push the stream up or down and initiate a wavelike undulation in the stream that propagates along it. As a result, the jet stream can play over the edge in periodic fashion—first below it, then, later in its cycle above it. This is shown in Figure 9.19.

The jet stream *can* play over the edge, but *why* does it? The answer lies in the interaction between the jet stream and the air column to which the jet–edge system is attached. As we know, an air column can vibrate with definite frequencies. If the ratio v/h for the jet stream has

Figure 9.19
The jet stream undulates so that it is successively below the edge (*a*) and above the edge (*b*).

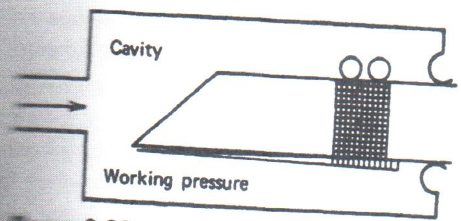

Figure 9.20
The reed system.

can freely pass. The reed's behavior is determined by the difference between two pressures: the pressure outside the reed maintained in the mouth of the performer and the pressure inside the mouthpiece. The outside pressure is always the larger of the two and it is essentially constant. By contrast, the inside pressure varies periodically. When play is begun, air streams from the high-pressure reservoir of the player's mouth into the mouthpiece and the reed begins to close. As the reed moves toward the mouthpiece, the flow of air into the mouthpiece is reduced; however, the air that slips through the narrowing reed–mouthpiece slit moves very rapidly (like the water of a lazy river moves quickly through a narrow channel). The constant pressure in the performer's mouth cavity provides the primary driving force to close the reed down on the mouthpiece, but the reed gets its final kick from this rapidly moving air due to the reduced pressure associated with its high speed, and it closes. In the meantime, the first rush of air into the mouthpiece starts the oscillations of the air column; and it is the periodic pressure variations in the mouthpiece that push the reed back away and reopen the space so that air can reenter. When the pressure in the mouthpiece is highest, the opening between the reed and mouthpiece is widest and the most air from the performer's mouth cavity enters. The cycle is repeated, with the reed opening and closing against the mouthpiece. FFT 12

As mentioned above, the first rush of air into the mouthpiece from the player's mouth sets the air column into oscillation. In fact, the burst of air initiates a compression that propagates along the air column. At the end of the tube opposite the mouthpiece, the compression is reflected and a standing wave is established in the tube. Since the reed and mouthpiece behave like a closed end, the fundamental mode has a pressure antinode at the mouthpiece. For half of the fundamental's period the pressure in the mouthpiece is high and for the other half it is low. This variation of the air column pressure in the mouthpiece effectively controls the vibration of the reed. (One can confirm this by blowing the mouthpiece without the tube and noting that it has a pitch quite different than the pitch perceived when the air column is in control.)

The pressure in the cavity (or player's mouth) is always higher than the highest pressure in the mouthpiece. Thus, when there is a pressure

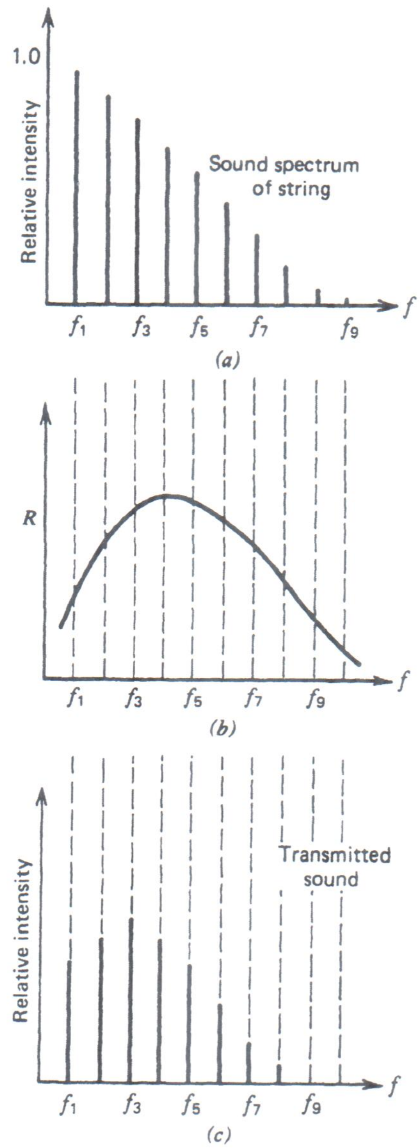

Figure 9.22
A vibrating string with the sound spectrum *a* is mounted on a structure with resonse curve *b*, which influences the timbre of the transmitted sound *c*.

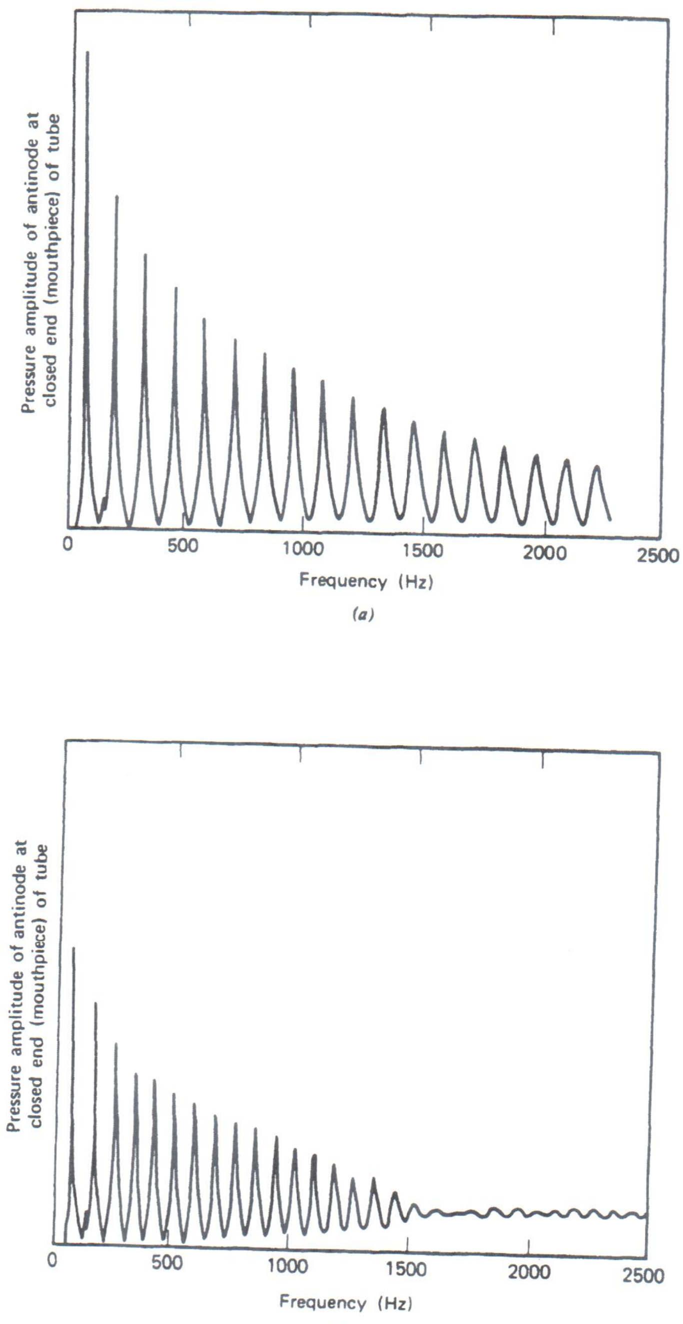

Figure 9.23
(*a*) Resonances of a trumpetlike tube. (*b*) Resonances after adding a bell to the trumpetlike tube. (From *Fundamentals of Musical Acoustics* by Arthur H. Benade. Copyright © 1976 by Oxford University Press, Inc. Reprinted with permission.)

frequencies (small wavelength) so little of the sound wave is reflected from the open end that standing waves cannot be established inside the tube. Furthermore, the addition of the bell squeezes the resonance peaks closer together. We shall discuss this in greater detail when we meet the brass instruments.

The bell radiates more effectively at high frequencies. Consequently, the sound spectrum of the complex tone inside the tube is different than the sound spectrum of the transmitted sound. This is illustrated in Figure 9.24.

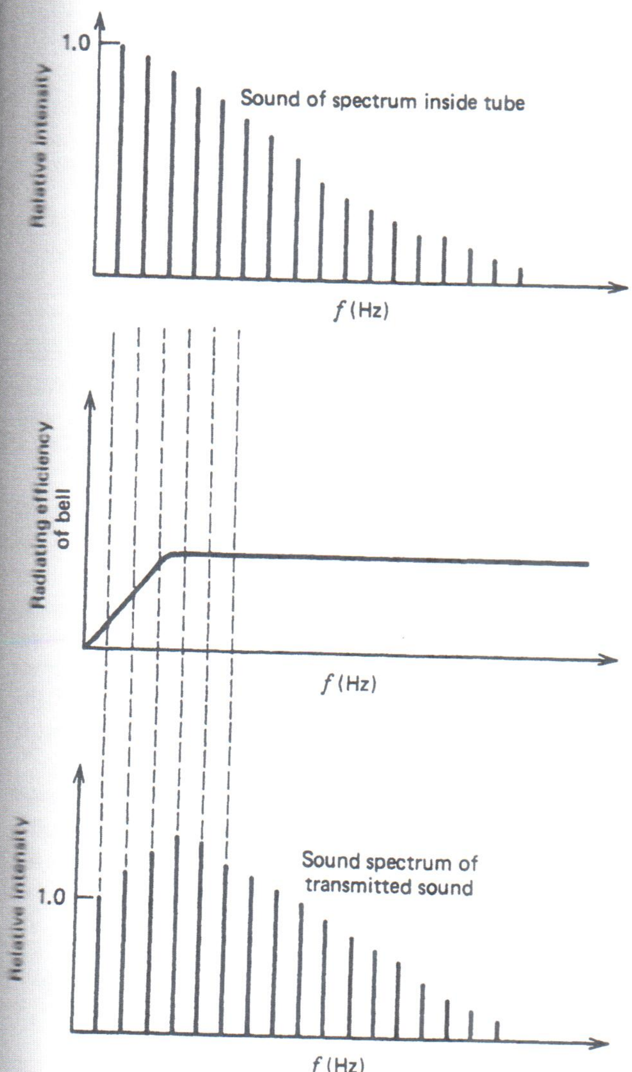

Figure 9.24
Influence of the bell of a brass instrument on the transmitted sound.