Balancing Odd and Even Harmonics in the Source Spectrum

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The pulse-like airflow in the glottis is the primary source of sound for vocalization. It is produced in the process of vocal fold vibration. When the vocal folds collide, airflow is suddenly interrupted. The sudden change from a pulse of airflow to little or no airflow generates a spectrum of harmonic frequencies. For a typical flow pulse, both odd and even harmonics are produced. The amplitudes of these harmonics decrease uniformly with increasing harmonic number. In other words, higher harmonics have progressively lower amplitudes. This harmonic amplitude decay (also known as spectral roll-off, slope, tilt) is often quantified in decibels per octave (dB/oct). A typical harmonic amplitude decay for normal voice registration is on the order of -10 to -15 dB/oct, with the negative sign indicating the loss of harmonic amplitude.

The questions arise: Can the glottal airflow exhibit a harmonic spectrum for which the roll-off is not evenly distributed across the harmonics? Can there be peaks and valleys in the source spectrum? More specifically, can the odd harmonic series be different from the even harmonic series? Interestingly, the often sketched caricature of a glottal flow waveshape answers these questions dramatically. A truncated sinusoid, for which the first half of the flow cycle is positive (a smooth rise and fall) and the second half is zero (glottal closure), *contains no odd harmonics other than first* (Figure 1). The third, fifth, seventh, etc. harmonics are all missing. The cause of this nonexistence of even harmonics is the perfect symmetry in the waveshape. There is symmetry in the rise and fall of the flow pulse, and there is symmetry in the duration of the flow pulse (half of the time "on" and half of the time "off").

Two metrics have been defined for these symmetry features. The first is known as the open quotient (Q_o), defined as the ratio of the time the glottis is open (there is glottal flow) to the total duration of the cycle. For the waveform in Figure 1, the open quotient is 0.5. The second metric is known as the skewing quotient, defined as the ratio of the time the flow rises to the time the flow falls. For the waveform in Figure 1, the skewing quotient is 1.0. The flow rises from 0–1.25 ms and falls from 1.25–2.5 ms. The loss of odd harmonics is a direct consequence of these exact symmetry ratios, $Q_o = 0.5$ and $Q_s = 1.0$.

Odd harmonics appear when either Q_o moves away from 0.5 or Q_s moves away from 1.0. Figure 2 shows a glottal waveform and its spectrum for $Q_o = 0.4$ and the skewing quotient Q_s remaining at 1.0. Note the appearance

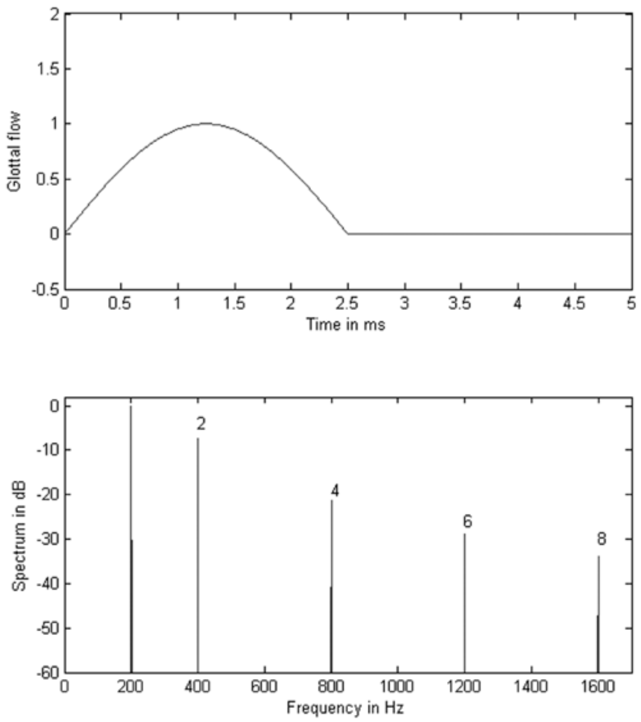

Figure 1. **(Top) One cycle of a glottal flow waveform with perfect rise/fall and open/closed symmetry; (Bottom) its frequency spectrum with even harmonic numbers labeled.**

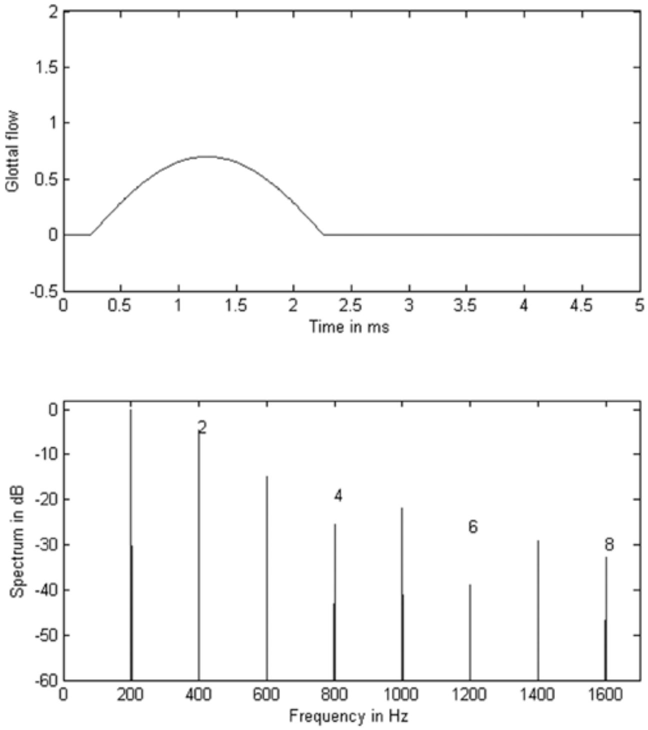

Figure 2. **(Top) One cycle of a glottal flow waveform with perfect rise/fall symmetry but no open/closed symmetry ($Q_o = 0.4$); (Bottom) its frequency spectrum with even harmonic numbers labeled.**

of all even harmonics (not labeled). The full harmonic spectrum of the fundamental frequency (200 Hz) is now represented. A similar spectrum appears when Q_o is raised to 0.6 (Figure 3).

Figure 4 shows a waveform and spectrum for which $Q_s = 2.0$, while Q_o is maintained at the symmetry value 0.5. Again, all odd harmonics are present for this asymmetric pulse shape. We conclude that some degree of asymmetry, in either Q_o or Q_s (or both), is needed to produce a full spectrum of odd and even harmonics. How is this guaranteed in singing, and why is it important?

For maximum power production in the glottal flow, a value of $Q_o \approx 0.5$ is desirable.[1] Some singers produce values below 0.4 to narrow the flow pulse, thereby producing not only the odd harmonics, but also more harmonic energy in general. Others produce values of 0.6 or greater to widen the flow pulse, thereby also producing the odd harmonics, but with less overall harmonic energy.

The most effective way to guarantee odd harmonic energy, however, is to use vocal tract inertance as a means of skewing the airflow pulse.[2] Vocal tract inertance is the acoustic "sluggishness" of the air column above the vocal folds. It delays the rise of the flow pulse so that the peak flow occurs later than half-way into the pulse. Skewing quotients of 2.0 to 5.0 can be achieved with proper choice of vowel and epiglottal tube configurations.

Consider a singing example. A vocalist produces B_4 on a neutral vowel /ə/ for which the first formant (F_1) is 500 Hz and the second formant (F_2) is 1500 Hz. With a perfectly symmetric waveform ($Q_o = 0.5$ and $Q_s = 1.0$), harmonic energy would be present only at the fundamental (494 Hz, near F_1), at the second harmonic (988 Hz, between F_1 and F_2), and at the fourth harmonic (1976 Hz, well above F_2). By skewing the waveform, however, third harmonic energy at 1492 Hz (near F_2) would be introduced, greatly boosting the overall energy of the spectrum. The importance of third harmonic energy in the voice of Luciano Pavarotti on notes between A_4 and C_5 has been discussed by Donald Miller.[3]

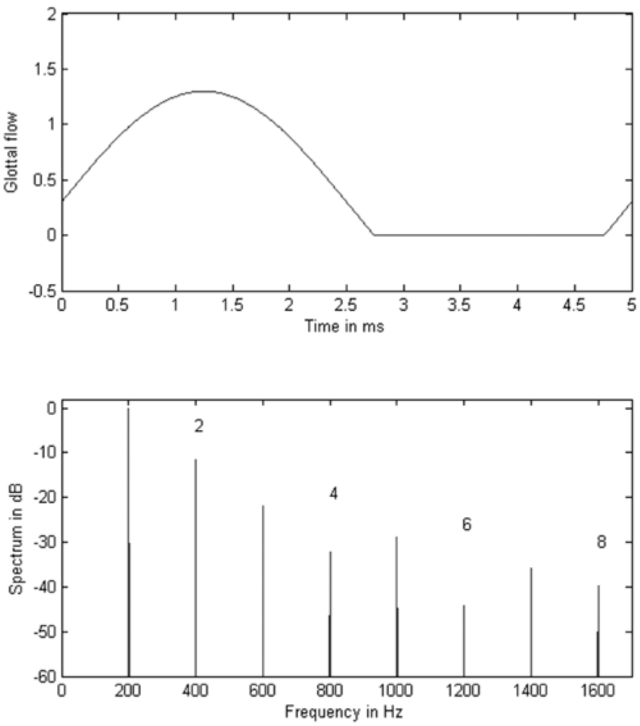

Figure 3. **(Top) One cycle of a glottal flow waveform with perfect rise/fall symmetry but no open/closed symmetry (Q_o = 0.6); (Bottom) its frequency spectrum with even harmonic numbers labeled.**

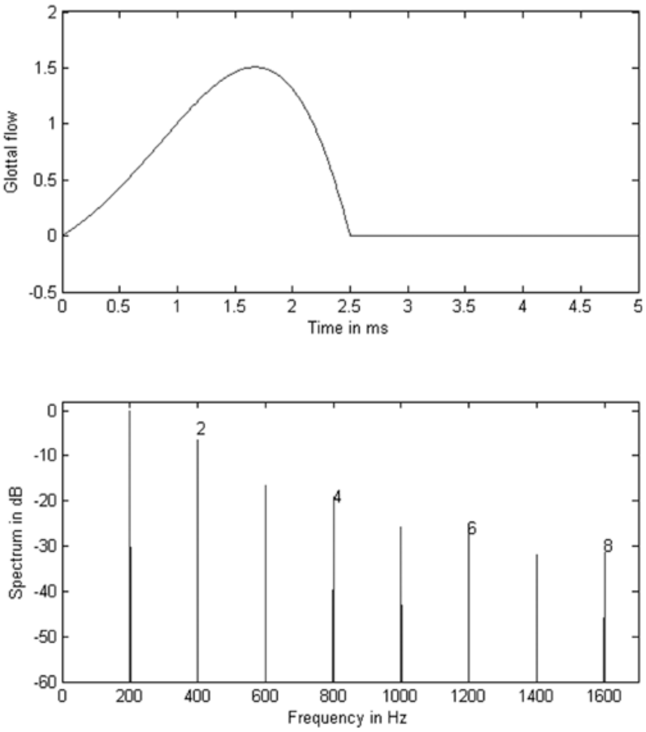

Figure 4. **(Top) Once cycle of a glottal flow waveform with no symmetry in rise/fall of the flow pulse (Q_s = 2.0) but with open /closed symmetry (Q_o = 0.5); (Bottom) its frequency spectrum with even harmonic numbers labeled.**

This brief essay on the balance of odd-even harmonics in the source spectrum is one more piece in the puzzle concerning source-filter interaction. If there is no interaction (linear source-filter combination), the odd-even harmonic balance must be regulated at the source with vocal fold adduction and tissue movement such that closing speeds are greater than opening speeds. If source-filter interaction is invoked, a second choice is available by skewing the glottal flow pulse with vocal tract inertance. For a given singer and a given musical context, it is not obvious what the choice would be, but it is likely that some combination of both is possible.

NOTES

1. Ingo R. Titze, *Principles of Voice Production* (Denver, CO: The National Center for Voice and Speech, 2000), Chapter 9.
2. Martin Rothenberg, "Acoustic Interaction between the Glottal Source and the Vocal Tract," in Kenneth Stevens and Minoru Hirmo, eds., *Vocal Fold Physiology* (Tokyo: University of Tokyo Press, 1981), 305–328; Ingo R. Titze, "Theory of Glottal Airflow and Source-Filter Interaction in Speaking and Singing," *Acta Acustica-Acustica* 90, no. 4 (July/August 2004): 641–648.
3. Donald G. Miller, *Resonance in Singing: Voice Building Through Acoustic Feedback* (Princeton, NJ: Inside View, 2008), Chapter 1.

Bring me all of your dreams,
You dreamer,
Bring me all your
Heart melodies
That I may wrap them
In a blue cloud-cloth
Away from the too-rough fingers
Of the world.
Langston Hughes, "The Dream Keeper"