signed for use in two pitches, B♭ and A, though an E♭ instrument is sometimes used in military bands. This means, as before indicated, that when C is written in ordinary music, B♭ is sounded by the player. The trumpet is therefore a transposing instrument.

An oscillogram showing a characteristic waveform of the trumpet appears in Fig. 13–39, and the corresponding spectrum is shown in Fig. 13–40. These records show that the first four harmonics are all strong, the second being as strong as the fundamental, and

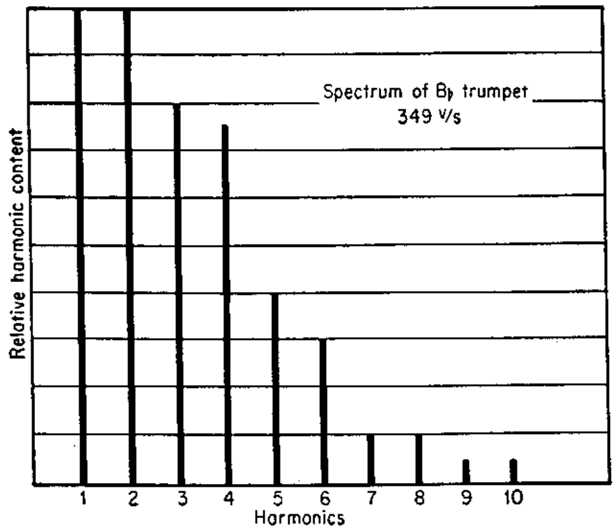

FIG. 13–40

that the remaining partials diminish in magnitude as the order increases. It is this spectral distribution of energy which gives to the trumpet its full and penetrating tonal characteristics. The range of the trumpet extends from E_3 to $B\flat_5$, thus giving it a compass of two and one-half octaves. The trumpet is the soprano instrument of the brass orchestral choir.

In the "Marche Slave" and the "1812 Overture" Tschaikowsky has assigned passages of great beauty to the trumpets.

13-16. *The Cornet*

In design the cornet differs from the trumpet in that its tube is shorter and the bore is larger, a greater percentage being conical.

from John Askill, Physics of Musical Sounds (1979)

As a consequence of the larger bore, the harmonics above the seventh cannot readily be produced. Because of the smaller number of partials evoked when blowing the cornet, this instrument does not require so careful an adjustment of the lip tension and air pressure as is required when sounding the trumpet. The cornet is therefore less difficult to play than the trumpet. In fact, the facility with which it can be played probably exceeds that of all other brass instruments. The characteristic waveform of the cornet is shown in Fig. 13–41, and a representative sound spectrum in Fig. 13–42. It will be noted that the harmonic content is by no means the same as that of the trumpet; in the cornet the second harmonic is stronger than the fundamental and there are fewer

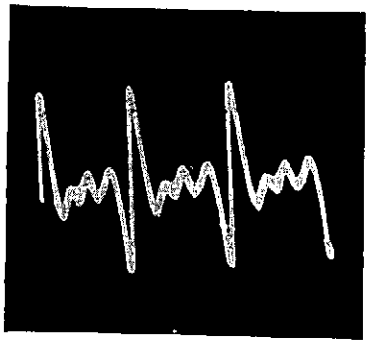

FIG. 13–41. Waveform of B♭ cornet, sounding A 440.

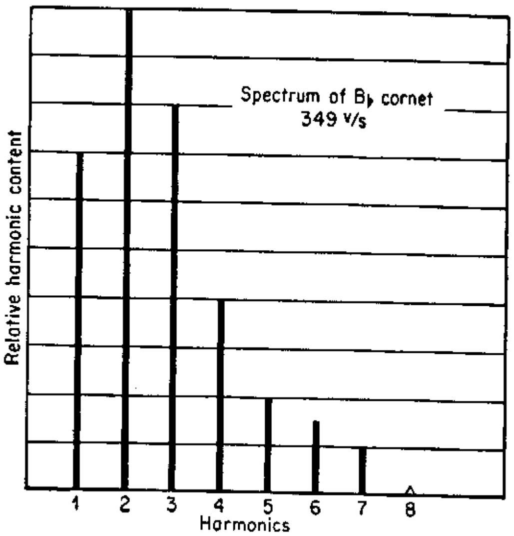

FIG. 13–42

partials than in the trumpet. The strong first and second upper partials give to the cornet its characteristic timbre—a brassy piercing tone. The range of the cornet is approximately the same

as that of the trump
types.

The cornet is us
carrying the lead par
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Minor.

13–17. *The Tuba*

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Fig. 13–43. The wav
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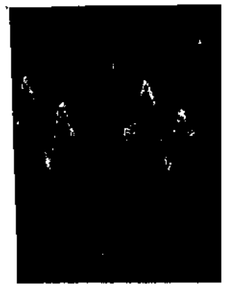

half octaves, from
from E_1 to $B♭_3$. Ow
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spectrum of the tuba is characterized by a limited number of harmonics of which the fundamental and the octave are the principal components. This and its low pitch account for its sonorous tone.

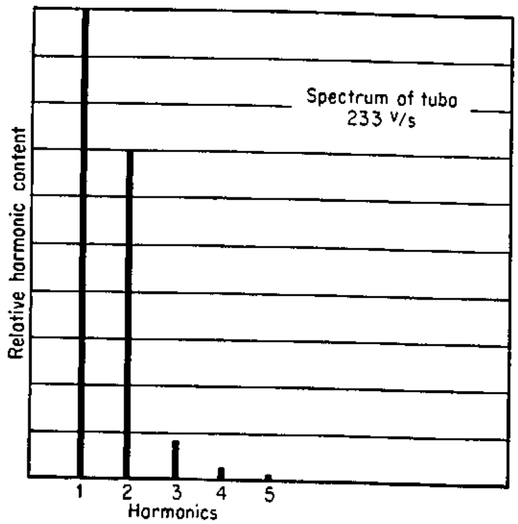

FIG. 13–45

Dvořák has used the tuba effectively in the *New World Symphony*. Another good example is to be found in *Finlandia*, by Sibelius.

13–18. *The Trombone*

The unique instrument among all of the wood winds and the brasses is the trombone (Fig. 13–46). Here we have an instrument without pistons, yet one which is capable of yielding the chromatic scale throughout more than three octaves. Throughout the major portion of its length it consists of a telescoping cylindrical tube terminating in a bell of moderate size; a cup-shaped mouthpiece is used. By making use of a U-shaped sliding crook, one side of which articulates with the mouthpiece portion, the acoustical length of the resonant air column can be adjusted within wide limits. In practice seven positions of the slide are commonly utilized. When the slide is closed, we have what is designated as the first position; the fundamental and seven upper partials can then be evoked.

use of three trombones, one of which (the bass trombone) is pitched considerably lower than the tenor instrument. Trombones speak a dramatic passage in the prelude to Wagner's *Lohengrin*. Another well-known example of the use of trombones occurs in the "Triumphal March" from Verdi's *Aïda*.

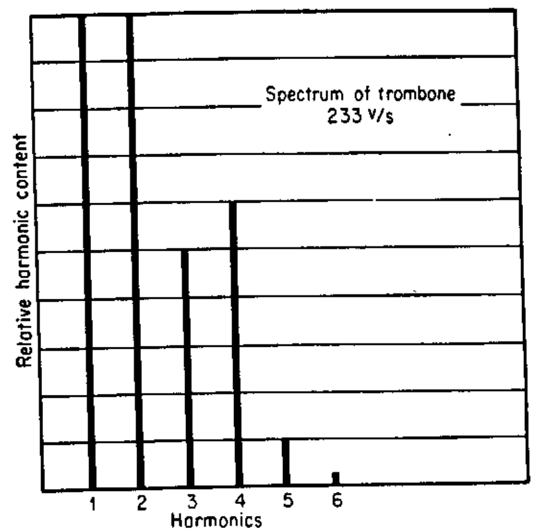

FIG. 13–48

The base trombone, referred to above, is similar to the tenor instrument in design and construction. Its range is from A_1 to $G\flat_2$.

13–19. *The Vocal Organs and the Voice*

The most perfect musical instrument known to man is the human larynx. In possible variations of pitch, timbre, and intensity, it has not been equaled by any of the musical devices that man has yet devised. Essentially the human vocal apparatus is a wind instrument of the double-reed type. The voice is produced by the forcing of air from the lungs through the opening (glottis) between two adjacent pieces of membranous tissue known as the vocal cords (Fig. 13–49), thus causing the free edges to vibrate as in any double-reed instrument. By means of muscles connecting these vibratile tissues with the walls of the larynx, the tension, the

By proper design of the reed and the other associated components, this reed type of electrostatic generator will develop an electrical output that is rich in harmonics. The sound of the reed is not utilized in any way; indeed, it is suppressed. Again by utilizing the principle of electrical filtering the desired form is secured, and in turn transformed into sound of the desired timbre, by the methods previously described. The instrument makes use of a series of such reed generators each of which develops a particular waveform when associated with a suitable electrical filter. It is to be noted that this

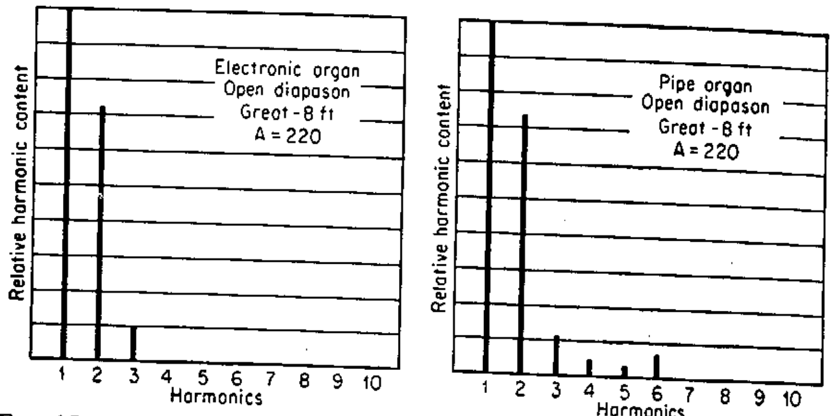

FIG. 15–9. Comparison of a certain note when sounded on a particular electronic organ with the same note when played on a conventional organ.

instrument, and the one employing a multiple-frequency tube generator, does not utilize the principle of synthesis.

Marked advances are being made in the design and construction of electronic organs, but it is probable that this type of instrument will never completely displace the traditional pipe organ. However, the new type of organ is coming into wide use, owing in part at least to its comparatively low cost. The spectrum of one tone on one of the well-known electronic organs is shown in Fig. 15–9. In the same illustration is also to be seen the corresponding tone spectrum of one of the better pipe organs. Note the difference in the harmonic content. It is of course possible to make the electronic instrument have exactly the same harmonic content as the conventional organ, if so desired.

For a detailed technical discussion of electronic organs the reader a metal tube closed at one end, obtained by the capillary excitation method; the resonance frequencies were quite accurately 3, 5, 7, and so on times the fundamental. If the clarinet mouthpiece with reed is placed on this metal tube and the resonances are again measured by the same method (with the reed closed against the mouthpiece), we get a curve essentially identical to that of Fig. 24, Ch. 4, except for slight changes in the positions of the high resonances (above the eleventh harmonic). These changes are due to the internal shape of the clarinet mouthpiece and are of no importance to our present discussion.

Now if the reed is blown in the usual way to produce a vibration in the metal tube at its fundamental frequency, an internal standing wave is obtained which contains mostly odd harmonics, since their frequencies coincide with the resonance frequencies. The even harmonics have small amplitudes, since their frequencies lie in between the resonance frequencies. In Fig. 9 is shown the harmonic structure of this

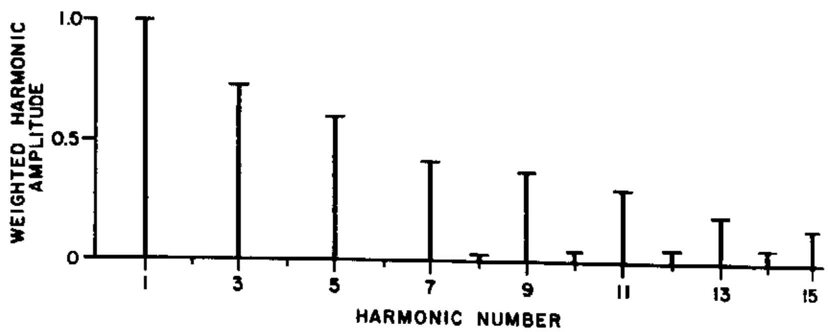

FIG. 9. Harmonic structure of the internal standing wave produced in a metal tube equipped with a clarinet mouthpiece and sounded by blowing. The actual amplitude of a harmonic has been multiplied by its number to get its weighted amplitude as plotted in the figure.

standing wave. The amplitude of each harmonic has been multiplied by its number to give the *weighted* harmonic amplitude shown in Fig. 9; that is, the weighted third harmonic amplitude is three times the measured harmonic amplitude, and so on. Since it can be shown that the higher the frequency of the harmonic, the better it radiates from the instrument, this weighting gives a more realistic representation of how the ear will appreciate the actual harmonic structure. It also makes the harmonics easier to see on the graph.

Now if the capillary excitation method is used to plot a resonance curve for the clarinet (again with the reed closed against the mouthpiece), it is found that it differs considerably from that for the cylindrical metal tube.[15] This is shown in Fig. 10 for the note "E_3"

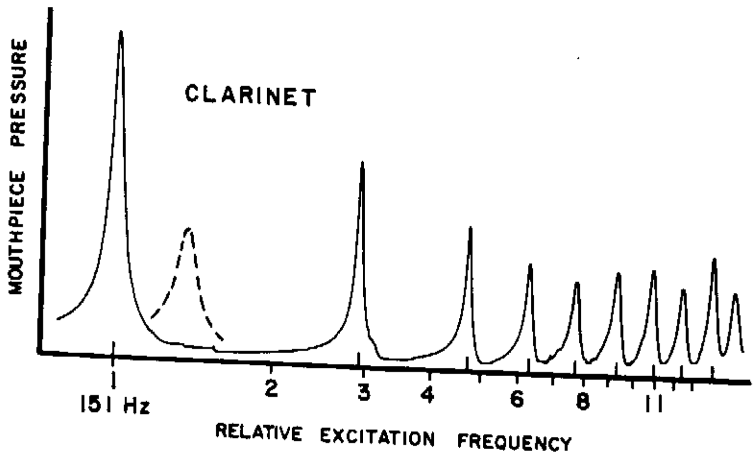

FIG. 10. Resonance curve for the note "E_3" on a clarinet. The dotted line shows the position of the lowest resonance with the vent-hole open.

on the clarinet. The resonance frequencies given by the peaks on the curve are shown, as before, by short vertical lines drawn above the horizontal axis; the frequencies of the harmonics (in terms of multiples of the fundamental frequency) are given by the short vertical lines below the axis. It will be seen that the resonance frequencies depart more and more from the harmonic frequencies as we go to higher values. The resonance curve is "compressed"; that is, the resonance frequencies are lower than the corresponding harmonic frequencies. For the note "E_3," the eighth harmonic, for instance, is quite close to the fifth resonance. Now if the clarinet is blown and the harmonic structure of its internal standing wave is analyzed, it is found that the eighth harmonic is quite prominent in this tone, as might be expected since it lies close to a resonance; this is shown in Fig. 11.

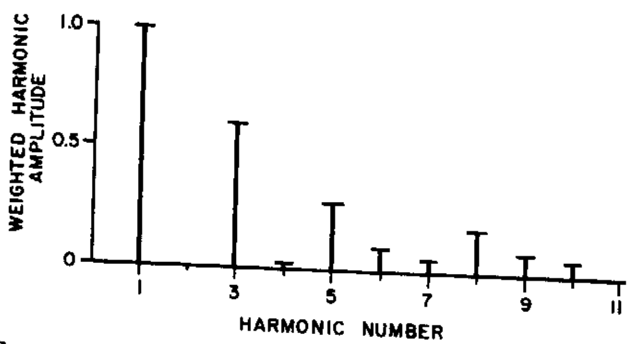

FIG. 11. Weighted harmonic structure of the internal standing wave in a clarinet sounding "E_3."

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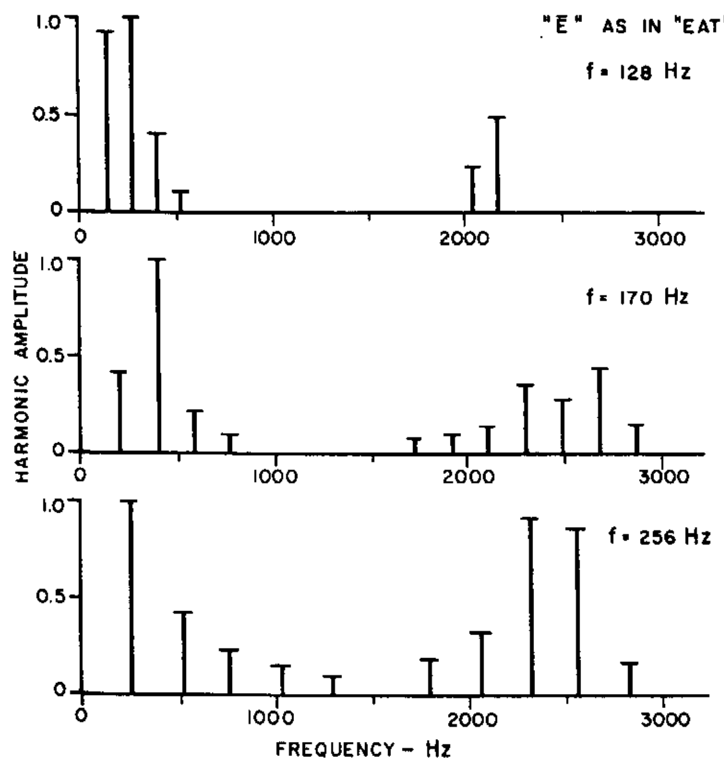

FIG. 22. Formant in the vowel sound ē as in "eat."

frequencies of the vocal cords, on the other hand, are not affected. Spoken sounds under these conditions will have a startling and amusing "Donald Duck" quality that shows in a striking manner the effect of formants on speech sounds.

In contrast to the extensive work done on speech sounds, much less research work has been done on the singing voice; however, recent work is beginning to give a better understanding of the acoustical and physiological factors involved. The male singer, by training, can develop a *singing formant* which is rather independent of pitch and vowel quality, and which occupies a frequency region in the neighborhood of 2.8 kilohertz.[32] The long-time average spectrum of a symphony orchestra shows that in this frequency region its sound output is some 25 decibels below its maximum value at lower frequencies. The singing formant thus emphasizes the frequencies for which there is not much competition from the orchestra, and so helps the singer's voice to stand out and not be masked by the orchestral accompaniment.

The female singer does not have this problem to the same degree, since for the higher ranges her voice is already in the frequency region

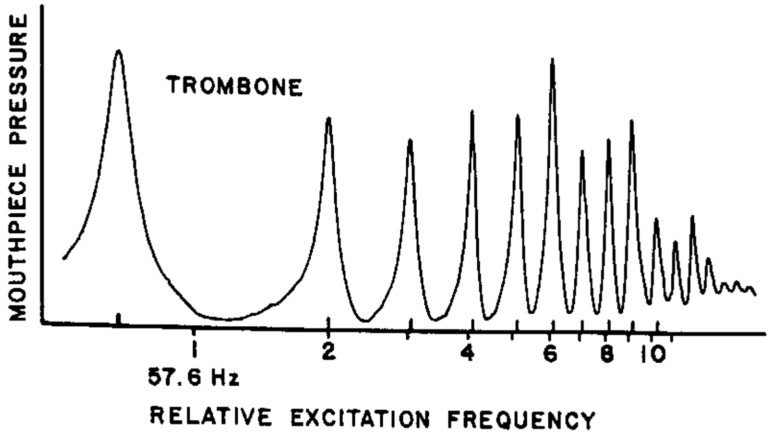

FIG. 7. Resonance curve for a trombone.

The resonance curve for a trombone (in first position) is shown in Fig. 7. As in Fig. 4 for the trumpet, a relative frequency scale is drawn along the bottom and the second resonance made to coincide with relative frequency 2. The higher ones then very nearly coincide with frequencies 3, 4, 5, and so on, forming an approximate harmonic series. As in the case of the trumpet, the lowest resonance of the trombone does not at all fit this series, being much too flat. The pedal tone on the trombone, used more than on the trumpet, is produced in the same way, by vibrating the lips at the fundamental frequency. The upper harmonics of the tone then match the higher resonance modes; this helps the lips to stay on the fundamental frequency. We note in Fig. 7 that the resonance peaks get small after about the ninth, so the trombone does not ordinarily play above this.

The French Horn

The *French horn* is based on the same acoustical principles as the other brass instruments, but differs from them in one fundamental respect; whereas the trumpet and trombone play up to about the eighth resonance mode, the horn uses the series up to an octave higher, as far as the sixteenth. This requires that the high resonances of the instrument be pronounced and distinct. The shape of the air column in the horn has been empirically developed to accomplish this; the bore is in the form of a long cone with a gradual taper for about two-thirds of its length, after which it flares rapidly to a large bell.

The resonance curve for an F horn (open) is shown in Fig. 8. It has more resonance peaks than that for the trombone; the 15th resonance in this instrument is still prominent. Above the 17th resonance the