

# Interactive Augmentation of Voice Quality and Reduction of Breath Airflow in the Soprano Voice

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**Summary:** In 1985, at a conference sponsored by the National Institutes of Health, Martin Rothenberg first described a form of nonlinear source-tract acoustic interaction mechanism by which some sopranos, singing in their high range, can use to reduce the total airflow, to allow holding the note longer, and simultaneously enrich the quality of the voice, without straining the voice. (M. Rothenberg, "Source-Tract Acoustic Interaction in the Soprano Voice and Implications for Vocal Efficiency," Fourth International Conference on Vocal Fold Physiology, New Haven, Connecticut, June 3–6, 1985.) In this paper, we describe additional evidence for this type of nonlinear source-tract interaction in some soprano singing and describe an analogous interaction phenomenon in communication engineering. We also present some implications for voice research and pedagogy.

**Key Words:** Singing–Voice–Nonlinear interaction–Source-tract interaction–Reduce airflow–Soprano.

## INTRODUCTION

In a 2014 interview by Jian Ghomeshi, the noted singer Barbra Streisand made the following comment on her ability to maintain a strong Eb5, or similar, high note: that she did not know how she did it, but would like to know the physiological mechanism. She said, "I want to understand the physiology, because that always interested me. What was I doing? People ask me 'How come you hold the note so long?' And I answer (simply) because I want to." This paper summarizes some attempts to explain the articulatory mechanisms underlying the effect Barbra Streisand was referring to. Also outlined is an analogous principle in radio engineering technology that is well known to radio engineers, but not known in the field of singing research and pedagogy, except, perhaps, for those of us who also have a background in radio engineering.<sup>a</sup>

In 1985, at a conference sponsored by the National Institutes of Health, Martin Rothenberg described a physiological/acoustic mechanism by which some sopranos, singing in their high range, can reduce the total airflow, to allow holding the note longer, and simultaneously enrich the quality of the voice, without straining the voice.<sup>1</sup> It is likely that this mechanism accounts for the strong maintained vowels that Barbra Streisand referred to.

Since his 1985 paper, there have been other research reports corroborating Rothenberg's findings. However, there has not been a wide acceptance of the use of this type of nonlinear source-tract interaction in soprano voice, with most of the literature tending to employ a linear analysis that does not explain the power and timbre of a strong soprano voice. In this paper, we will put forth the evidence for nonlinear source-tract interaction in some soprano singing and describe an analogous interaction phenom-

enon in radio technology. We also present some implications for voice research and pedagogy.

An analysis of this mechanism leads us to the conclusion that not all singers can achieve this interactive reduction of airflow. It appears that to do this, a singer's vocal fold vibration pattern should have a "closed quotient" of roughly 50%, or at least about 30% (meaning that the vocal folds remain closed during at least a third of the vibratory period), and also have a good vocal fold closure (no air leakage) during most of the closed phase. The precise value of the closed quotient is not important, as long as a good closure is attained to prevent airflow during the closed phase. (Apparently Barbara Streisand's voice has these characteristics.) The singer would then adjust the vowel being sung so that the lowest vocal tract resonance (usually termed the "first formant") falls at a frequency that is approximately the pitch frequency of the note. An example of this type of interaction in a soprano voice is shown in [Figure 1](#), taken from figure 19-3 from Rothenberg's 1985 paper.

The explanation for the reduced air consumption is that each airflow pulse through the glottis after the first is suppressed in amplitude by a peak in the oral pressure just above the glottis that occurs each time the glottis is open. (This tends to give the glottal airflow pulses a double-humped appearance in some cases.)

[Figure 2](#) shows diagrammatically how the pressure pulse from a previous glottal airflow pulse (rising arrow A), when returning from the mouth (descending arrow B), can suppress the airflow in the succeeding airflow pulse. The timing of the returning pressure pulse will be correct for suppressing the succeeding airflow pulse if the frequency of the first formant F1 is approximately the same as the frequency of the glottal pulses, F0.

As pointed out by Rothenberg,<sup>1</sup> this principle of tuning to reduce airflow is well known in the field of radio engineering, but until now, is not known in singing voice analysis. (This is documented below.)

The observation that many sopranos tend to tune F1 close to F0 at higher pitches is supported in the literature. Johan Sundberg<sup>2</sup> has found that a professional soprano he recorded tended to place F1 near F0 at higher pitches, supporting the thesis of this paper. More recently, Andrea Deme<sup>3</sup> showed formant measurements that lead to the same conclusion. Deme justified this F1 placement as required for voice strength, because placing F1 above F0 would mean that F1 would amplify no glottal harmonic

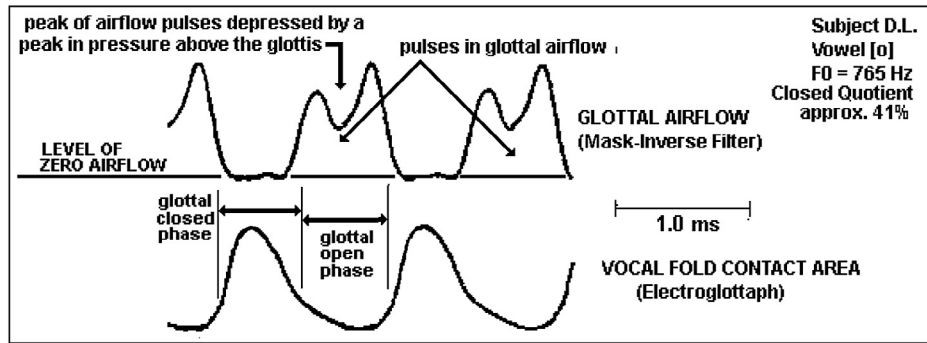
<sup>a</sup>Dr. Rothenberg received a First Class Radiotelephone Operators license at the age of 18 and subsequently serviced transmitters and receivers in the US Army Signal Corps while serving in Korea, where he learned to "tune for the dip." Dr. Schutte, MD-ENT, PhD, was trained as a radar engineer in the Dutch army in 1960–1962. He has been an amateur radio operator since 2003, with the call letters PC5BV, and enjoys building and working with vacuum tube transmitter amplifiers.

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**FIGURE 1.** Adapted from figure 19-3 in Rothenberg.<sup>1</sup> Glottal airflow as obtained by inverse filtering oral airflow for a trained soprano singing F#5. The electroglottograph signal was used to corroborate the inverse filter settings by indicating the approximate closed and open intervals. To preserve time alignment between EGG and airflow, the EGG signal was electronically delayed by a time interval equal to the delay in the glottal flow signal with respect to the EGG signal.

(because F1 could not reach the second glottal harmonic at a high pitch). However, neither author comments that for F1 near F0, a linear acoustic interaction model would predict a vocal quality with a dominant fundamental component, such as in breathy voice or falsetto voice. The possibility of nonlinear acoustic interaction in which the amplitude of the fundamental component in the glottal airflow wave was depressed by the interaction was not considered.

In the year following the presentation of Rothenberg,<sup>1</sup> Gunnar Fant, as well as Harm Schutte and Donald Miller published data corroborating the theory proposed by Rothenberg in 1985.<sup>1</sup>

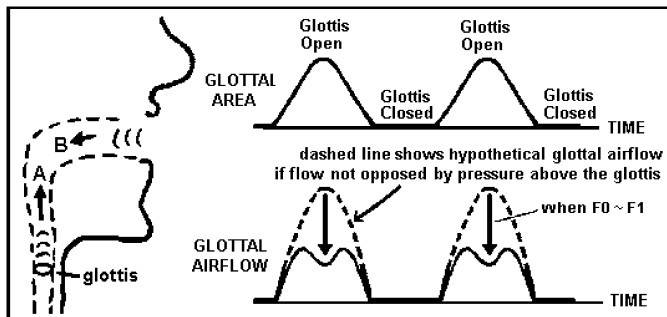
**CORROBORATION BY FANT**

Figure 6 from Fant’s paper “Glottal Flow: Models and Interaction,”<sup>4</sup> showing a computer simulation result, and some of his conclusions, are reproduced here.

In the simulation shown in Figure 3, the formant value chosen resulted in a strong, harmonic-rich output volume and low airflow consumption caused by the suppression of glottal airflow by the pressure wave above the vocal folds.

Fant concludes:

“One aspect of such superposition interaction at high F0 is the situation of a soprano singing at an F0 coinciding with F1. As shown in fig. 6, the peak value of the supraglottal F1 component pressure is slightly greater than the subglottal pressure and occurs just before the instant of maximum glottal aperture thus highly reducing the maximum rate of airflow,

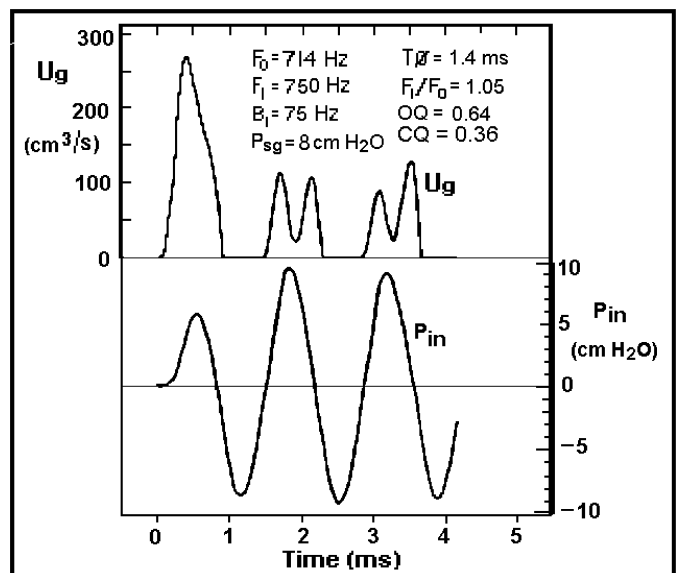


**FIGURE 2.** Diagrammatic explanation of airflow suppression when F1 is approximately equal to F0.

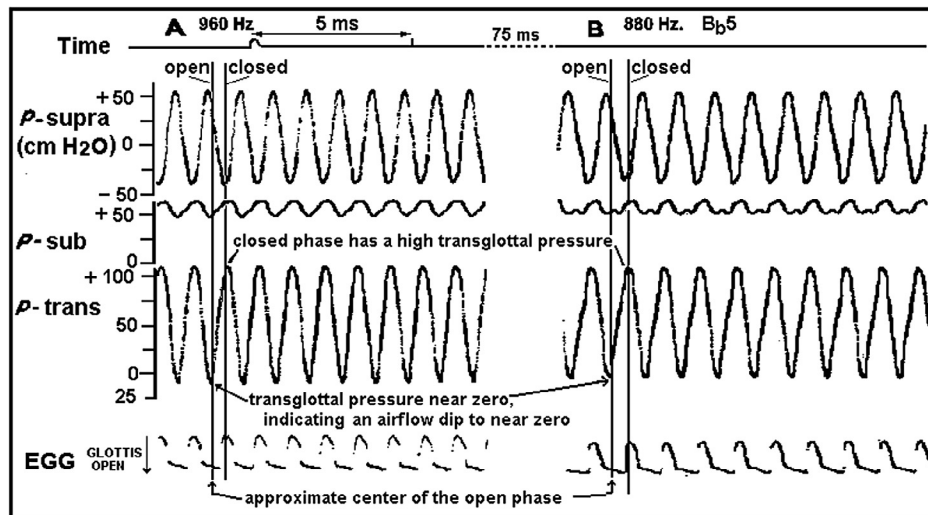
whilst retaining a high flow pulse steepness at closure. This simulation supports the suggestion of Rothenberg (1985)<sup>1</sup> that an F0/F1 coincidence minimizes the air consumption of soprano phonation.”

**CORROBORATION BY SCHUTTE AND MILLER**

Using miniature pressure transducers suspended just above and below the vocal folds with two sopranos, Schutte and Miller<sup>5</sup> corroborated the Fant simulation results, namely that when the lowest formant is tuned close to the pitch of the voice, the resulting pressure oscillations in the pharynx (p-supra in Figure 4) can result in a pressure peak at the approximate center of the glottal open phase, with the open and the closed glottal phases interpreted approximately from the electroglottograph (EGG) waveform. This would cause a reduction in the transglottal pressure (p-trans) that drives the air through the glottis. Although airflow was not measured directly in the present study, the sharp drop in transglottal pressure during each glottal open phase could



**FIGURE 3.** Figure 6 from Fant,<sup>4</sup> showing simulated glottal airflow and supraglottal pressure, assuming a one-formant vocal tract with the formant frequency (750 Hz) close to F0 (714 Hz).



**FIGURE 4.** Adapted from figure 4 of Schutte and Miller.<sup>5</sup> Shown are pressure and EGG waveforms at two pitches during a vibrato cycle for a soprano with a perceptually strong voice.

be assumed to cause a decrease in the glottal airflow. The waveforms in Figure 4 are from the singer identified as having the stronger voice, perceptually more rich in harmonics, and were taken from two locations in a vibrato cycle. A careful analysis of Figure 4, taken from the Schutte and Miller paper, indicates that although the minimum in the p-trans appears to occur at a slightly different location in the open glottis phase, as indicated by the EGG waveform, at both pitches, the minimum pressure did occur during the open phase. Likewise, the maximum transglottal pressure appears to occur in the closed glottis phase at both pitches.

Schutte and Miller conclude, “the duration of the period of reduced p-trans in the fully open phase suggests an important effect, in which one would expect the glottal volume velocity waveform to have a large depression somewhere near the center of open phase, the point where the highest flow would be predicted by a linear model based on the glottal area function.”

#### USING AN EGG TO VERIFY THE PRESENCE OF VOCAL FOLD VIBRATORY ACTION NEEDED TO SUPPORT NONLINEAR SOURCE-TRACT ACOUSTIC INTERACTION

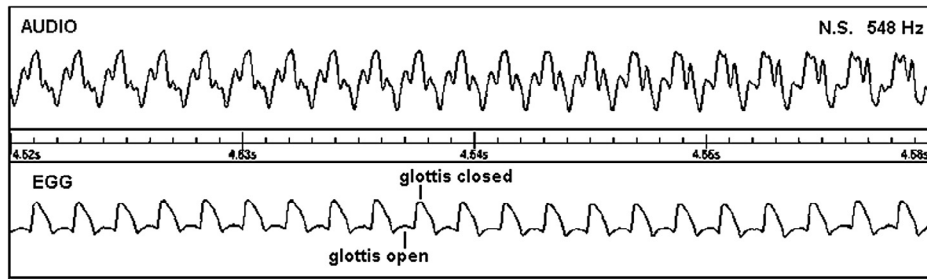
Of the numerous methods developed for monitoring vocal fold vibratory behavior, the most convenient noninvasive method is undoubtedly the EGG. The EGG shows the patterning of the vocal fold contact area. The instants of vocal fold closing and the patterning of the closing gesture can usually be deduced from the EGG signal waveform. The patterning of vocal fold separation can also usually be deduced, but with less certainty. The completeness of the vocal fold closure is not shown directly in the EGG signal, but can often be estimated from the speed and amplitude of the closing segment of the EGG waveform. Likewise, a fully open phase of the vocal fold vibratory period, if present, can often be identified by a relatively flat segment of the EGG waveform at its most open extremity. (Because during a fully open phase there is little or no variation in vocal fold contact area.)

The EGG waveforms shown in Figure 4 appear to us to represent a vocal fold vibratory in which both the closing and the opening segments of the EGG waveforms are relatively abrupt, and what can be considered the fully open phases can be estimated as the relatively flat segments in each cycle. Although the completeness and the firmness of the vocal fold closure cannot be deduced directly from the EGG waveform, the steepness of the closing segment leads us to speculate that a fairly complete and firm closure occurred.

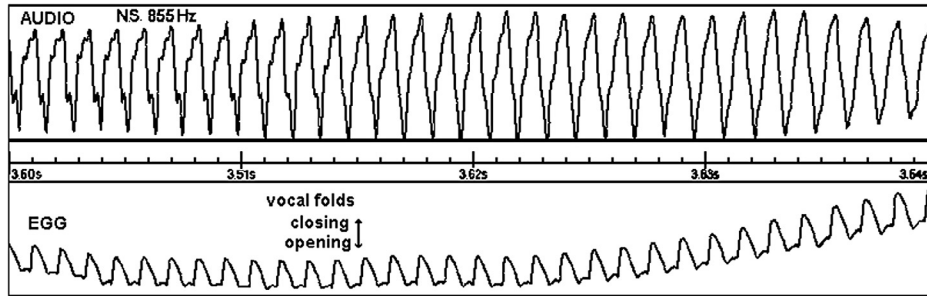
To further illustrate the potential utility of an EGG signal in evaluating the soprano voice, Figures 5 and 6 show typical segments of the microphone waveform and EGG signal from a prominent dramatic soprano singing a short aria (Elisabeth’s Greeting Song from *Tannhäuser*, Act 2 by Richard Wagner), as recorded by Johan Sundberg and shown here with his permission. The segments shown in the figures were selected by the authors only to characterize the pitch range in the piece sung. The EGG waveforms were similar to those in the figures throughout the piece, and were similar to those in Figure 4. It is our opinion, from the quality of her voice, that she used throughout the song the type of nonlinear source-tract interaction we are discussing.

In summary, we estimate from the EGG signals that in Figures 4, 5 and 6, the vocal fold vibratory pattern was one in which the glottal area in each vibratory cycle could be readily separated into closed and open intervals, with relatively rapid transitions between the two states. For brevity, we will refer to this type of vocal fold vibratory pattern as a “gated” vibratory pattern, with the term “gated” meant to suggest relatively abrupt transitions between open and closed vocal fold states.

In both Figures 5 and 6, the EGG waveforms were indicative of a vocal fold vibratory pattern in which the vocal folds approached closure and separated with a parallel motion, and with a closed quotient close to 50%. The abruptness of the closure hints that the closure was complete, with no air leakage, although this cannot be ascertained with certainty from the EGG signal alone.



**FIGURE 5.** EGG and audio at 548 Hz from a prominent dramatic soprano, showing an EGG waveform similar to the waveform of the singer in Figure 4. Figures 5 and 6 were derived by the first author from recordings made by Johan Sundberg and printed here with his permission.



**FIGURE 6.** EGG at  $F_0 = 855$  Hz; from the singer in Figure 5.

The bowing in the open phases in Figure 5 indicates that there may have been some vocal fold motion during the open phase, although tissue vibration can also be the cause. The overall falling-rising pattern for the EGG signal in Figure 6 is from low frequency artifacts possible in an EGG signal, and should be ignored in an analysis.

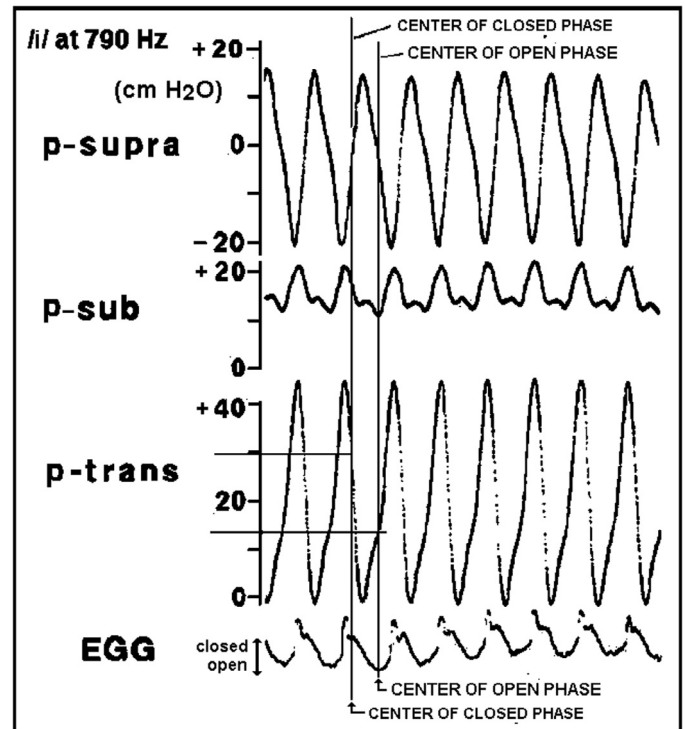
The EGG waveform in Figure 7, for a perceptually weaker voice than that portrayed in Figure 4, does not show the clear open and closed phases shown in the waveforms in Figures 4, 5 and 6. Nor does the minimum in the translottal pressure clearly occur during the glottal open phase. (Most of the cycle-to-cycle irregularity of the EGG waveform is probably caused by a weak signal and can be ignored.)

In Figure 8, the various EGG waveforms from Figures 1–7 are compiled for the convenience of the reader. Mentioned above is the abruptness of closing and opening segments of the EGG waveforms from the professional singers in boxes A, B, and C.

The waveform in box E in Figure 8, taken from Figure 1, is from a student singer who performed occasionally in amateur productions at that stage in her career, but who would not be considered to have the vocal power of a dramatic soprano. We note that although glottal open and closed periods can be estimated from the waveform, these periods are not sufficiently differentiated in the waveform to label the underlying vibratory pattern as “gated” using our terminology. Unlike the waveforms in boxes A, B, and C, there is no flat open phase. Instead, the glottal opening motion appears to end with a rolling apart of the vocal folds, and the closing motion appears to begin with a rolling together for approximately 25% of the final maximum contact area.

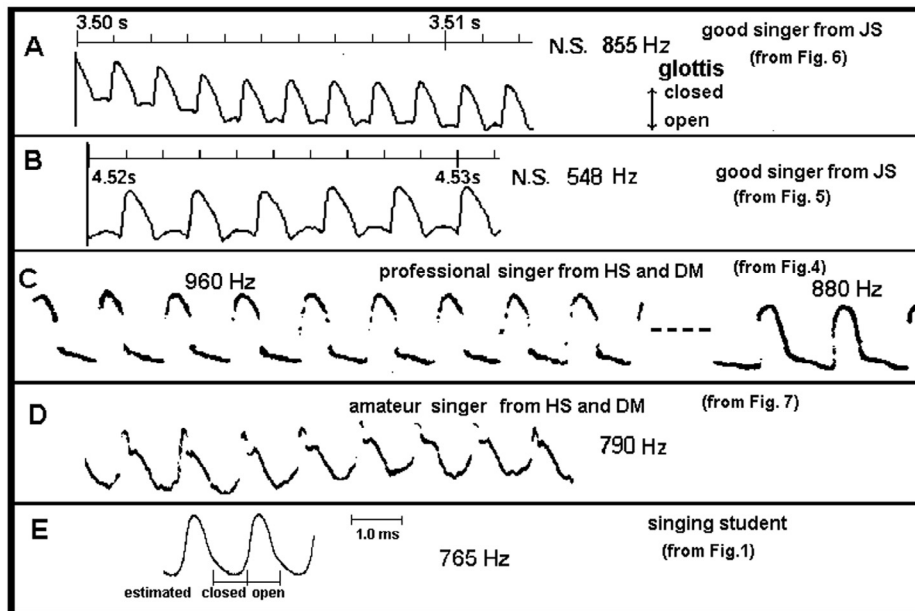
### AN ANALOGOUS TUNING PRINCIPLE IN RADIO ENGINEERING

The average “plate” or power supply current of a vacuum tube amplifier driving the antenna circuit in a radio transmitter is



**FIGURE 7.** Vocal tract pressures and EGG waveform from Schutte and Miller,<sup>5</sup> for a soprano with a perceptually weaker voice than the singer portrayed in Figure 4.





**FIGURE 8.** All EGG waveforms from Figure 1 and Figures 4–7, compiled for comparison. Amplitudes and time scales were changed to facilitate comparisons.

directly analogous to the average airflow from the lungs in singing, in that it is the source of energy driving the system. For optimal operation, the necessary resonant circuit “tank circuit” (an inductor and a capacitor in parallel) loading the amplifier must be tuned to the same frequency as the sinusoidal carrier signal applied to the input of the amplifier. This tuning is usually accomplished by adjusting the inductor or capacitor so as to minimize the “plate current,” or, as it is commonly said, by looking for a “dip” in the plate current. This is a principle recognized for over 50 years in the field of radio engineering. In a then-standard reference text, Terman<sup>6</sup> (pp. 173–177) explains the mechanism underlying the dependence of plate, or power supply, current on plate load-circuit tuning in an output-tuned amplifier in which the input is biased such that the plate current is “cut off” for most of the cycle of the input carrier. (Such biasing is termed class C or class B in radio engineering terminology, and is analogous to a vocal fold vibratory pattern in which the vocal folds are closed for at least about 30% of the vibratory cycle.)

In making the analogy to soprano singing, the “load circuit” for the vacuum tube amplifier is directly analogous to the acoustic loading presented to the glottis by the supraglottal vocal tract. F<sub>0</sub> in the case of singing (the fundamental frequency of the vocal fold oscillations) is analogous to the frequency of driving voltage presented to the input of the amplifier, and matching the “resonance” of the amplifier load tank circuit to the frequency of the input to the amplifier is analogous in singing to matching F<sub>1</sub> (the lowest formant of the vocal tract) to F<sub>0</sub>.

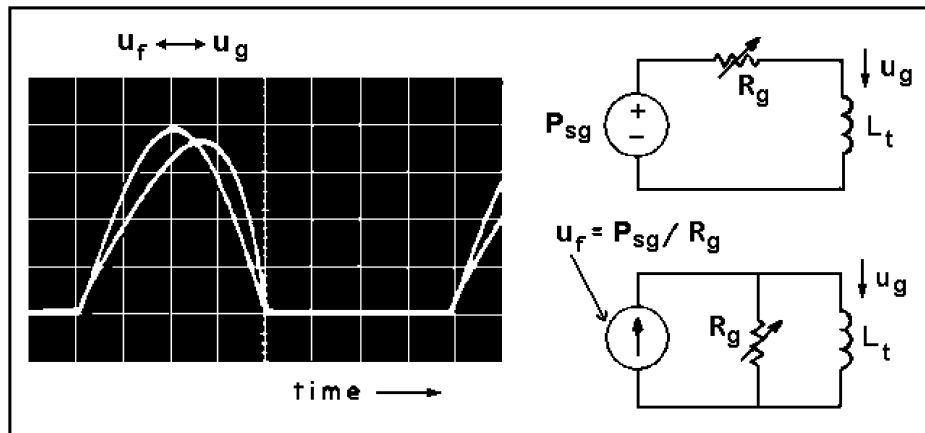
There are numerous references posted on the internet by amateur radio operators that advise that the final amplifier in a transmitter can be expeditiously tuned to the frequency of the driving oscillator by the operator tuning for a dip in the supply current. This is analogous to tuning F<sub>1</sub> to F<sub>0</sub> in the voice ap-

plication. In the amateur radio field, this is often referred to as “tuning for the dip.”

As explained by Terman,<sup>6</sup> the mechanism underlying the reduction in the electrical current from the power supply when the amplifier load is tuned near the carrier frequency can be described as follows. When the resonant circuit loading the amplifier (an L-C “tank circuit”) is tuned near the carrier frequency, the ac voltage wave across the tank circuit has a phase such that during the conducting phase of a class B or class C amplifier (analogous to the open phase of the vocal fold vibratory cycle), the tank circuit voltage cancels all or part of the dc plate supply voltage. This reduction in voltage reduces the current from the power supply. During the nonconducting phase of the amplifier (analogous to the closed phase of the vocal fold vibratory cycle), the additional tank circuit voltage adds to the power supply voltage (the plate voltage might be as much as double the dc plate supply voltage), but there would nevertheless be no current flow because the tube was cut off or nonconducting. Thus, the net effect would be a reduction in the average current from the power supply. (This principle was demonstrated using an electrical circuit simulating the action of a class B amplifier in the paper “Nonlinear Interaction on a Mountaintop,” presented by M. Rothenberg at the International Voice Symposium at New York University, Jan. 5–7, 2012.)

### STRENGTHENING OF HIGHER HARMONICS CAUSED BY THE NONLINEAR INTERACTION

When the average glottal airflow for a soprano is reduced by tuning the glottal load close to the source frequency (tuning F<sub>1</sub> close to F<sub>0</sub>), there is a second important effect. The resulting distortion of the glottal airflow waveform will generally strengthen some of the glottal harmonics above F<sub>1</sub>, while reducing the amplitude of the fundamental component. Some voice research-



**FIGURE 9.** Taken from figure 10 of Rothenberg and Zahorian.<sup>7</sup> The figure uses a simple lumped parameter model to show the change in the glottal volume velocity waveform that would be caused by the interaction of a time-varying glottal flow resistance and an inertive vocal tract loading. On the right are the Thevenin and Norton equivalent models for the system used in the model.

ers may find it difficult to accept that tuning F1 to near F0 can strengthen harmonics well above F1, and contribute to a richer voice quality. This nonacceptance probably stems from a dependency on linear system thinking. But it should be kept in mind that it is widely accepted that in some situations it is possible for other types of nonlinear distortion to strengthen higher harmonics, for example, in the peak clipping of a signal. The problem in the case of the nonlinear source-tract acoustic interaction in the soprano voice is that the nonlinear distortion in this case is associated with a resonance, and the term resonance tends to trigger linear system thinking. Linear system thinking tends to say that only the Fourier components at or near a resonance are strengthened.

It may be noted that the same result can be found in the transmitter amplifier analog. The strengthening of higher harmonics that occurs when the amplifier load is resonated at the amplifier's driving frequency is accepted in radio engineering technology, although the result is not as fortuitous as in the singing analog. Generating or strengthening of harmonics of the driving frequency (the "carrier" frequency) is frowned upon by the Federal Communications Commission, and therefore special circuitry must be included in the antenna drive network to suppress those harmonics (sometimes referred to as spurious emissions).

It is informative to compare the nonlinear source-tract interaction that can result in strengthening of higher harmonics caused by F1/F0 tuning, as described herein, with the strengthening of higher harmonics that can be caused by nonlinear source-tract interaction that results in a tilting to the right of the glottal airflow pulse and is related to the glottal flow resistance interacting with the inertance of the airflow near the larynx, as first described by Rothenberg and Zahorian,<sup>7</sup> and more completely by Rothenberg.<sup>8</sup> Figure 10 from Rothenberg and Zahorian<sup>7</sup> is shown here in Figure 9. This interaction is largely responsible for the strength of the voice of many male singers and professional speakers, and in fact for a certain reduction in the average glottal airflow. However, the main contribution to voice quality is to lift the spectral energy of the higher harmonics of the glottal airflow waveform, in a manner independent of the action of the vocal

tract formants, including formants the frequency of which may have been affected by the vocal tract inertance  $L_t$ .

We have argued that in an analogous nonlinear source-tract acoustic interaction, it is possible for pharyngeal F1 energy to depress only a part of the glottal airflow pulse, so as to cause a distortion of the glottal airflow pulse, as illustrated in Figures 1, 2 and 3, that will selectively amplify certain glottal harmonics above the fundamental.

### SOME CONCLUSIONS

For brevity, we have termed the vocal fold vibration pattern in which the closed quotient is near 50% (more precisely, over about 30%) and there is a complete closure during most of the closed period, with no air leakage, as a "gated" vibratory pattern. Using this terminology, we can say that in the presence of "gated" vocal fold vibratory action, tuning F1 to near F0 can result in a reduction in average glottal airflow and a strengthening of selected glottal airflow harmonics above F1, and thus a richer sounding voice quality.

The stipulation of a gated (or near-gated) vocal fold vibratory action is very important here for the occurrence of the type of nonlinear source-tract interaction that we describe. A vocal fold vibratory pattern that is not "gated," using our terminology, may result in a linear, or quasi-linear, source-tract interaction in which tuning F1 to F0 will result in a strengthening of only the F0 component, and a weaker sounding voice quality. Thus, it may be possible that singers who are restricted to nongated vocal fold vibratory patterns by their laryngeal physiology, or who choose those patterns for artistic reasons, may not place F1 close to F0, and instead use another formant placement to enrich the quality of the voice.

It is possible that other researchers measuring F1 in soprano singing will find alternate placement of F1 because of their selection of singing without a strong gated vocal fold vibratory action. Thus, in analyzing the voice of a soprano, formant placement cannot be separated from vocal fold vibratory behavior.

The theoretical explanation for the reduced air consumption is that airflow pulses through the glottis, occurring each time the

glottis is open, are suppressed in amplitude by a peak in the oral pressure just above the glottis generated by the previous airflow pulse. One result of this is that estimating the frequencies of formants above the first by the strength of the harmonics, as is often done with male voices at lower values of  $F_0$ , may not be valid, and other methods must be used. The inadequacy of using harmonic amplitudes to estimate formant frequencies at high values of  $F_0$  has long been recognized, with the wide spacing of the harmonics as the cause. However, the changes in harmonic amplitudes that can be caused by nonlinear source-tract acoustic interaction are another important factor that must be recognized.

What remains to be done in evaluating nonlinear source-tract interaction in the soprano voice is to verify the reduction in airflow when  $F_1$  approaches  $F_0$ , and possible occurrence of double-humped glottal airflow pulses, in a few more strong soprano voices, presumably by using inverse filtering combined with an EGG signal carefully synchronized with the airflow signal to determine the glottal closed phase. In addition, EGG signals can be obtained from a range of voice types in both soprano and tenor voices, to see if the EGG patterns noted in Figures 4, 5, and 6 are consistently found in professional dramatic sopranos with a strong voice at the top of their range, as well as other categories of soprano, and tenors, to see if this principle extends to male singers.

It should be noted that in pursuing this research, the type of pressure measurement performed by Schutte and Miller and shown in Figure 4, in which pressure is recorded simultaneously above and below the glottis, can be performed less invasively by measuring only the pressure above the vocal folds (the pharyngeal pressure). In doing this, the average subglottal pressure can be extrapolated from the pharyngeal pressure by using an unvoiced pressure consonant between vowel segments, as in papapa or tatata. (Rothenberg<sup>9</sup> used this technique with only bilabial consonants because the oral pressure behind a lingual closure was not available.)

More research is also needed on the implications for singing pedagogy of the use of this type of nonlinear acoustic interaction for increasing the efficiency of the voice of a soprano. For example, is it possible to screen young singers to see if they have the laryngeal characteristics that are needed for this type of nonlinear acoustic interaction? Also, are the laryngeal characteristics of a particular singer in any way dependent on the health of the

singer at the time of the performance, especially factors that might limit the mobility of the vocal folds? Conversely, can the health of the vocal folds be in any way compromised by a singer reaching for strong high notes when he or she does not have the glottal vibratory pattern required for reducing the glottal airflow by the type of nonlinear acoustic interaction discussed here?

It would also be of interest to see how a young singer blessed with the prerequisite vocal fold vibratory behavior learns to sense when the tuning is correct, as she (or he) obtains the proprioceptive or auditory feedback required to sense when the airflow is minimum. To use the radio engineering terminology, does a singer who has a gated vocal fold vibratory action learn to “tune for the dip,” and how can that be expedited in singing pedagogy?

Finally, it is clear that much more research is needed in the interpretation of EGG waveforms from singers in the pitch ranges of interest here. One can envision a databank of such waveforms, along with airflow recordings, or at least microphone recordings suitable for inverse filtering.

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