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Tuvan throat singing and harmonics

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Abstract

Tuvan throat singing, also called overtone singing, provides for an exotic demonstration of the physics of harmonics as well as introducing an Asian musical aesthetic. A low fundamental is sung and the singer skillfully alters the resonances of the vocal system to enhance an overtone (harmonic above the fundamental). The result is that the listener hears two pitches simultaneously. Harmonics such as H8, H9, H10, and H12 form part of a pentatonic scale and are commonly selected for melody tones by Tuvan singers. A real-time spectrogram is provided in a video (Ruiz M J 2018 *Video: Tuva throat singing and harmonics* http://mjtruiz.com/ped/tuva/) so that Tuvan harmonics can be visualized as they are heard.

Where is Tuva?

Richard Feynman, who shared the 1965 Nobel Prize in physics for his work on quantum electrodynamics, answered in a British documentary [1]: 'just outside of Outer Mongolia, in the middle of Central Asia, in the depths of Russia, far away from anything.' Feynman's interest in Tuva (also called Tannu Tuva) dated back to when, as a child, his father told him about interesting stamps from this captivating land. Later in life, he attempted to go to Tuva [2] with his friend Ralph Leighton (son of Caltech physicist Robert B. Leighton[3]), but Feynman passed away before finally getting permission to travel there.

Not only is the location far out, but Tuva is also a very important region for throat singing. In throat singing, at least one overtone is emphasized with the fundamental pitch. The composer and later ethnomusicologist A. N. Aksenov wrote:

> Throat singing is known not only to the Tuvins, but also to several neighboring peoples (Mongols, Oirats, Khakass, Gorno-

[3] Leighton senior is coauthor of *The Feynman Lectures on Physics* (Richard P. Feynman, Robert B. Leighton, and Matthew Sands), first published in 1964.

> Altais and Bashkirs). However, among the Tuvins it has been preserved in the most developed and widespread form, ... [3].

Tibetan monks also have a tradition of throat singing with an extremely low fundamental pitch (first harmonic), close to 75 Hz. [4] In contrast, the typical Tuvan fundamental is near 150 Hz, an octave higher, as demonstrated in this paper.

Throat singing is also called overtone singing. Individual overtones (harmonics above the fundamental) are enhanced in this type of singing, which is a beautiful demonstration of the laws of physics. Students can visualize Fourier's theorem, which states that any periodic tone with frequency f can be constructed by adding sine waves with frequencies f, $2f$, $3f$, and so on, the harmonics.

Some students may already be familiar with Tuvan throat singing from the popular television show ‘The Big Bang Theory’, where the fictional character Sheldon Cooper demonstrates the art in an episode. Students will find throat singing especially fascinating if the teacher begins by asking them if it is possible for the human voice to sing two or three different notes at the same time. The skill employed in throat singing allows the singer to enhance harmonics above the fundamental, which creates the illusion that one is singing a musical interval (two notes) or even a chord (three or more notes). The practice for singing a tune is to emphasize one overtone so that by hearing the fundamental and the amplified higher harmonic, one perceives two simultaneously sounding notes. The melody is carried by the overtone and the fundamental serves as a constant pedal bass tone.

Coauthor David Wilken first learned how to sing the base pedal-tone pitch with a particular sort of constriction that closes the ventricular folds, sometimes called the ‘false folds’. These false vocal folds are ‘paired tissues that occur directly above the true folds’ [5]. This practice helps the oral cavity resonate more and brings out the overtones. Then he learned to employ a two-cavity technique by creating a second resonance chamber by raising his tongue up to the roof of the mouth. The cavity configuration is varied by adjusting the position of the tongue against the roof of the mouth. In this manner higher harmonics can be selected for emphasis. A single harmonic has an ethereal whistle quality characteristic of sine waves with midrange to high frequencies perceived by humans. Melodies with tones that fit the pitches available in the overtone series can then be sung. Since your students are likely to ask about the mechanism by which throat singing works, we include a more detailed description in the following section.

The mechanism of throat singing

The Tuvan style of throat singing, known generically as khoomei, begins with applying a particular type of constriction of the vocal folds in order to help isolate the harmonics inside the oral cavity. It can be learned by softly singing a low pitch using the lowest register of the voice (the vocal fry). Maintaining the vocal folds in the same position add a bit of volume and tone to the voice. This throat constriction closes the vocal folds somewhat and helps to create the resonance chamber inside the mouth.

To produce the harmonics, the tongue must raise and lower inside the mouth in a manner similar to whistling. The tip of the tongue is placed behind the upper teeth, as if saying the letter "L" and the sides of the tongue are brought against the molars. By raising and lowering the middle of the tongue while the tip and sides are in this position, the harmonics are isolated and melodies can be sung. It takes some practice and experimentation for the singer to learn the precise position of the tongue in order to isolate the specific partials and bring out the harmonics.

When initially learning to sing in this way the singer's throat can itch, causing a coughing fit. Singers in training must be careful not to sing too loud and when the throat itches, the singer should stop, drink some water, and take a break to avoid damaging the vocal folds. The above description is informational and not intended to be instructional. As with any advanced vocal technique, it is best to learn with a professional voice teacher.

There are other variants to throat singing among the indigenous populations of Siberia (Tuvans), Mongolia, and Tibet. In all cases, the physics of resonance is important. The two resonances described earlier lead to the listener's perception of two distinct tones. Levin and Edgerton describe the lower pedal tone as 'a low, sustained fundamental pitch, similar to the drone of a bagpipe' [5]. They describe the whistle-like overtone as a sound in 'a series of flutelike harmonics, which resonate high above the drone and may be musically stylized to represent such sounds as the whistle of a bird, the syncopated rhythms of a mountain stream or the lilt of a cantering horse' [5]. Later we will show why these higher tones are typically between three and four octaves above the fundamental. To read more about the different styles of throat singing with accompanying diagrams of the vocal system, the reader is encouraged to consult the excellent references [5, 6].

Formants

Before analyzing the harmonics of throat singing, first consider speech and usual singing. The resonances in the vocal system, unique to each individual due to variation in biological structure, enhance some frequency regions of the speech or song. These enhanced regions are called formants or formant regions. Throat singing is a skillful control of these enhancements.

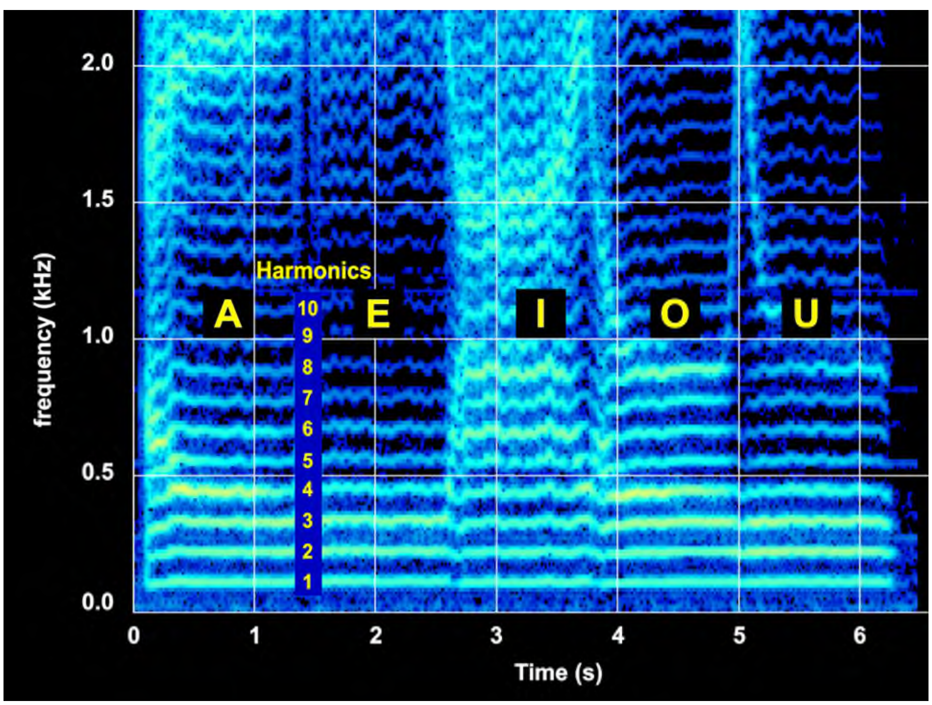

Figure 1. Coauthor Michael Ruiz (with no voice training) singing the vowels A, E, I, O, and U. Note the harmonics and the brighter areas. These enhanced brighter regions are called formants or formant regions.

See figure 1 for a spectrogram of coauthor Michael Ruiz singing the vowels A, E, I, O, and U with no voice training. The raw spectrogram for figure 1 came from the PC desktop software called ‘Spectrogram 16’, developed by Richard Horne years ago. A spectrogram is a plot of sine frequencies against time. Note the presence of many harmonics with various degrees of brightness. The stronger the presence of the harmonic, the more pronounced the harmonic appears in the spectrogram. The harmonics have equal spacing for a sung pitch since the nth harmonic is given by $f_n = n\, f_1$ from Fourier's theorem, with n = 1, 2, 3, etc, the first harmonic f_1 being the fundamental or singing pitch.

It is instructive to ask students to estimate the fundamental frequency from the spectrogram of figure 1. Observing that the 9th harmonic is very close to the grid line at 1.0 kHz, the fundamental can be estimated to be 1000/9 = 110 Hz, to two significant figures. Ask the students why using the 9th harmonic gives a better approximation rather than focusing directly on the first harmonic.

The brightest color (yellow) appears in the 4th harmonic for the A vowel, 3rd harmonic for the E, 8th harmonic for the I, 3rd and 4th for the O, and 2nd and 3rd for the U. Therefore, strong overtones are present in normal singing. In Tuvan singing, the strength of individual overtones can be expertly controlled by the singer. In this light, Tuvan throat singing is not so strange after all. All of us naturally have enhanced harmonics in our voice and song. Mark van Tongeren emphasizes this connection in his book *Overtone Singing* [6].

> The throat singer ‘Michael Vetter has said that when we speak we produce sequences of chords. These are not the triads that our beloved great composers used, of course. But it is true that when we speak we rapidly produce a complex of layered pitches, from which the brains pick out the strongest and most essential ones’ [6].

Which harmonics do Tuvan singers use?

Figure 1 in the previous section illustrates the fundamental and rich overtones that are produced even in non-trained singing. The experienced overtone singer can make selected harmonics stand out at will. The choice depends on musical aesthetics. Figure 2 provides a keyboard with the closest matches for the harmonics where the fundamental is C_3 = 130.8 Hz. The harmonics in red indicate that the pitch correlations with the respective keys are not very good. Our convention is defined so that middle C on the piano is C_4 = 261.6 Hz, where A_4 is set to the concert reference pitch of 440.0 Hz.

From figure 2, the musical intervals (distances) between adjacent harmonics decrease as the harmonic numbers increase. Think of C, D, E, F, G, A, B, and C on the small keyboard inset of figure 2 as Do, Re, Mi, Fa, Sol, La, Ti, and Do-prime (the start of the next musical octave). The intervals for the first few harmonics are fairly large with H1 to H2 being an octave (Do to Do') and H2 to H3 being a fifth (Do to Sol). However, the harmonics cluster closer together in smaller musical intervals for the upper harmonics shown in figure 2. Beyond the twelfth harmonic, the harmonic tones eventually get so close together that they produce microtonal intervals (notes closer than a semitone, i.e. closer than adjacent keys on a piano). Therefore, the harmonics H8, H9, and H10, which are equivalent to Do, Re, Mi, are prime candidates for pitches to use in a melody.

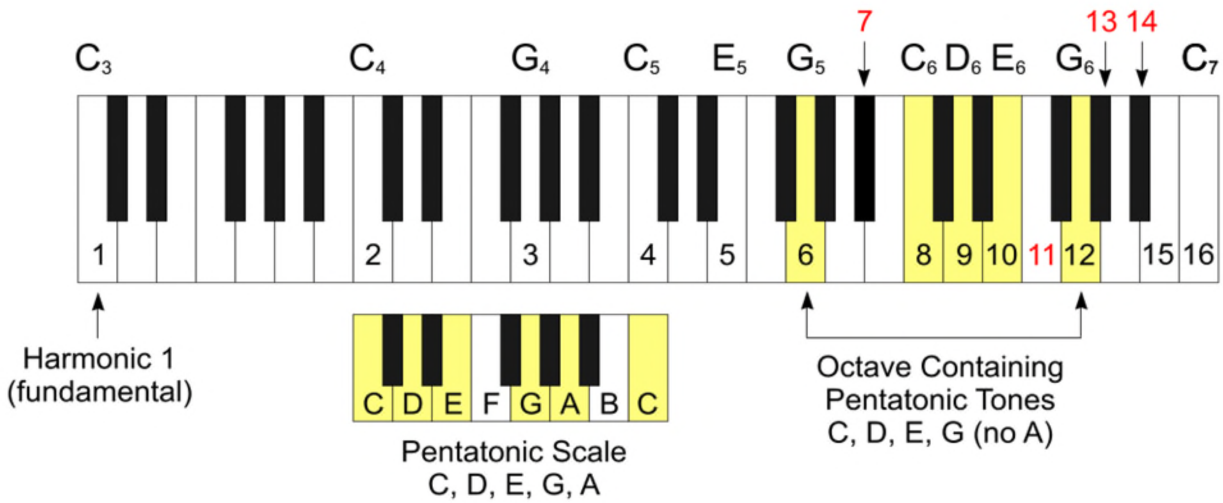

Figure 2. First sixteen harmonics and their best matching positions on the keyboard. The pitches of harmonics 7, 11, 13, and 14 are not very close to their respective keyboard notes. Key C_3 is 130.8 Hz.

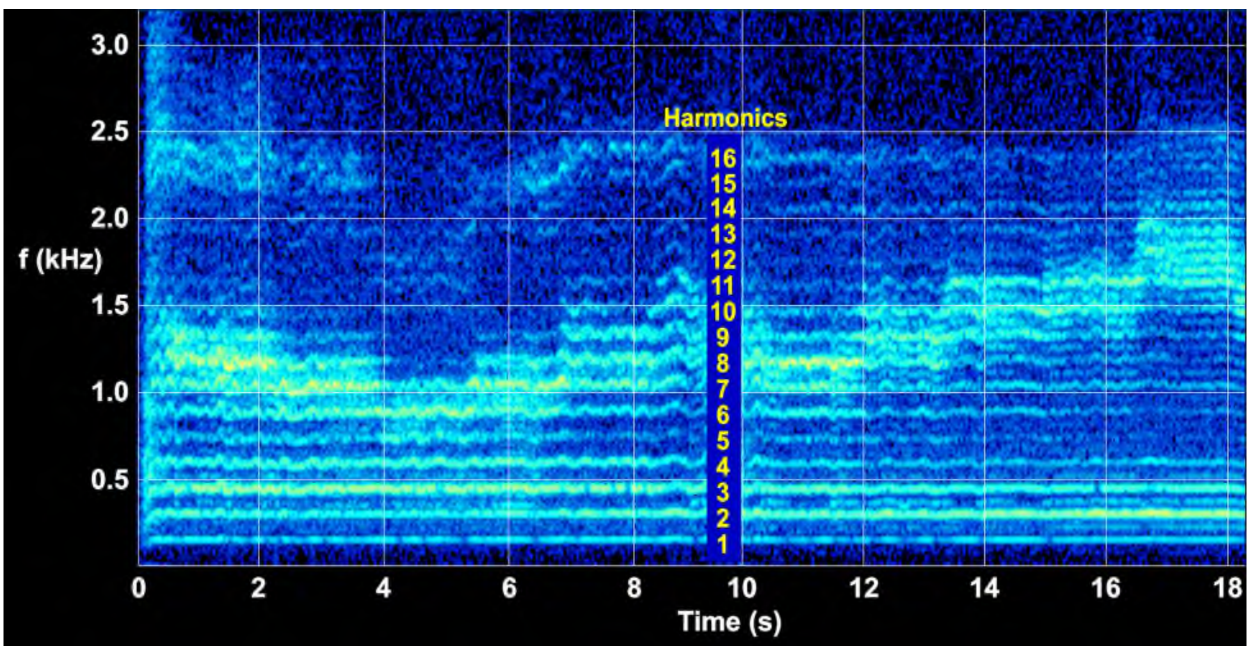

Figure 3. Spectrogram of coauthor David Wilken throat singing harmonics in the following order: H8, H7, H6, H7, H8, H9, H10, H11, and H12. Note the brightening of these harmonics as they are sung during the time frame of the spectrogram.

A second consideration is the Asian aesthetic preference for the pentatonic scale. The common pentatonic scale can be easily demonstrated by restricting keyboard notes to the black keys on the piano. Consider five black keys on the piano: a triplet of black keys and the adjacent doublet to the right (higher in pitches). The three black keys in the triplet are spaced by intervals of two semitones, as are the two black keys in the doublet. The triplet and doublet are separated by an interval of three semitones.

Harmonics H8, H9, H10, and H12 coincide with four of the tones in the pentatonic scale, where H8, H9, and H10 are equivalent of the black-key triplet and H12 is the lower pitch in the black-key doublet. It is natural that Tuvan singers focus on these four harmonics. Levin and Edgerton point out the importance of these harmonics in their paper 'The Throat Singers of Tuva' [5], and add H6 for the 'scale used by Tuvan throat-singers'. Harmonic H6 is included since it is an octave lower than H12 and is therefore located in the lower adjacent octave of the four pentatonic notes. The harmonics are also shown on the musical staff in [5]. Tuvan throat singers avoid harmonics H7 and H11 as these tones fall outside the pentatonic scale.

As mentioned above, harmonics H8, H9, and H10 match the pitches of Do, Re, Mi. Harmonic H12 is Sol. If a keyboard is available in a small class, ask a student to play 'Mary Had a Little Lamb' with these notes. If a keyboard is not available, it is actually better for a larger group of students to pull up an online keyboard projected in class and have a musical student play the song by clicking on the keys with a mouse. Then everyone in a larger class can easily see the demonstration as well as hear it.

Figure 3 is a spectrogram of throat singer coauthor David Wilken bringing out harmonics H6 through H12 through overtone singing. He starts with H8 and proceeds downward to H7 and H6. He then swings upward to achieve H7, H8, H9, H10, H11, and H12. Ask students to estimate the fundamental. Notice that the 7th harmonic is very close to the grid line at 1.0 kHz. From this measurement, the fundamental is 1000 Hz / 7 = 140 Hz, to two significant figures. Note that this pitch is near C_3 = 130.8 Hz of figure 2. As mentioned earlier, Tibetan monks sing an extremely low fundamental of 75 Hz. Their pitch is near D_2 = 73.4 Hz on the keyboard.

A video [7] is provided for readers and students to watch and hear Tuvan throat singing. Real-time spectrograms appear in the video so that the singing and visual representation of the singing can be experienced simultaneously. Coauthor David Wilken concludes with the Tuvan folk song *Artii-Sayir* in our video. The title *Artii-Sayir* can be translated as 'On the Other Side of the Dry Riverbed' or 'The Far Side of a Dry Riverbed' [5]. Western musical notation for the song can be found in [5].

Conclusion

A discussion of throat singing is a very interesting application of the physics of harmonics. Fourier's theorem, where a periodic wave is expressed as a sum of harmonics, is clearly evident in the spectrograms analyzing throat singing. The topic is also interdisciplinary with connections to music. Furthermore, throat singing presents an opportunity to integrate multiculturalism into a science course, where an Asian musical aesthetic is experienced and studied. The spectrogram presents a beautiful visualization of the physics and music.

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References

[1] British Documentary 1988 *The Quest for Tannu Tuva* (UK: British Broadcasting Corporation TV Series Horizon).
1989 *Last Journey of a Genius* (US: Public Broadcasting Service TV Series NOVA) (a revised version appearing in the United States)
[2] Leighton R 2000 *Tuva or Bust! Richard Feynman's Last Journey* 3rd edn

(London: W. W. Norton & Company Ltd.)
[3] Aksenov A N 1973 Tuvin folk music *Asian Music* **4** 7-18
[4] Smith H, Stevens K N, and Tomlinson R S 1967 On an unusual mode of chanting by certain Tibetan lamas *J. Acoust. Soc. Am.* **41** 1262-4
[5] Levin T C and Edgerton M E 1999 The throat singers of Tuva *Sci. Am.* **281** 80-7
[6] van Tongeren M C 2002 *Overtone Singing: Physics and Metaphysics of Harmonics in East and West* (Amsterdam: Fusica), p 7
[7] Ruiz M J 2017 *Video: Tuvan Throat Singing and Harmonics* http://www.mjtruiz.com/ped/tuva/

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