The Physics of Singing Vibrato

Christa R Michel[1] and Michael J Ruiz[2]

[1]Christa R Michel Voice Studio, Geneva, Switzerland

[2] Department of Physics, University of North Carolina at Asheville, Asheville, North Carolina, USA

E-mail: christarmichel@gmail.com and mjtruiz@gmail.com

Website: www.christarmichel.com and www.mjtruiz.com

Abstract

A spectrogram of a singer's vibrato presents a striking way to introduce students to frequency, Fourier spectra, and modulation. Vibrato is discussed from the perspectives of the physicist and the musician. A dramatic spectrogram is included where coauthor soprano Michel suppresses her vibrato so that acoustical characteristics can be compared to the same note sung with vibrato. A video (Ruiz M J 2017 *Video: Vibrato* http://mjtruiz.com/ped/vibrato) is provided of this demonstration.

Introduction

The word vibrato has been used with different meanings over the past few centuries. *The Oxford Companion to Music* states "For many writers of vocal texts, 'vibrato' was interchangeable with 'tremolo', as indeed it was for the violinists Spohr (1832) and Leopold Mozart (1756; as *tremulant* or *tremoletto*)." [1] Due to this past ambiguity, some physicists use vibrato in the broad sense of periodic variation of one or more characteristics of sound, using *frequency vibrato* for frequency variations and *amplitude vibrato* for amplitude variations. [2]

In common everyday language, vibrato refers to periodic frequency change, while tremolo indicates periodic amplitude change. However, a singer's vibrato is usually accompanied by pulsations in both amplitude and waveform (timbre), pointed out by the psychologist Carl E. Seashore in the 1930s. He wrote “A good vibrato is a pulsation of pitch, usually accompanied with synchronous pulsations of loudness and timbre, of such extent and rate as to give a pleasing flexibility, tenderness, and richness to the tone.” [3] Seashore’s description is often quoted in the literature. [4-6]

“In practice it is virtually impossible to have frequency vibrato without amplitude vibrato because of the effect of room resonances and resonances in the source instrument.” [2] Therefore, voice vibrato is a simultaneous variation of the three basic acoustical characteristics of sound: frequency (pitch), amplitude (loudness), and waveform (timbre). The result is a combined frequency modulation (FM), amplitude modulation (AM), and timbre modulation (TM).

Be careful in discussing the perceptual characteristics of sound with your students since frequency also affects perceived loudness, described by the Fletcher-Munson curves. [7] Generally, humans are more sensitive to higher pitches and shrill sounds can appear extra loud and annoying.

Timbre and the Spectrogram

Students feel comfortable associating amplitude with loudness and frequency with pitch, but often find timbre mystifying. A dramatic way to demonstrate timbre is to use the online spectrograph available at https://academo.org/articles/spectrogram/ and have students sing vowels at the same pitch and loudness. A spectrograph gives a plot, called a spectrogram, of the sound’s Fourier sine frequencies against time. Differences in timbres of a periodic tone heard are visually evident as the brightening of different

Fourier components, also called harmonics. Fourier spectra and harmonics are discussed in more detail later in this paper. The relative brightenings of harmonics on a spectrogram depend on the vowel sound sung, where enhanced groups of harmonics are called formant regions.

The vibrato spectrogram

See figure 1 for a photo of a soprano singing with vibrato. The vibrato rate (VR) is the number of pitch pulsations per second. The vibrato extent is the range of frequencies for the vibrato, typically reported as a plus or minus band on either side of the average pitch.

Figure 1. Coauthor soprano Dr Christa R Michel.

See figure 2 for a spectrogram of Michel singing two seconds of a Mozart aria. This spectrogram is so rich in physics that we will take some time to discuss each feature, eventually getting to VR. We start first with the Fourier spectrum.

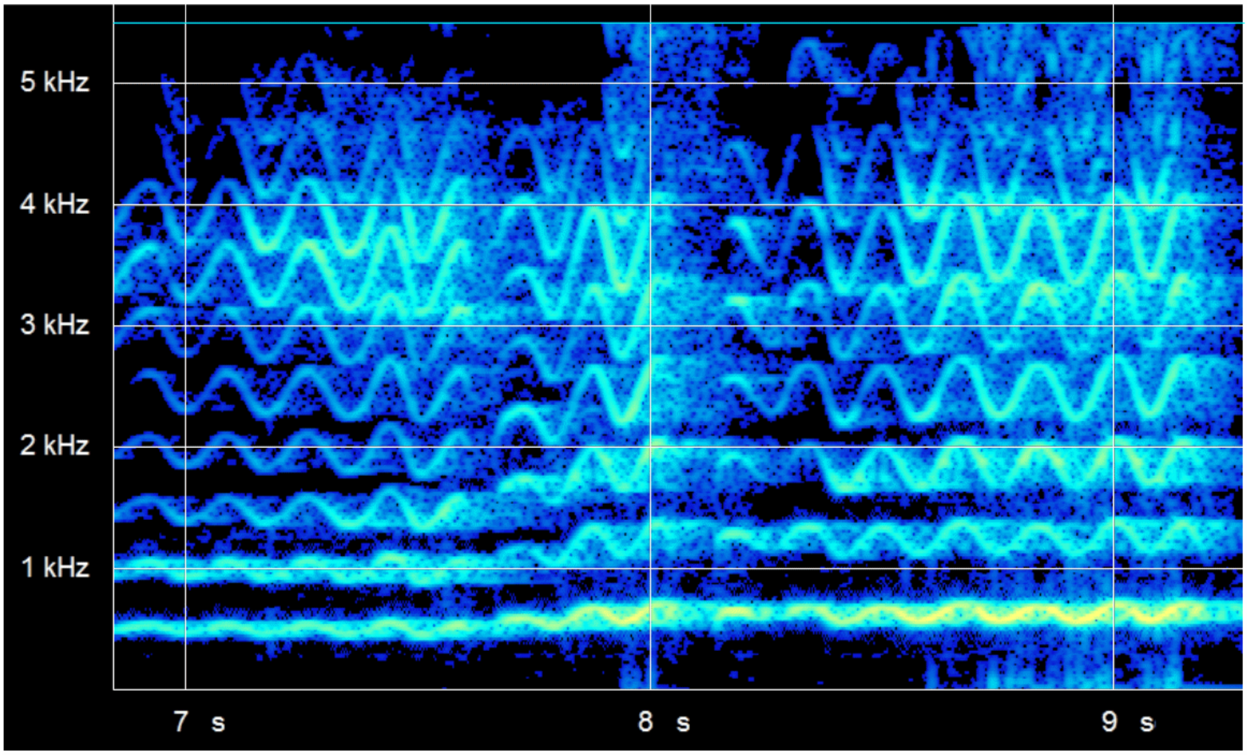

Figure 2. Spectrogram excerpt of Michel singing Mozart. The figure was made with *Spectrogram 16*, a desktop program developed for the PC by Richard S Horne.

The Fourier spectrum

Fourier's theorem states that a periodic tone with frequency f can be decomposed into a series of sine waves given by f, 2f, 3f, and so on with their corresponding Fourier amplitudes and phases. These sine waves are the harmonics or partials and their frequency values are found along the vertical axis in a spectrogram. The strength of each harmonic is seen in figure 2 by its relative brightness. There are at least eight harmonics visible in the spectrogram of figure 2, with the lowest one, also called the fundamental, being the brightest. The various strengths of the harmonics are due to the unique vocal system and training of the singer, and the Fourier spectrum gives the specific timbre for the singer's unique sound.

The fundamental

The fundamental of a periodic tone is typically the strongest harmonic and indicates the perceived pitch. The other harmonics, the overtones, color the tone and shape its timbre. At the far left of the spectrogram in figure 2 the second harmonic is on the 1 kHz line. Dividing by 2 gives an estimate of 500 Hz for the fundamental. Since concert pitch $A_4 = 440\ \mathrm{Hz}$, we can keep multiplying the A_4 frequency by the twelfth root of 2, i.e. $\sqrt[12]{2} = 1.05946...$, in order to climb by semitones[1] until we get close to our estimate of 500 Hz. In this manner we can determine the concert note the soprano is singing at that instant. Starting at A_4 and raising by semitones using the rule, the frequencies are $A_4 = 440\ \mathrm{Hz}$, $A_4^{\#} = 466\ \mathrm{Hz}$, $B_4 = 494\ \mathrm{Hz}$, and $C_5 = 523\ \mathrm{Hz}$. We conclude that the soprano is singing a B_4 (B above middle C) at the beginning of the spectrogram in figure 2.

The vibrato rate (VR)

The vibrato rate is found by counting the number of undulations for one second in the spectrogram. The vibrato rate in figure 2 is found to be roughly 6 Hz. Ask your students the best way to determine this result from the spectrogram. Some tricks include looking at the harmonic where the vibrato is easier to see or estimating the number of frequency modulations in one-half second and then multiplying by 2. Note that VR can change in time.

Prame [8] found in a study of vibrato rates for ten singers from commercial CDs

[1] The rule of multiplying by the twelfth root of two in order to raise a semitone comes from the fact that to raise a pitch by one octave, i.e. twelve semitones, the frequency needs to double.

singing Schubert's *Ave Maria* that the VR for the singers had an overall average of 6.0 Hz with a standard deviation 0.24 Hz. The VR in figure 2 is very near the 6.0 Hz reported by Prame in his studies of classical western opera. In nonwestern Chinese classical Peking opera typical VR is only 3.5 Hz, which is about 2 Hz lower than VR in western operatic singing. [9]

Titze et al. point out that VR in western opera has lowered during the 20th century (e.g. comparing Caruso's 6.5 Hz to Pavarotti's 5.5 Hz) and they suggest that the reason is a preference today for a more "settled" sound with less overt emotion. [5] Ferrante's study of the western soprano voice over one century found the average change of VR to be -1.8 ± 0.3 Hz/century [10].

The vibrato extent

Students viewing figure 2 may wonder why the vibrato undulations are greater for the higher harmonics. Consider this analogy. Suppose an investor, called "fundamental," invests $1000 with a 10% return, making $100. Suppose another investor, called "fifth harmonic," invests $5000. The same 10% return now brings in $500, five times as much as "fundamental." This scheme is seen in figure 2, where the same gain and loss percentages oscillate above and below their respective average values.

To estimate the vibrato extent, focus on harmonic 8 at the vertical time line labelled 7 s. Estimate the trough to be at 3700 Hz and the crest on either side of the trough to be at 4200 Hz. The average frequency for the 8th harmonic is then

$f_8 = \frac{3700+4200}{2} = 3950$ Hz, with the frequency varying ± 250 Hz from the average value. The percentage variation from the average frequency is $\pm\frac{250}{3950}\cdot 100\% = \pm 6\%$.

We can check our earlier analysis of the fundamental, which was $B_4 = 494\ \mathrm{Hz}$, by calculating $f_1 = \frac{f_8}{8} = \frac{3950}{8} = 494\ \mathrm{Hz}$. Our former result is nicely confirmed.

Note that the twelfth root of 2, $\sqrt[12]{2} = 1.05946...$, indicates that rising by a semitone is about a 6% increase. Therefore, $\pm 6\%$ variation is a semitone variation above and below the average pitch. Ferrante found that from 1900 to 2010 the average soprano vibrato extent increased from roughly $\pm 2\%$ (in 1900) to about $\pm 6\%$ (in 2010). [10] The later $\pm 6\%$ value reported for the year 2010 is the same value we calculated from figure 2, equivalent to ± 1 semitone.

The singer's formant

There is a brightening of harmonics between 3000 Hz and 4000 Hz in figure 2, easily seen between the vertical lines labelled 7 and 8 seconds. As mentioned earlier, such a region of enhanced harmonics due to the vocal system is called a formant region. The formant region near 3500 Hz is known as the singer's formant. The ear canal closed at the eardrum has a resonance near 3300 Hz [11], which further amplifies this formant. However, the pervasive importance of the singing format for various voice types has been debated for years. [12]

Synchronous amplitude variation

The brightening of tips of some crests between 8 s and 9 s indicate that pulsations in amplitude accompany the vibrato. The physicist Rossing [2] indicates that at a vibrato rate of 6 Hz, the listener cannot discern the quick variations in pitch, but rather perceives an average pitch with intensity fluctuations at the frequency of the vibrato. This observation explains why the singer is heard to be on pitch, as the amplitude fluctuations play an important perceptual role in perceiving the vibrato.

Synchronous timbral variation

Since the brightening of the crests mentioned in the previous subsection does not appear consistently among the harmonics at any given horizontal time instant, there is a subtle timbral variation. When one harmonic brightens more than another, the Fourier amplitude for that harmonic increases. The result is a timbral change.

The modulator waveform of the vibrato

The plot for an unmodulated sine wave on a spectrogram can be thought of as a dot moving horizontally where the height corresponds to the frequency. When the sine wave is frequency modulated, the dot changes altitude as it moves along the horizontal time axis. The frequency modulator waveform is the waveform pattern that the dot traces out, which in figure 2, is a sine wave with frequency 6 Hz, the vibrato rate (VR).

Where does singing vibrato come from?

Singing vibrato is due to air flow modulations by the vocal folds (glottal source) coupled with modulations due to resonances in the vocal system. [13] The variations in fundamental frequency (FM) generated in the glottal source modify amplitude (AM) and timbre (TM) [13], as we discussed earlier. Discussion of physiological studies can be found in the classic text by Miller [4] and in the more recent publication by Titze et al. [5].

Vibrato is naturally found in the typical adult voice. Although some singers develop vibrato relatively early, many children who appear to have vibrato are mimicking adult voices. The older a child gets, the more likely vibrato is to appear and after puberty it is much more common. As young singers learn to “support” their voices by both proper posture and by providing a steady and controlled air stream, vibrato becomes more pronounced.

In order to be heard in large spaces, it is necessary that classical singers learn how to use air properly to support a sound that can be effectively projected. With this classical technique, the naturally occurring vibrato is inevitably heard, barring intentional interference from the singer. An amateur singer who has not mastered this support of the voice may have an inconsistent vibrato, one that slows down or speeds up, or disappears altogether at times. An advanced voice student will reach the stage where airflow is consistently and correctly applied in such a manner that the natural vibrato is even and steady throughout the entire vocal range. This control is the goal of the virtuoso classical singer.

Professional pop singers use microphones, where operatic control of air for projection is not necessary and therefore they can sing in a way where vibrato is not heard. Additionally, pop singers are often using speech-like singing styles where notes are not sustained for a long time. When they sing ballads or more lyrical songs, vibrato tends to appear, e.g. Lady Gaga performing *Speechless*. [14]

Vibrato isn’t taught in the sense that attempts are made to intentionally produce it, however singers learn how to create the circumstances that allow for the vibrato to flourish in its natural state. Nix points out that as “postural balance, breath management, laryngeal coordination, and vowel shaping improve, vibrato tends to become more regular.” [15]

The natural rate of vibrato varies from person to person and one shouldn’t try to change one’s natural rate. Such attempts would not be sustainable and could be damaging to the voice. An experienced teacher can tell if a student’s vibrato rate is natural or a result of unhealthy tensions or bad vocal technique.

Non-vibrato tone (straight tone)

A non-vibrato tone is one where there is no perception of vibrato, a sound often referred to as a straight tone. A pilot study suggests that the perception of a non-vibrato tone can occur since vibrato extent and rate work together to fix a perceptual threshold for a listener to hear vibrato. [16] Below this threshold no vibrato is heard.

Sometimes a non-vibrato effect can be momentarily applied for artistic effect. Such non-vibrato singing is commonly heard at the beginning of sustained notes that start out soft and get louder; as the note grows, vibrato is added back in. In addition, some listeners prefer non-vibrato singing in Renaissance and Baroque music.

In choral settings, non-vibrato singing is more common, especially in the higher voices. The reason for this preference is partly an aesthetic choice, possibly from the influence of boy choirs, whose natural lack of vibrato lends itself to a pure and perfectly blended sound. There are also practical reasons. It can be challenging to have a cohesive sound with a large group of singers with differing rates of vibrato, especially if the singers are untrained.

The spectrogram in figure 3 illustrates the same pitch alternately sung with non-vibrato and with vibrato. To sing the non-vibrato in figure 3, the throat and mouth were held in a rigid position, in contrast to the open and supple position maintained for normal singing. This spectrogram was produced from the free online spectrograph published in *Physics Education* [17] and available at https://academo.org/articles/spectrogram/. This online spectrograph is described in detail in reference 17.

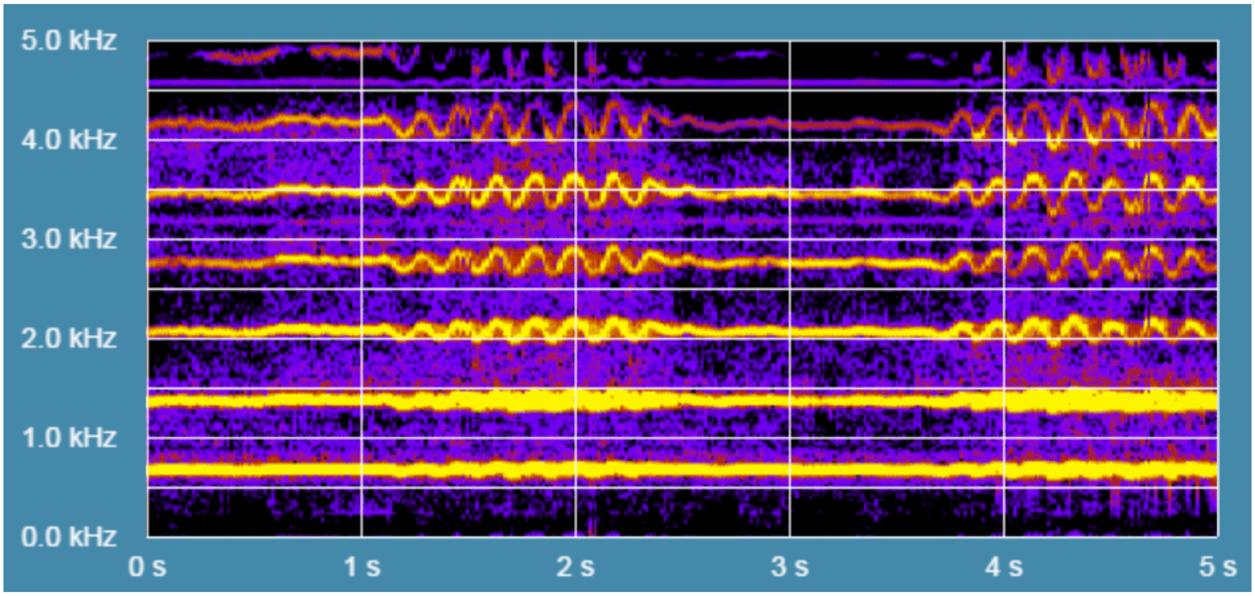

Figure 3. Coauthor Michel's spectrogram of singing with non-vibrato (flat harmonics) and with vibrato (harmonics with ripples). This spectrogram was made with the free online spectrograph published in *Physics Education* [17].

Conclusion

Vibrato has been discussed from both the perspectives of a physicist and opera singer. We have prepared a video where coauthor Michel demonstrates the non-vibrato and vibrato in the spectrogram of figure 3. [18]

Vibrato and its visualization in a spectrogram convey a wealth of physics about the acoustics of singing tones. The spectrogram reveals the Fourier spectrum, vibrato rate, vibrato extent, formant regions, synchronous amplitude and timbre variations, as well as enabling the student to make measurements of frequency, frequency modulation, and vibrato extent. Students can also sing in class and observe their own vibratos in real time. They will enjoy the physics-music connection and rich variety of activities.

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Authors

Christa R Michel is a teacher and performer based in Geneva, Switzerland. She received her Doctorate in Music from Indiana University Bloomington, USA in 2015. Her performances as a soprano soloist include appearances with the A. J. Fletcher Opera Institute of the University of North Carolina School of the Arts and the Jacobs School of Music Opera Theatre at Indiana University. Her scholarly interests include 20th-century music and holistic education. She is the daughter of coauthor Michael J Ruiz.

Michael J Ruiz is professor of physics at the University of North Carolina at Asheville (UNCA), USA. He received his PhD in theoretical physics from the University of Maryland, USA. His innovative courses with a strong online component aimed at general students have been featured on CNN.