CHAPTER 3

A Subharmonic Vibratory Pattern in Normal Vocal Folds

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This study observes in detail an $F_0/2$ (sounding an octave below an original tone) subharmonic vibratory pattern produced in a normal larynx. Simultaneous electroglottographic and photoglottographic measurements reveal two different open phases within a subharmonic cycle—the first shorter with a simple shape, the second longer with a shape containing a "ripple." Such parameters as the large open quotient (ca. 0.8) and the high airflow values (ca. 1000 cm$^3$/s) distinguish this phonation from the vocal fry (pulse) register. Using an electronic divider to track the subharmonic frequency, a method has been developed to observe the subharmonic vibration of the vocal folds stroboscopically. The stroboscopic visualization reveals an unusual mucosal movement during the "ripple," characterized by an opening movement of the upper margins, which interrupts the closing movement of the vocal folds. An explanation is offered that this vibratory pattern arises as a consequence of detuning of the usually identical frequencies of the dominant modes of the vocal folds, with 3:2 entrainment replacing the normal 1:1 pattern.

KEY WORDS: vocal folds, stroboscopy, vibrational modes, bifurcation, entrainment

It has been shown that the voice source constitutes a nonlinear dynamic system that may fulfill the conditions for a chaotic vibration of the vocal folds (Titz, Baker, & Herzl, 1993). Under certain conditions subharmonic frequencies may occur in the voice. The creation of subharmonic frequencies can be explained as a special case of behavior of a nonlinear system. In the larynx such a vibratory pattern has most often been assumed to result from left-right asymmetry of the vocal folds (Ishizaka & Ishihiki, 1976; Ishihiki, Tanabe, Ishizaka, & Broad, 1977; Steinecke & Herzl, 1995; Titz, 1994; Titz, Baker, & Herzl, 1993), although subharmonic phonations in the absence of such asymmetry have also been modelled (Berry, Herzl, Titz, & Krischer, 1994; Herzl, Steinecke, Mende, & Wermke, 1991) and enumerated (Herzel, Berry, Titz, & Saleh, 1994), suggesting that subharmonic phonation may have other origins.

The purpose of the present study is to make a detailed empirical description of the subharmonic vibratory pattern that we observed, in an earlier study (Švec & Pešák, 1994), accompanying voice breaks. Electro- and photoglottography, as well as videostroboscopy, are used for observation of a normal male larynx in vivo. Besides helping to clarify how subharmonic and irregular vibration might be generated in a normal larynx, the results may provide information relevant to the modelling of the voice source.

Method

A Subharmonic Vibratory Cycle

The vocal sound investigated in the present article was produced under the following conditions: a male subject, sustaining a tone of moderately low pitch in the
chest register, simultaneously (a) made a large increase in airflow (at least doubling the normal flow), and (b) slightly reduced the adduction of the vocal folds. The intended result is a marked loss of original periodicity. Apart from irregular vibration, this voicing may result, under certain conditions that will be discussed later in this article, in a clearly perceivable $F_0/2$ subharmonic frequency, sounding an octave below the original tone. This vocal phenomenon will be the main object of attention of the present study.

Figure 1 shows the occurrence, during the vocal maneuver described above, of a subharmonic frequency as registered in a narrow-band spectrogram. The original frequency ($F_0$) is about 140 Hz. The arrow marks the entry of a clearly observable (and clearly audible) subharmonic frequency of about 70 Hz. In terms of nonlinear dynamics a period-doubling bifurcation arises here (see, e.g., Herzel, Berry, Titze, & Saleh, 1994; Titze, Baken, & Herzel, 1993). The transition (bifurcation) from the original to the subharmonic frequency will be investigated in detail.

An electroglottograph (Laryngograph) and a photoglottograph (Frejkaer-Jensen LG 900) were used to obtain direct information about the vibration of the vocal folds. Figure 2 depicts the EGG and PGG signals (recorded simultaneously with the audio signal whose spectrum is analyzed in Figure 1) during the time segment containing the period-doubling bifurcation. In the PGG signal it is evident how the original simple open phase (C) changes to create the subharmonic cycle. First, two different open phases (E,F) can be distinguished in the signal. A moment later, the second opening (F) is modified by a "ripple," and finally we can identify three local maxima (I,J,K) within a single subharmonic cycle. The change of the original period $T$ (indicated in Figure 2 between two moments of initial contacts of the vocal folds) into two alternating periods $T_S$ (short) and $T_L$ (long) can be observed in the EGG signal. The resulting subharmonic period $T_{sub}$ is the sum of the periods $T_S$ and $T_L$, and it is about twice as long as the original period $T$.

Not only the duration of periods but also amplitude of contact between vocal folds is modified. The originally similar negative peaks in the EGG signal (D) split into two different alternating peaks (S,W—strong, weak), indicating two different areas of contact alternating within a subharmonic cycle. Note that the change from the E,F-pattern to I,J,K-"rippled" pattern, visible in PGG curve, is not reflected in the curve of the EGG, which is insensitive to phenomena occurring within the open phase of the glottis.

A "rippled" subharmonic cycle is presented in detail in Figure 3. A sudden drop in the EGG curve clearly indicates the moment of contact of the vocal folds (the start of phases $C_S$, $C_i$ in Figure 3), which corresponds with the lowest point in the PGG curve. Another change in the scope of the EGG curve (designated as ends of phases $C_S$, $C_i$ in Figure 3) reflects most probably the complete separation of the vocal folds. If we use the time segments C and O marked in Figure 3 for an estimate of the open quotient (OQ), we obtain values $O_S/T_S = 0.68$, and $O_L/T_L = 0.84$ for the periods $T_S$ and $T_L$, respectively, or $(O_S + O_L)/T_{sub} = 0.77$ for the whole subharmonic cycle. In accordance with the definition of the abduction quotient (Titze, 1984, 1988a, 1994), these values are evidence of weak adduction of the vocal folds in this phonation.

The short-long pattern presented here could be confused with a vocal fry (pulse) register in which a subharmonic frequency can appear as well, and it is important to distinguish between the two vibratory patterns. The vocal fry register is usually characterized by very low values of the

**FIGURE 1.** Narrow-band spectrogram of an audio signal of male voice producing $F_0/2$ subharmonic frequency (period-doubling bifurcation—marked by arrow) during a vocal maneuver. The subject was instructed to sustain a tone of moderately low pitch in the chest register (here ca. 140 Hz) and then simultaneously (a) to increase the airflow (the measured increase was roughly from ca. 300 cm$^3$/s to ca. 1000 cm$^3$/s), and (b) to slightly reduce the adduction of the vocal folds. Where the adduction and airflow return to the original adjustment, the subharmonic frequency ceased. The dashed lines mark a time-interval investigated in Figure 2 in more detail.
open quotient (ca. 0.2 [Hollien, Girard, & Coleman, 1977]) and low mean volume velocity of air flow (ca. 40 cm$^3$/s [Hollien, 1974; McGlone & Shipp, 1971]), whereas the measurements of subharmonic phonation described here show exceptionally high values for both these parameters (OQ ca. 0.8, flow ca. 1000 cm$^3$/s). The value for flow is exceptionally high not only with respect to vocal fry register, but also with respect to normal phonation (see, e.g., Schutte, 1980).

**Application of Videostroboscopy**

Considering the EGG and PGG curves in Figures 2 and 3, the question arises whether such a vibratory pattern is the result of nonsynchronous movements of the left and right vocal folds. The PGG and EGG signals provide no information about possible asymmetries in the movements of the folds; therefore we used videostroboscopy to investigate this question. Our first videostroboscopic attempts to observe the subharmonic vibratory patterns of the vocal folds with commercially available equipment were unsuccessful because of an evident triggering problem, and it was necessary to modify the videostroboscopic system by adding an electronic divider for an adequate observation of the subharmonic pattern.

**Application of the electronic divider.** The alternation of the periods $T_S$, $T_L$ during the subharmonic vibratory pattern causes an instability of the triggering signal of the stroboscope, resulting in apparently noncontinuous motion of the vocal folds. To solve this triggering problem an electronic divider was constructed to transform the EGG signal into a square-wave signal related to the subharmonic frequency. This square-wave signal was fed to the stroboscope as the signal that triggered the light flashes. The whole transformation is depicted in Figure 4.

The advantage of this transformation is apparent from Figure 5. Although the EGG signal is changed substantially during the period-doubling bifurcation, the divider signal, being already subharmonic, maintains its shape and frequency, properly triggering the stroboscope. The result was a reproducible visualization of a subharmonic vibratory pattern of the vocal folds.

**Experimental setup.** The experimental setup is schematized in Figure 6. An EGG (Laryngograph) signal is delivered to the electronic divider. The divider signal is sent to the stroboscope (Brüel & Kjær type 4914) controlling the light flashes, which are led via an optical cable into a von Stuckrad 90° rigid endoscope (R. Wolf, Knittlingen), providing the image of the vocal folds. A Hitachi CCD camera with a control unit registers this image, which is fed to a PC (IBM clone, type 286).
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The EGG signal is digitized by an A/D card and presented on the computer screen by means of software developed in the Voice Research Lab in Groningen. Via a Magni VGA Producer Pro Image Card, the EGG curve is then presented together with the camera image on a monitor. The resulting video signal is recorded by an s-VHS recorder (Blaupunkt RTV-915 HI-Fi). The audio signal from a microphone mounted on the camera and the signal of the divider are recorded in the audio channels. (The purpose of recording the divider signal is to recheck the divider, as its improper function could substantially confuse the resultant recorded stroboscopic motion of the vocal folds.) Further, the divider and triggering signals are simultaneously monitored on an oscilloscope to check the proper functioning of the divider during recording.

The phonation was furnished by the first author, a 26-year-old tenor-baritone and amateur pop-jazz singer, whose larynx showed no pathology. Representative examples of subharmonic cycles were carefully selected from the data recorded on tape (see Appendix A for potential pitfalls in videostroboscopy) and further processed (Appendix B).

Results

The resulting videostroboscopic view of a single subharmonic glottal cycle is depicted in Figure 7, and corresponding sketches of vocal folds are shown in Figure 8. The frequency of the subharmonic glottal cycle presented stroboscopically is 60 Hz. Using the degree of glottal opening as a reference, the numbers of the consecutive images of the vocal folds were manually placed along a PGG subharmonic cycle (depicted at the bottom of Figures 7 and 8), which had been taken from the same subject during a different experimental session.

Frames 1–7 depict the first opening movement of the vocal folds. Both the vocal folds move laterally, the right vocal fold being slightly delayed with respect to the left one. In frame 8 the maximum opening is reached. In frames 9–13 the vocal folds exhibit closing movement. Signs of mucosal movement were observed here on the surface of the left vocal fold (frame 11) and on the right vocal fold (frame 12). In frame 13 the vocal folds are closed. Then they open again (frames 14–18). The following maximal opening (frame 18) is not as wide as the one in the previous open phase (frame 8). The vocal folds begin a second closing movement (frames 19–21). This movement is, however, interrupted by a lateral motion of the upper margins of the vocal folds, creating the “ripple” seen in the PGG curve.

This “ripple” motion is first observed in frame 22 on the anterior part of the left vocal fold. In the same frame the lower margin of the vocal fold becomes visible, and a discrepancy becomes apparent between the movements of the upper and lower margins. The upper margins move laterally (frames 22–27), whereas the lower margins exhibit a medial movement until frame 24, where they reach the most medial position. In frames 25–28 the lower margins reverse direction and move laterally, and they are hidden in frame 29. The third maximal glottal opening within the subharmonic cycle occurs in frame 27, corresponding to the third

FIGURE 5. EGG signal and divider signal during a period-doubling bifurcation. Note that although the EGG signal is changed substantially during the bifurcation, the divider signal maintains its shape and frequency.
maximal opening of the upper margins. Close examination of the left vocal fold reveals a propagation of the lateral movement from anterior to posterior (frames 22–27). Frames 28–31 show the final closing. A mucosal wave is observed on the right vocal fold just before the definitive closure (frame 31). Frames 32 and 33 present the end of the cycle: The glottis is closed.

**Discussion**

Although some degree of left-right difference between the vocal folds is noted, the slight evidence of asymmetry observed in this detailed description of the vocal fold movement seems insufficient to create the marked disturbance of the normal pattern of vibration. Thus we dismiss, in the present case, the explanation of subharmonic phonation as a result of asymmetrical movement.

The most salient and peculiar feature of this subharmonic cycle is the "ripple" in the second open phase (frames 22–28), created when lateral movement of the upper margins interrupts the closing movement of the vocal folds. Such an effect is not observed during normal phonation. During the "ripple" the movement of the upper margins precedes that of the lower margins; thus this effect is distinct from the normal mucosal movement in chest register, in which the upper margins lag behind the lower margins of the vocal folds (Baer, 1975, 1981; Berke & Gerratt, 1993; Fams-worth, 1940; Hirano, 1981; Moore & von Leden, 1958). This "preceding" movement of the upper margins is observable only during the "rippled" opening; in the two other openings (frames 1–7 and 14–18) the lower margins are not clearly visible.

The observed anomalous mucosal movement can be related to desynchronization of the normal modes of the vocal folds (for theory of normal modes in vocal folds see, e.g., Titze, 1994; Titze & Strong, 1975). Let us first consider the relationship between the mucosal wave and the normal modes of the vocal folds. As noted by Titze (1994), a mucosal wave model (Titze, 1988b) and a two-mass model of the vocal folds (Ishizaka & Flanagan, 1972) are equivalent in forming similar (alternately convergent and divergent) shapes of the vocal folds during vibration. In the two-mass model the two normal modes are synchronized to vibrate with identical frequencies (the so-called 1:1 entrainment) to produce a normal mucosal movement (see, e.g., Herzel, Steinke, Mende, & Wermke, 1991; Ishizaka, 1988; Ishi-zaka & Flanagan, 1972; Titze, 1976). In higher-order models, as well, the normal mucosal movement is approximated when the dominant modes (empirical eigenfunctions) vibrate with identical frequencies (Berry, Herzel, Titze, & Krisher, 1994). Taking into account these relationships between the modes and mucosal movement, an anomalous mucosal movement might be related to the fact that the frequencies of the modes become unequal. Indeed, by altering the
frequencies of the modes, as a result of varying the parameters of the models, one can obtain various vibratory patterns, including subharmonic regimes, toroidal vibration, and chaos (Baken, 1995; Berry, Herzel, Titze, & Krischer, 1994; Herzel, Steinbecke, Mende, & Wemke, 1991; Titze, Baken, & Herzel, 1993).

From the theory of superposition in nonlinear systems (e.g., Sedlák, 1956) it is well known that the resultant frequency is halved (the resultant period is doubled) when a vibration with an original frequency $f_1$ is combined with a second one having frequency $f_2$ related to the original one by the ratio $f_2/f_1 = 3:2$. For instance, a subharmonic frequency of 70 Hz is produced (as a "difference tone") when the original vibration with a frequency of 140 Hz is combined with a second vibration having a frequency of 210 Hz (3/2 times 140 Hz). Accordingly, we shall explore the possibility that the 3:2 frequency ratio is a determinative factor in the measured subharmonic phonation and consider whether this ratio can be found in the properties of the vocal folds.\(^1\)

Empirical evidence for this hypothesis appears in connection with voice breaks from the chest (modal) to falsetto register. In our previous study we measured a "spontaneous break interval" (i.e., a frequency jump during a voice break produced without intending any specific pitch interval—

\(^1\)The reader is referred to studies of Feigenbaum (1983) or Titze, Baken, & Herzel (1993) for other possible nonlinear mechanisms of production of subharmonic patterns (for instance, the phenomenon of period-doubling bifurcation appears as a precursor to chaotic behavior in nonlinear systems) as well as for more general theoretical background of the nonlinear dynamics.
FIGURE 8. Sketches of vocal folds during their subharmonic vibratory cycle. Sketches 22–28 show the creation of the “ripple” in the second open phase.

Contradistinction to, e.g., yodelling technique where the pitch interval during the breaks is intended to have a determined value, produced by the same subject as analyzed here, close to that of a perfect fifth, constituting a frequency ratio of 3:2 (Švec & Pešák, 1994). Subsequent informal investigations on a small number of other subjects revealed interindividual differences in magnitudes of the spontaneous break interval that were reflected in differing abilities of subjects to produce this subharmonic pattern. Subjects with a spontaneous break interval substantially different from the 3:2 value (intervals up to more than a tenth [5:2] were observed) were not able to produce the $F_0/2$ subharmonic pattern by our vocal maneuver, and their attempts usually resulted in irregular vibration. The closer the interval of the break from the chest to falsetto register was to the 3:2 value, the more easily the subjects could produce this $F_0/2$ subharmonic pattern. (In this sense the subject investigated in this study appeared to be particularly well suited for production of this phonation.)

The 3:2 ratio can also be compared with data in the literature concerning the resonance frequencies of natural modes of the vocal folds. Titze (1976) calculated the natural frequencies of the normal modes in the two-mass model of the vocal folds as 120 and 201 Hz for typical Ishizaka and Flanagan (1972) parameters. The ratio between these frequencies is almost exactly 5:3 (in musical terms, a major sixth), thus slightly higher than the 3:2 (a perfect fifth) ratio considered here. Measurements of the resonance characteristics of the normal human vocal folds in vivo and in vitro (Kaneko, Masuda, Shimada, Suzuki, Hayasaki, & Komatsu,
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1987) confirm these values. Kaneko et al. established values for the two dominant resonance frequencies in several subjects, yielding ratios ranging from ca. 3:2 up to above 2:1. Considering the natural variability of the vocal fold parameters, the 3:2 entrainment appears to be a rather specific but plausible alternate mechanism of vibration of the vocal folds when the normal 1:1 entrainment of the modes is desynchronized. More detailed information about the mechanism of the vibration of the vocal folds can possibly be obtained from careful modelling studies, which go beyond the scope of the present study.

Besides the above-mentioned limitations pertaining to the individual voice in producing this pattern, a further limitation on the acquisition of data is that a stable subharmonic phonation of relatively long duration is necessary to produce an acceptable stroboscopic cycle (in the present case, more than 3/4 s). Moreover, in order to obtain useful PGG data, the subject’s epiglottis must leave a clear path between the glottis and the sensor. Thus our data, particularly those from PGG and stroboscopy, are not easily obtainable from every person. Measured EGG and audio data, however, together with the spectral analysis and perceptual evaluation of phonations of other subjects, confirm that the observed phenomenon is not just an individual peculiarity.

One of the merits of the study is that it describes data that are not easily obtainable. However, although what we have presented here as 3:2 entrainment appears to be specific to voices of a particular type, the coherence of the data with established theoretical considerations justifies the claim that they point to generally valid properties of the vocal folds.

Conclusion

In the case of a subject exhibiting a “spontaneous” chest-falsetto break interval close to a musical fifth (i.e., 3:2 value) a \( f_2/2 \) subharmonic vibratory pattern of the vocal folds (period-doubling bifurcation) has been observed during a pharyngeal maneuver characterized by high airflow and low adduction. Stroboscopic visualization of such a pattern of the vocal folds can be accomplished with the help of a simple electronic divider. The experimental data together with theoretical considerations suggest that the observed subharmonic vibratory pattern of the vocal folds might result from a combination of two vibrational modes whose frequency ratio is \( f_2/f_1 = 3:2 \). The results are presented as evidence that the normal 1:1 entrainment of the dominant vibrational modes of the vocal folds is replaced by 3:2 entrainment in the case under study.

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References


Appendix A

Potential Pitfalls in Videostroboscopy

As the motion observed by means of stroboscopic light is illusory, one could encounter possible pitfalls that could interfere with the videostroboscopic observation of the vocal folds:

1. Frequency perturbations of observed vibration are reflected in perturbations within stroboscopic cycles (see, e.g., Hirano & Bless, 1993). Larger frequency instabilities result in apparent discontinuities in the stroboscopic motion of the vocal folds. Therefore the subject must keep the phonation as stable as possible.

2. The functioning of the camera (frequency of 50 Hz) is independent of the stroboscope (varied frequency triggered by the larynx). Therefore, (a) if there is more than one stroboscopic flash within the integration time of the CCD camera (usually ca. 20 ms), these are registered within a single half-frame, sometimes producing a fuzzy image (possible source of a lack of clarity of frame 10 in Figure 7); (b) if the CCD camera has functional “gaps” between integration periods, a stroboscopic flash that falls in a “gap” will not be registered.

These pitfalls cannot be entirely avoided in videostroboscopy. They should be taken into consideration in processing the video-frames, in order to recognize artifacts in stroboscopic motion of the vocal folds.

Appendix B

Processing of Video Frames

Representative examples of subharmonic cycles of vocal folds were selected from the s-VHS tape and copied on a U-matic videotape. Using half, instead of whole, video-frames (50 Hz instead of 25 Hz) resulted in a smoother rendering of the motion of the vocal folds. One stroboscopic cycle contained an average of 33 half-frames. Each half-frame image of a selected cycle was captured and put into memory by means of an U-matic video recorder (Sony VO 5800PS) and a Video Production System (FORA type VPS-560P). Then the half-frame images were printed out on a color video printer (Hitachi model VY-255). The result was a series of 33 pictures corresponding to different phases of the subharmonic glottal cycle. These appear in Figure 7.

The same series of half-frames were digitized in a computer (Macintosh Quadra 950) by means of a digital video card (SuperMac-VideoSpigot), using the software Screenplay (version 1.1.1). Those frames were further processed by software (Adobe Photoshop, version 2.0.1), converted into black and white, and exported in TIFF files. These TIFF files were used as models for tracing sketches of the vocal folds, which was done on a PC computer (386 SX) using Corel Draw (version 3.0) software. The sketches were traced carefully by hand to obtain pictures illustrating the most substantial visible features of the motion of the vocal folds (Figure 8). No quantitative analysis of the images was done.