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The Effect of Single Harmonic Tuning on Vocal Loudness

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Summary:

The study addresses the benefit of tuning single harmonics with vocal tract resonances to increase vocal loudness. The loudness of theoretically constructed vocal sounds with variable levels of sound energy in the first, second, and third harmonics is computed on the basis of ISO standard 226:2003. In comparison to increased loudness with changes in overall spectral slope, it is shown that single harmonic tuning requires a greater range of SPL to produce a similar range of loudness. For example, a 10–40 dB increase in the level of a single harmonic produces less than two doublings of loudness, whereas a spectral slope change from 12 dB/octave to 3 dB/octave can produce a similar doubling of loudness with only a 5 dB SPL increase.

Keywords

Harmonic tuning; Resonance; Vocal loudness

INTRODUCTION

Vocal loudness is often assessed by measuring sound pressure level. It is known, however, that loudness as quantified perceptually in *sones* does not have a direct relation to SPL, especially when the sound has multiple frequencies. The auditory system is more sensitive to some frequency components than others. In speech and singing, various harmonics can contribute more to total loudness than they contribute to total SPL.

In most musical instruments, the resonating structures are designed so that multiple harmonics of the sound source can be reinforced by natural resonances of the instrument.^{1–3} That often guarantees a rich spectrum of harmonics. In human vocalization, multiple-harmonic tuning is generally not possible because the supraglottal airway is too short for alignment of an entire series of source harmonic with an equivalent series of the airway resonances. On average, a 17.5 cm long male vocal tract can resonate at 500, 1500, 2500, 3500 ... Hz in a neutral vowel configuration. For a fundamental frequency of 500 Hz, odd harmonics could be reinforced collectively, but for 250 Hz only the 2nd and 6th harmonic (500, 1500 Hz) line up well with these resonances. For females the airway resonance frequencies average around 600, 1800, 3000, ... Hz for a neutral vowel, which gives similar tuning possibilities at 15%–20% higher source frequencies. However, for most vowel

configurations the resonances are not spread evenly (with integer ratios). Resonances cluster and spread apart for the purpose of vowel distinction and clarity.

Unfortunately, the acoustic vocal tract length cannot be changed dramatically, as is possible in man-made instruments with valves, slides, or tone holes. The larynx can be lowered on the order of 1 cm and the lips can be protruded a similar length. In combination, that changes the resonances by about 10%. Thus, the only major control over the airway resonances is to alter the shape of the airway, but the variability with articulatory gestures generally does not produce a harmonic series of resonances. Usually only one (and rarely two) harmonics can be tuned to vocal tract resonances for a given f_0 .

In a recent paper by Titze and Palaparthi, it was shown that spectral slope change is highly effective for loudness regulation.⁴ For modal (chest) register, a small change in sound pressure level (SPL) from a variation in spectral slope was shown to produce a large change in loudness. The investigation was a new step toward understanding control of loudness in vocalization, but did not yet consider how harmonic tuning by vocal tract resonances can affect perceived loudness. Such tuning has been of major interest in various styles of singing and is the essence of “harmonic singing,” also known as overtone singing, where the melody is played by jumping from harmonic to harmonic with resonance tuning.^{5–11}

Single harmonic tuning is not likely to occur often in speech because vocal tract resonances are broad enough, and fundamental frequencies are low enough, that amplitudes of several adjacent harmonics are raised simultaneously. In singing and calling, however, the harmonics are spread farther apart due to higher f_0 , allowing resonances to be placed on a single harmonic.

The fundamental question to be answered in this study is to what extent perceived loudness can be altered by tuning a vocal tract resonance to a single harmonic and how that compares with multiple harmonics being reinforced with spectral slope variations described earlier.⁴ Both techniques are used in singing.

METHODS

Computation of loudness in sones from a sound spectrum followed a previous publication.⁴ A script published by Tackett was used to convert SPL to loudness level in phons and then to loudness in sones in the range of 10–90 phons.¹² Equations are given in the earlier publication and are reproduced here in the Appendix.⁴ The procedure is based on International Standards Organization ISO 226:2003, reviewed and confirmed in 2014. Frequencies available for direct calculation were 20 Hz–12.5 kHz in third-octave steps. This included a chosen set of male and female fundamental frequencies for this study, namely 125, 250, 375, 500, 625, 750, 875, 1000 Hz, with at least 12 harmonics for each f_0 . For frequencies other than the specific third-octave frequencies, linear interpolation was used. The range of f_0 was sufficient to make calculations of loudness in sones with complex tones having spectral content in the singing and speaking range. For several values of f_0 , the amplitudes of individual harmonics were increased in steps of 10, 20, 30, and 40 dB to simulate overall dB SPL and loudness change with harmonic tuning. These changes

in loudness were compared to changes in loudness achievable with overall spectral slope change in the previous publication.⁴

RESULTS

First harmonic tuning

The effect of raising the level of the first harmonic f_0 on vocal loudness was calculated. Apart from the level of f_0 , the spectral slope of the source was kept constant at -6 dB per octave roll-off for all conditions. The level of the fundamental was successively increased by 10, 20, 30, and 40 dB. Figure 1 shows the results for $f_0 = 125$ Hz. Part (a) shows the classical equal loudness level curves defined by the standard ISO 226. Part (b) shows the spectral envelope for the stylized spectra chosen. Harmonic frequencies are indicated with vertical dashed lines. Part (c) shows the loudness in sones contributed by each harmonic. The sone scale on the horizontal axis is purposely large for comparison with later plots. Part (d) shows the overall SPL (dashed line) in dB and the overall loudness (solid line) in sones. The same axis with a common scale is applicable. It is seen that overall SPL is dominated by fundamental frequency energy, increasing linearly from baseline 50 dB (not drawn) to 90 dB with four 10 dB steps in the level of the fundamental. The loudness variation follows the SPL nonlinearly. There is less than a doubling for every 10 dB increase in SPL. The range is from 7 sones to 25 sones, slightly less than two doublings. The standard of comparison is a pure tone at 1000 Hz, which would double in loudness with every 10 dB increase above 40 dB. In other words, a 1000 Hz pure tone would have 3 doublings, more than the 125 Hz complex sound with a tuned fundamental.

There is generally not much benefit obtained from boosting the amplitude of the fundamental in speaking or singing when f_0 is as low as 100–200 Hz. The spectrum would be highly unbalanced toward low-frequency and the timbre would be pure-tone-like. Furthermore, there is not much opportunity for tuning the fundamental with vocal tract resonances, which are generally well above 200 Hz for all vowels.

To the contrary, results are more interesting for $f_0 = 1000$ Hz, a fundamental frequency encountered in female (and some male) singing. Operatic sopranos appear to make use of f_0 tuning in the 1000 Hz to 1500 Hz region (C6–F6).⁶ Results are shown in Figure 2. For the same SPL range as for the $f_0 = 125$ Hz case, tuning the fundamental at this higher frequency produces more overall loudness, 10–40 sones instead of 7–25 sones. The fundamental is now in a sensitive part of the equal loudness level curves. However, the loudness variation is not much different (about 2 doublings) with the same SPL range as for $f_0 = 125$ Hz.

Second harmonic tuning

Of similar interest is 2nd harmonic tuning an octave lower, in the $f_0 = 500$ Hz region. This is utilized by operatic males and female theatre belters. Figure 3 shows the result for 2nd harmonic tuning at 500 Hz. Total loudness ranges from 12 to 35 sones, slightly less than for 1st harmonic (fundamental) tuning an octave higher.

Third harmonic tuning

Third harmonic tuning at $f_0 = 500$ Hz is not quite as effective as 2nd harmonic tuning at $f_0 = 500$ Hz, as Figure 4 shows. The 1500 Hz harmonic frequency is slightly above the sensitive 1000 Hz region of the equal loudness level curves. A slightly lower f_0 , around 400 Hz, would be more favorable. One famous operatic tenor, Luciano Pavarotti, often exhibited a strong 3rd harmonic in the 400–500 Hz region, with almost similar strength in the 2nd harmonic.¹³

Overall comparison between spectral slope change and harmonic tuning for loudness control

Spectral slope has been kept constant at 6 dB/octave in the above calculations. This would correspond to a typical 12 dB/octave roll-off at the source and a +6 dB/octave for radiation at the mouth. No resonance structure was imposed. It is informative to compare the range of loudness achievable with single harmonic tuning to that achievable with variation in spectral slope. In an earlier publication by Titze and Palaparthi, SPL and loudness changes were calculated for four spectral slopes, 3 dB/octave, 6 dB/octave, 9 dB/octave, and 12 dB/octave.⁴ Figure 5 (a) shows overall SPL in dB (dashed lines) and loudness in sones (solid lines) for four spectral slopes. The most profound result was the small variation in SPL with spectral slope change, from a baseline of 50 dB to about 55 dB across the entire range of spectral slopes (dashed lines). In contrast, Figure 5(b) shows SPL changes from slightly above 60 dB to nearly 90 dB (dashed lines) for first harmonic tuning, and slightly less for 2nd and 3rd harmonic tuning in Figure 5 (c)–(d). The difference in loudness variation between spectral slope change and harmonic tuning is not nearly as large. If the 40 dB gain in harmonic tuning were not included (focusing on the bottom three curves only) there would not be much difference in the loudness ranges in sones between harmonic tuning and spectral slope change. However, the SPL range would still be remarkably different, suggesting that SPL range is not a reliable predictor of loudness range.

Commenting further on the 40 dB amplitude gain in harmonic tuning, it is unlikely that vocal tract resonance can produce such a high gain for a single harmonic, given typical bandwidths in the range of 25–200 Hz. *Harmonic (overtone) singers* can achieve up to 30 dB increases in a welltuned single harmonic, but it requires a great level of skill with precise articulatory gestures and little vibrato or other frequency modulation.¹⁰ The timbre is whistle-like.

A most important summary finding in this study is the *rate of change of loudness with change in SPL*. This can be expressed as L/SPL in sones per dB, as shown in Figure 6. It is basically the sensitivity of loudness variation to SPL variation. This sensitivity is obtained by taking the differences between the four curves in Figure 5, which results in three sensitivity curves. Spectral slope produces by far the best results in this analysis. Note the scale change by a factor of 2 in part (a). Spectral slope delivers between 2 and 5 sones per dB SPL, 1st harmonic tuning delivers between 0.5 and 2 sones per dB SPL, and 2nd and 3rd harmonic tuning deliver less than 1 sone per dB SPL. Also note a broad maximum in the spectral slope sensitivity curve at about 400 Hz and a broad minimum above 500 Hz in the 2nd and 3rd harmonic sensitivity curves.

DISCUSSION AND CONCLUSIONS

A fundamental question to be answered in this study was the degree to which single harmonic tuning affects SPL and loudness in vocalization. In general, the doubling of loudness per 10 dB SPL increase (the pure tone standard at 1000 Hz above 40 dB) is not reached for harmonic tuning across the entire vocal fundamental frequency range of 125–1000 Hz. This is simply due to the lack of auditory sensitivity in frequencies below 1000 Hz. On the order of 5–20 sones (about two doublings of loudness) are achievable by raising the level of a harmonic 10–30 dB above the remainder of the harmonic levels. In comparison, 20–50 sones per 10 dB SPL are achievable by changing the spectral slope from –12 dB/octave to –3 dB/octave. Thus, varying the spectral slope (more or less energy distributed into higher harmonics) is more effective for achieving a wide loudness range (eg, the musical dynamic levels *pp-p-mp-mf-f-ff*).

A further disadvantage of tuning a single harmonic is the loss of a rich timbre. Basically, the sound becomes a loud whistle. The results explain why singers and talkers tend to favor vocal fold adduction and voice registration to increase loudness and why singers search for strategies to reinforce multiple harmonics simultaneously with source-filter interaction.

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APPENDIX

For the following third-octave frequencies,

$$nf = [202531.540\ 506380100125160\ 200250315400500\ 630800100012501600200025003150400050006300\ 80001000012500]\text{Hz}$$

the coefficients af , Lu , and Tf are provided to relate SPL in dB to phons to sones,

$$af = \begin{bmatrix} 0.5320.5060.4800.4550.4320.4090.3870.3670.349 \\ 0.3300.3150.3010.288 \\ 0.2760.2670.2590.2530.2500.2460.2440.2430.243 \\ 0.2430.2420.2420.245 \\ 0.2540.2710.301 \end{bmatrix}$$

$$Lu = \begin{bmatrix} -31.6 - 27.2 - 23.0 - 19.1 - 15.9 - 13.0 - 10.3 \\ -8.1 - 6.2 - 4.5 - 3.1 - 2.0 - 1.1 - 0.40.0 \\ 0.30.50.0 - 2.7 - 4.1 - 1.01.72.51.2 - 2.1 - 7.1 \\ -11.2 - 10.7 - 3.1 \end{bmatrix}$$

$$Tf = \begin{bmatrix} 78.568.759.551.144.037.531.526.522.117.9 \\ 14.411.48.66.24.4 \\ 3.02.22.43.51.7 - 1.3 - 4.2 - 6.0 - 5.4 - 1.56.0 \\ 12.613.912.3 \end{bmatrix}.$$

For a given loudness level LL at any of the 29 frequencies nf above, a function Af is first computed,

$$Af = 4.47E - 3 * (10 \wedge (0.025 * LL) - 1.15) \\ + (0.4 * 10 \wedge (((Tf(nf) + Lu(nf))/10) - 9) \wedge af(nf))$$

Linear Interpolation is used for any frequency between the third-octave frequencies. The above equations assume that loudness level LL is the known input variable. By computing Af from Eq. (2), SPL can then be computed explicitly from Af ,

$$SPL = ((10/af(nf)) * \log_{10}(Af(nf)) - Lu(nf) + 94$$

For the current application, SPL is the known input variable. The equations cannot be inverted algebraically to solve explicitly for LL in terms of SPL. To obtain a numerical solution for a given SPL, trial loudness levels LL are incremented in 1000 steps from 10 – 90 phons for the given SPL, from which Af is computed in each iteration. A trial SPL is then calculated at each step and the absolute error $|SPL_t - SPL|$ is minimized with repeated trials. The loudness L in sones is then computed from the LL corresponding to the minimum error:

$$L(nf) = (LL/40) \wedge 2.86 - 0.005 \quad LL < 40 \text{ phons}$$

$$L(nf) = 2 \wedge ((LL - 40)/10) \quad LL > 40 \text{ phons}$$

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FIGURE 1.

First harmonic tuning at $f_0 = 125$ Hz, (a) equal loudness levels, 10–90 phons bottom to top (b) SPL in dB for four f_0 gains, vertical dashed lines showing harmonics up to 3 kHz (c) loudness in sones across harmonics, and (d) total SPL (dashed line in dB) and total loudness (solid line in sones) for four f_0 gains.

FIGURE 2.

First harmonic tuning at $f_0 = 1000$ Hz, (a) equal loudness levels, 10–90 phons bottom to top (b) SPL for four f_0 gains, vertical dashed lines showing harmonics up to 10 kHz (c) loudness in sones across harmonics, and (d) total SPL (dashed line in dB) and total loudness (solid line in sones) for four f_0 gains.

FIGURE 3.

Second harmonic tuning at $f_0 = 500$ Hz, (a) equal loudness levels, (b) SPL for four $2f_0$ gains, (c) loudness in sones across harmonics, and (d) total SPL (dashed line in dB) and total loudness (solid line in sones) for four f_0 gains.

FIGURE 4.

Third harmonic tuning at $f_0 = 500$ Hz, (a) equal loudness levels, (b) SPL for four $3f_0$ gains, (c) loudness in sones across harmonics, and (d) total SPL (dashed line in dB) and total loudness (solid line in sones) for four f_0 gains.

FIGURE 5.

Loudness in sones (solid lines) with increase in SPL (dashed lines) for (a) spectral slope variation, (b) f_0 tuning, (c) $2f_0$ tuning, (d) $3f_0$ tuning over a wide f_0 range.

FIGURE 6.

Sensitivity L/SPL in sonos per dB (a) spectral slope variation, (b) f_0 tuning, (b) $2f_0$ tuning, (d) $3f_0$ tuning over a wide f_0 range.