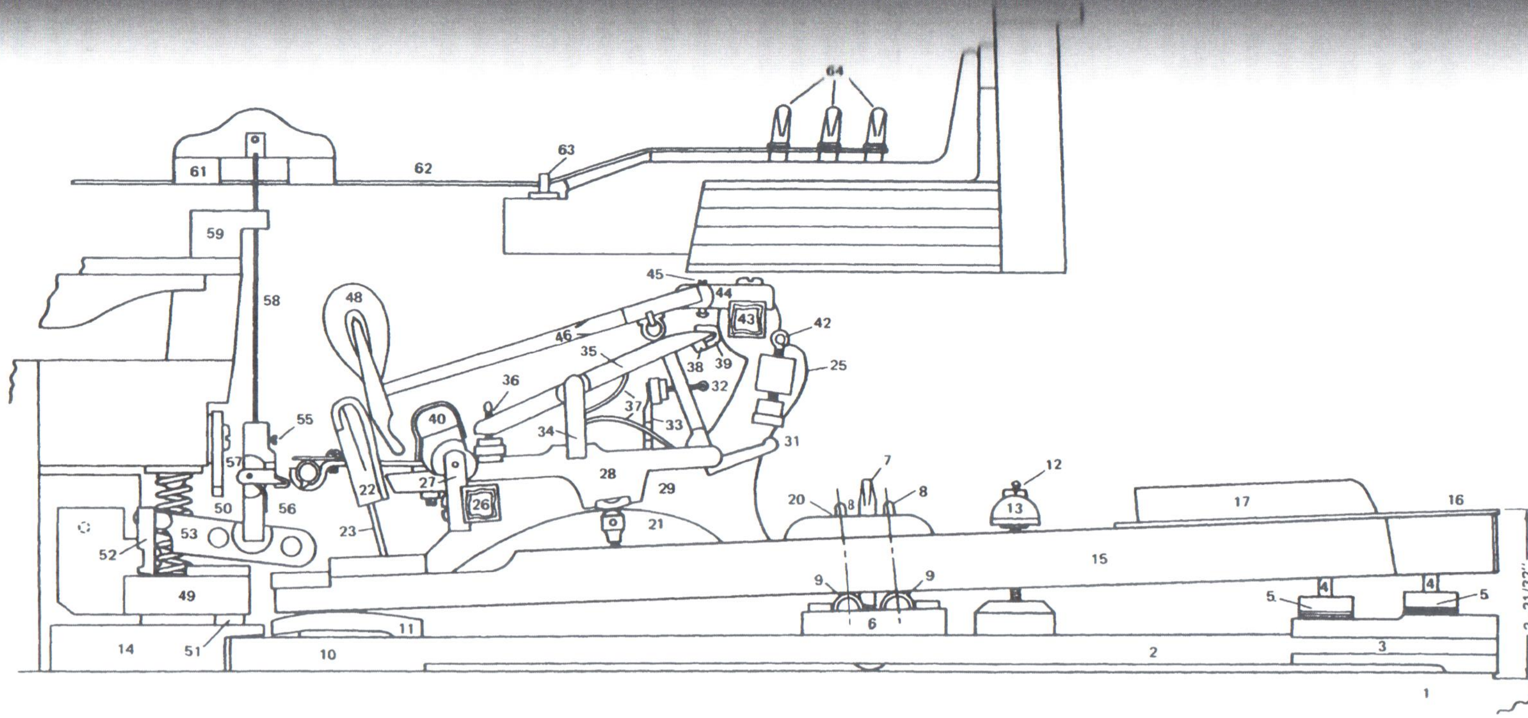


1 Keybed
2 Keyframe
3 Front Rail
4 Front Rail Pin
5 Front Rail Pin Punching
6 Balance Rail
7 Balance Rail Stud
8 Balance Rail Pin
9 Balance Rail Bearing
10 Back Rail
11 Back Rail Cloth
12 Key Stop Rail Prop
13 Key Stop Rail
14 Dag
15 Key
16 Key Covering
17 Sharp
18 Front Pin Bushing
19 Key Button
20 Balance Pin Bushing
21 Capstan Screw
22 Backcheck
23 Backcheck Wire
24 Underlever Key Cushion
25 Action Hanger
26 Support Rail
27 Support Flange
28 Support
29 Support Cushion
30 Fly
31 Tender
32 Fly Regulating Screw
33 Spoon
34 Support Top Flange
35 Balancier
36 Balancier Regulating Screw
37 Repetition Spring
38 Repetition Felt
39 Balancier Covering
40 Hammer Rest
41 Regulating Rail
42 Letoff Regulating Screw
43 Hammer Rail
44 Hammershank Flange
45 Drop Screw
46 Hammershank
47 Knuckle
48 Hammer
49 Underlever Frame
50 Underlever Frame Spring
51 Underlever Frame Cushion
52 Underlever Flange
53 Underlever
54 Underlever Top Flange
55 Damper Wire Screw
56 Tab
57 Damper Stop Rail
58 Damper Wire
59 Damper Guide Rail
60 Damper Head
61 Damper Felts
62 String
63 Agraffe
64 Tuning Pin
65 Sostenuto Rod

Figure 11.24
The action of a modern piano. (Reprinted with permission of Steinway & Sons.)

ic energy to the air. The piano string forces the soundboard into oscillation.

We concluded Chapter 2 with the question concerning the physical requirements of a soundboard. Do you know the answer? Clearly, the ideal soundboard would have a uniform response across the frequency range of the piano. A soundboard with a strong response for C_4, a weak response for A_4, and so on, is unacceptable.

FFT 21
FFT 22

The Character of the Sound Transmitted by the Piano

In Chapter 13 we shall learn that there are different ways of building a musical scale. The scale used for the modern piano is the *tempered scale.* In this scale the octave is divided into 12 equal frequency intervals.

Let us consider some of the factors that contribute to the complex sound radiated from the piano.

1. Inharmonicities

The stiffness of piano strings destroys the harmonic character of its sound. This inharmonicity makes the piano's sound distinctive. Juries of both musicians and nonmusicians have been asked to identify pianolike tones produced synthetically. With overwhelming consistency only those tones were selected that correctly introduced inharmonicities to the sound.

Piano sounds have been carefully analyzed. As we would predict from our earlier discussion, the higher the frequency of the overtone for any note on the piano, the more it departs from its harmonic counterpart. The overtones become sharper and sharper as their frequency increases. The overtone character of the lowest note of the piano, A_0, is shown in Figure 11.25. If the complex tone were made up of harmonics, it would follow the straight line. The curved line identifies the frequencies of the overtones. Obviously the tone is inharmonic.

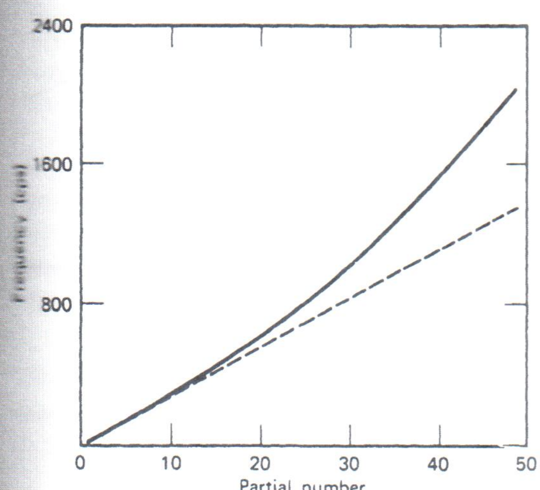


Figure 11.25
The frequencies of the lowest note, A_0, on the piano. The higher the harmonic number, the greater the departure from true harmonic behavior.

2. Attack and Decay

As we have already seen, the attack and decay of a tone are characteristic of an instrument. When a hammer strikes a piano string, energy is transferred to the string(s) in sudden, percussive fashion. As soon as the hammer has done its job, the strings are free to vibrate and they do so with a decreasing amplitude. The piano sound is characterized by an initial burst of sound that decays quickly, followed by a lingering sound that decays much more slowly (see Figure 11.26). The two rates of decay are due to the fact that the vibration of a piano string is really the superposition of two vibrations: a vertical vibration (perpendicular to the soundboard) and a horizontal vibration (parallel to the soundboard).

The vertical vibration is responsible for the initial burst of sound, but it decays quickly because the energy from this vibration is efficiently transferred to the soundboard. The lingering sound is due to the horizontal vibration. The energy from the horizontal vibration is not as easily transferred to the soundboard, so it is "trapped" in the string. Slowly the energy is lost and the sound decays.

The piano sound is further characterized by the fact that different overtones decay at different rates. Figure 11.27 on page 194 shows the decay of note C_1. Some overtones, like the fifth, decay and then build up again to increased loudnesses. Others, like the second and fifteenth overtones, decay more uniformly. Thus the timbre of a piano tone changes as it decays.

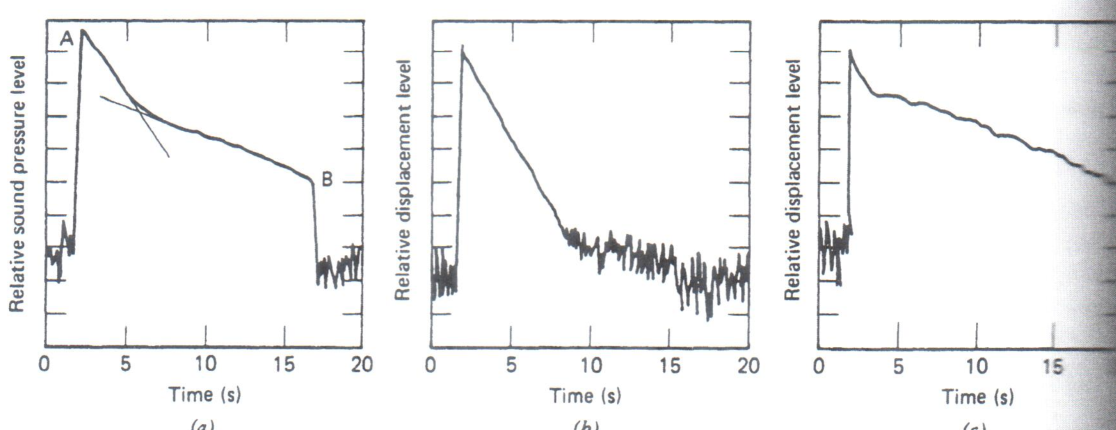
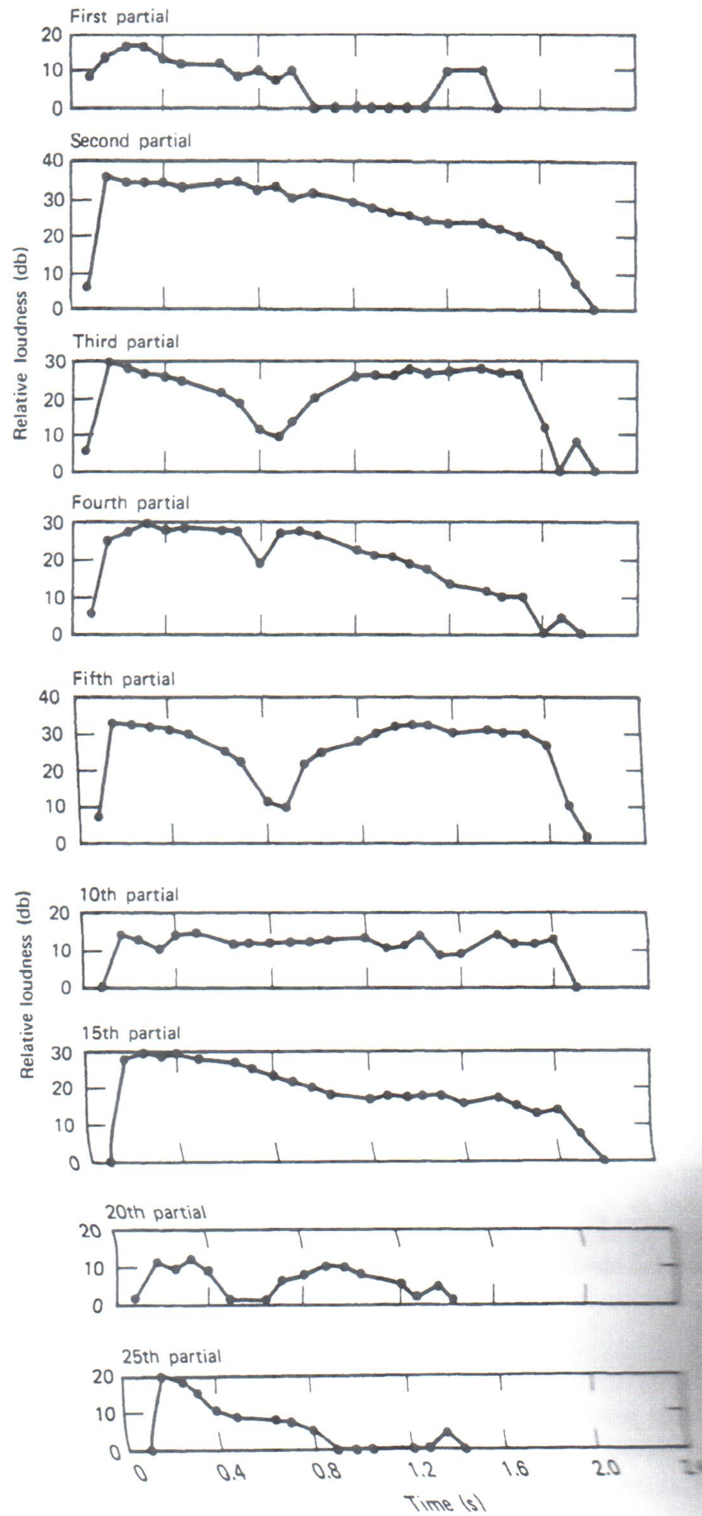
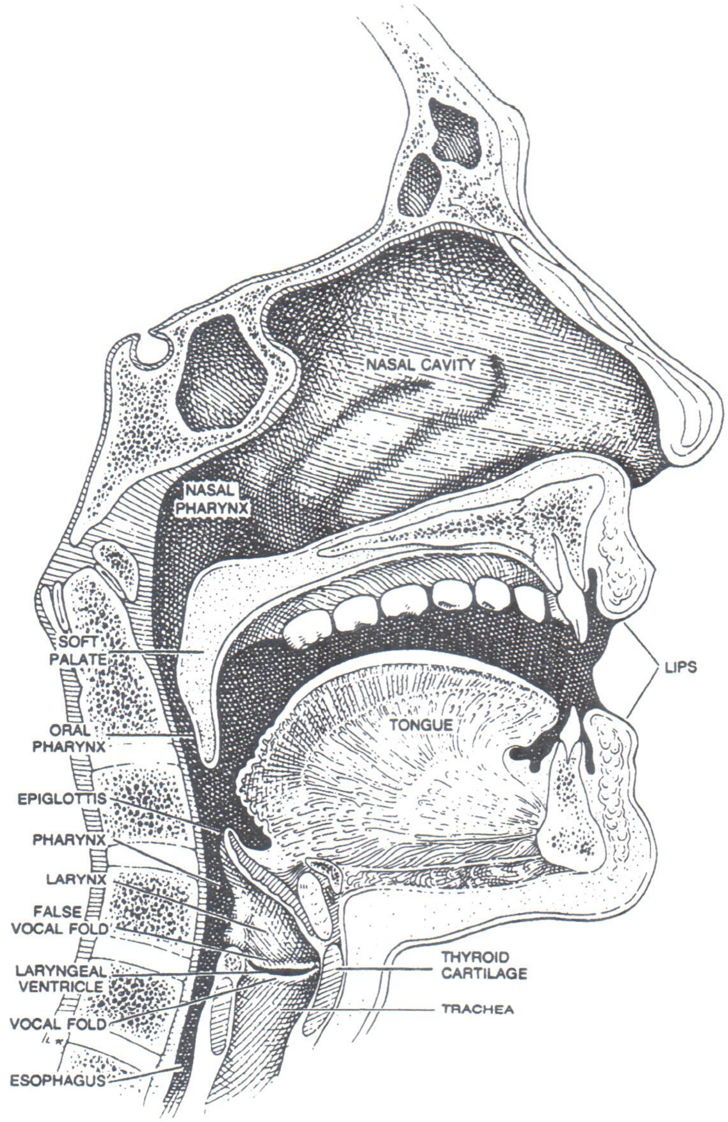


Figure 11.26
The sound of a piano string decays (after being struck) at two rates (*a*): one fast rate (*b*) and one slow rate (*c*).


First partial
20
10
0
Second partial
40
30
20
10
0
Third partial
30
20
10
0
Fourth partial
30
20
10
0
Relative loudness (db)
Fifth partial
40
30
20
10
0
10th partial
20
10
0
15th partial
30
20
10
0
Relative loudness (db)
20th partial
20
10
0
25th partial
20
10
0
0
0.4
0.8
1.2
1.6
2.0
Time (s)



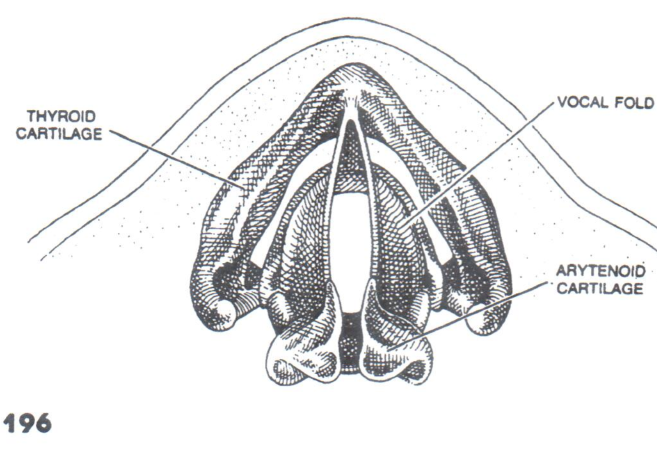


Figure 11.28
The human vocal system. (From "The Acoustics of the Singing Voice" by J. Sundberg. Copyright © 1977 by Scientific American, Inc. Reprinted with permission.)

The cross-sectional area as well as the other dimensions of the vocal tract can be altered by movements of the lips, the tongue, and the jaw. These movements change the resonance characteristics of the vocal tract and shift the formant frequencies. In the act of singing (or talking) the movement of jaw, tongue, and lips shifts the formant frequencies and produces the desired sounds.

How does the system work? The vocal folds oscillate and permit a succession of air pulses into the vocal tract. The frequency of the open–close cycle of the vocal folds is determined by two factors: first, by the pressure of air below the vocal folds (in the lungs and trachea) relative to the pressure above the vocal folds (in the larynx); second, by the thickness and tension (controlled by muscles) in the vocal folds. High frequencies are favored by high lung pressure and by stretched, thin vocal folds. The higher the frequency of the open–close cycle of the vocal folds, the higher the pitch of the sound produced.

FFT 23

The air pulses coming from the glottis are shaped by the formant frequencies of the vocal tract, as shown in Figure 11.29 (on next page). For different formant frequencies different sounds are produced. Consider the vowel sounds. The vowel sounds, such as *ee* as in "eel" or *oo* as in "pool," require very different lip, tongue, and jaw positions. More accurately, they require very different formant frequencies, which are established in the vocal tract by the proper positions of lips, tongue, and jaw. As the formant frequencies are changed, the resulting sound is changed. A few examples are given in Table 11.3.

FFT 24

The Singer's Formant

If the average bathroom singer got up on the concert stage, it is unlikely that she or he could be heard above the orchestra . . . at least for very long. With an orchestra playing behind them, how do opera singers make themselves heard? Johan Sundberg has given an answer to this question, at least for the operatic tenor. (See the reference at the end of this chapter.)

Professional male singers have an extra formant, called the *singer's formant*, at a frequency 2500–3000 Hz. (See Figure 11.30.) This formant

TABLE 11.3
Formant Frequencies for Some Vowel Sounds

Vowel	First Formant Frequency (Hz)	Second Formant Frequency (Hz)
ee (heed)	270	2300
oo (who)	300	900
ae (had)	640	1700
e (head)	500	1850

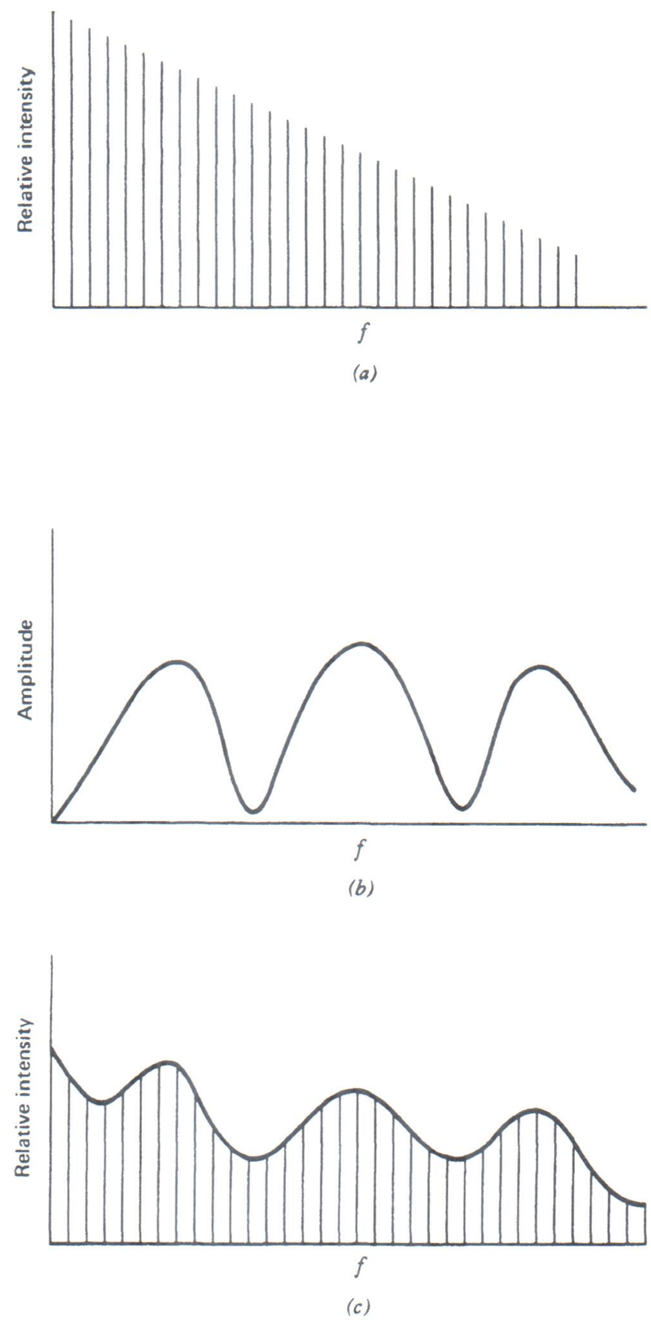


Figure 11.29
(*a*) The stream of pulses that enter the vocal tract from the larynx contains a large number of harmonic frequencies. (*b*) The formant frequencies in the vocal tract. (*c*) The spectrum of the transmitted sound.

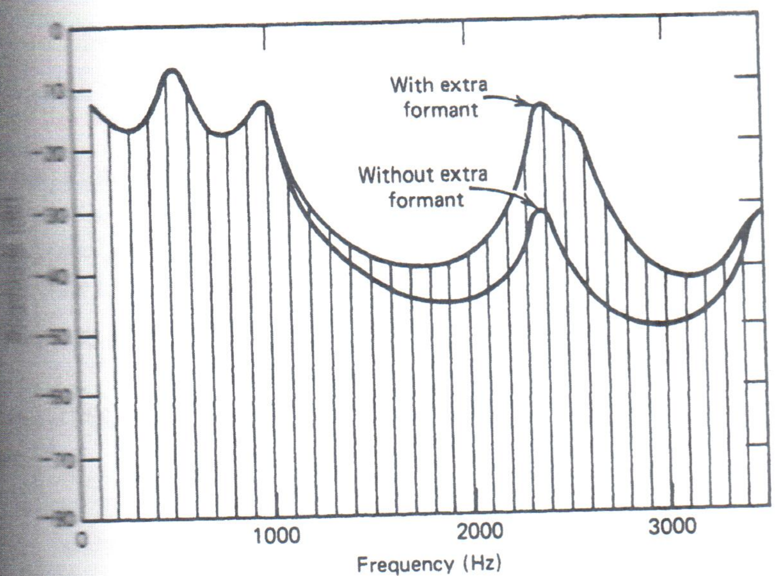


Figure 11.30
The singing formant occurs in the frequency region between 2000 and 3000 Hz. The effect of this formant is to increase the amplitudes of frequencies in this region. (This figure from Sundberg's article. See reference at the end of the chapter.)

apparently originates within the larynx. In singing, as opposed to speaking, the larynx is lowered, and the operatic singer has developed the ability to expand the throat just above the larynx. An acoustic discontinuity is created between the larynx and the expanded throat above it so that some of the sound pulses are reflected back into the larynx. This reflected wave allows the standing waves to be set up in the larynx itself. The frequency of these standing waves is in the range 2000–3000 Hz. The resonance behavior of the larynx is the origin of the singer's formant. Fortunately, this extra formant is at a frequency where the output of an orchestra is not so strong. This is how the operatic tenor manages to be heard so distinctly. FFT 25

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