On vibration properties of human vocal folds
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CHAPTER 1

Introduction
Introduction

There are two main aims of the dissertation:

• to provide new information on discontinuities in the transition between chest and falsetto voice registers. (As shown here, the question of transition between chest and falsetto registers is highly complex and addresses the problem of the basic underlying mechanism of the vocal-fold vibration).

• to develop a (cost-friendly) method which would provide more detailed information on the vibratory behavior of the vocal folds. The need for a new method arose from the fact that currently available methods visually observing vocal-fold vibrations are either not capable of observing fast phenomena (stroboscopy), or are not easily available due to the high costs (high-speed imaging systems).

In accordance with these two aims, the dissertation is divided in two sections. The first part brings original experiments exploring phenomena related to abrupt chest-falsetto transition and provides new information on resonance properties of the vocal folds. The second part describes development and application of an original method, called “videokymography,” for examination of vocal fold vibration.

SECTION I: Voice registers, bifurcations, resonance properties of the vocal folds

Chest and falsetto voice registers

When a naïve (particularly male) singer sings an ascending scale with a moderate loudness, around the frequency of ca. 300–350 Hz (tones D₄ – F₄) he reaches a point of instability where the voice “breaks” (e.g., [41; 94; 95; 122]). Pitches above this limit cannot be sung in the same way but only with a different, “thinner,” voice quality. The division of the singing voice into two gross parts is an important issue in (professional) singing which has been described already for centuries (for historical overview see, e.g., [82; 109]). These two qualities of voice have been traditionally designated as “chest” (or “modal”) and “falsetto” registers, even if the terminology problem is far from resolved. The problem of voice registers represents one of the most controversial and least-understood topics of singing voice. The physiological reason for the division of the singing voice into the chest and falsetto registers has not been sufficiently explained yet.

Valuable overviews on registers from a scientific point of view can be found, e.g., in publications of van den Berg [11; 12]; Large [82]; Hollien [65]; van Deinse [128]; Hirano [59]; and Titze [122]. Among the potential factors that can play a role for the occurrence of the voice registers, there are (a) the mechanism of oscillation of the vocal folds [12; 15; 32; 56; 82; 99; 104; 122], (b) resonance of the vocal tract [82; 93; 133], (c) interaction of the subglottal and supraglottal resonances with the vocal-fold oscillations [3; 91; 119; 122], as well as (d) the perceptual factors [23; 24; 76; 84; 113; 122]. In this book the attention is focused mainly on the role of the vocal folds.

It has been known that the chest and falsetto registers differ in the amount of tissue which is incorporated in the vibration of the vocal folds [11; 12; 15; 32; 40; 90; 99; 104; 108]. In the simplest representation, the vocal fold is divided in two tissue layers, “cover” (created by mucosa and ligament of the vocal fold) and “body” (mostly created by the thyroarytenoid, TA, muscle) [56; 57]. In chest register, both the body and cover participate in the vibration of the vocal folds while in falsetto only the cover is involved [56; 57; 60; 125; 126] (Fig. 1). In falsetto, the frequency is increased mostly passively, by longitudinal stretching (elongating) the cover of the vocal folds by means of the activity of the cricothyroid (CT) muscle, whereas when raising the frequency in the chest register, the stretching of the vocal fold cover is accompanied also by an active contraction of the TA muscle forming the body of the vocal fold [11; 56; 57; 59; 60; 62; 122; 126; 129].

The differences between the chest and falsetto registers are reflected in specific vibratory patterns of the vocal folds —the chest register is characterized by more pronounced vertical phase differences [5; 56; 57; 104; 107; 122], larger contact area [80; 102; 106; 132], larger closed quotient¹ [58; 80; 122], and lower

¹ Closed quotient (CQ) is calculated as the duration of the closed phase of the vocal folds divided by the duration of the whole vibratory cycle [58; 98; 117]. Sometimes instead of closed quotient an open quotient (OQ) is used, which is calculated as the duration of the open phase of the vocal folds divided by the duration of the whole vibratory cycle. (The open quotient is closely related to the closed quotient since it holds OQ + CQ = 1)
fundamental frequencies, although there is a considerable range of fundamental frequencies where the two registers overlap in most voices. (See, e.g., Fig. 2 in Chapter 8 for an example of the two different vibratory patterns).

One of the practical singing issues is the problem of the transition between the chest and falsetto registers in singing. Different singing styles approach the register transition differently. The western operatic singing tradition aims at eliminating any discontinuity by “equalizing” the registers, reaching a “smooth register transition” and a “uniform voice quality” across the whole range of singing (e.g., [41; 82; 83; 86; 94]). A successful accomplishment of this goal usually requires a lot of practice. An “improperly balanced” voice leads to an involuntary spontaneous “register break” or “abrupt register transition.” Such an abrupt register transition is usually accompanied by a spontaneous sudden change (leap, jump) of frequency [22; 102–104].

While the western operatic tradition considers such sudden changes accidents to be avoided, some other singing traditions—for example yodeling and country and western—voluntarily exploit the chest-falsetto jumps in a controlled way for artistic purposes. The chest-falsetto jumps are also related to specific voice disorders, such as “mutational dysphonia,” and are generally known as pitch jumps occurring spontaneously and out of control during speech [44; 100; 134].

Very few objective data on the chest-falsetto discontinuity have been available. The original goal of the research presented in this book was to investigate the mechanism of the spontaneous sudden changes of frequency of the vocal-fold vibration, in more detail. Philosophically taken, understanding better the underlying principle of the register jumps should be helpful also in understanding the mechanism of a smooth register transition which is based on eliminating these abrupt changes.

Titze [120; 122] formulated, on a basis of investigations of several authors, two hypotheses on the possible mechanism of the spontaneous register transitions:

A) the sudden change from chest to falsetto arises due to a sudden spontaneous relaxation of the TA muscle (maximum active thyroarytenoid stress hypothesis). This change happens spontaneously especially at high frequencies of the chest register in which the activity of the TA muscle reaches the maximal value that cannot be sustained any longer.

B) interaction of the subglottal (tracheal) resonance with the voice source negatively influences the vocal fold oscillation at specific phonational pitches and causes a change in the resulting voice quality (subglottal resonance hypothesis).

As Titze noted, however, from these two, only the first hypothesis would explain also the sudden changes of fundamental frequency observed during the chest-falsetto jumps [120].

Abrupt frequency changes are not exclusively related to voice only. A well-known example can be taken from a simple musical instrument – a flute. When an input air pressure of (or the airflow velocity in) a flute is continuously increased, the original tone suddenly leaps into another, higher frequency (“overblown-flute phenomenon”) [29; 31; 130; 131]. This effect is known to be caused by existence of a number of resonance frequencies of the flute. When “overblown,” the pitch jumps from a lower to a higher resonance frequency. Since the resonance frequencies reflect the given setup of the flute [29; 31; 112; 114], the frequency jump reflects inherent information on the flute properties. This leads us to express a hypothesis that the pitch jumps observed during the chest-falsetto transition might, analogously, reflect inherent vibration properties of the vocal folds and be related to their resonance frequencies.

The aim of Chapter 2 was to explore experimentally whether the “overblown flute” analogy can be adapted for studying the properties of the voice source. Two main questions of the chapter are:
1) Is it possible to elicit pitch jumps in voice analogously as in a flute, i.e., by increasing the phonatory airflow and “overblowing” the voice source to a different frequency?

2) If yes, what is the magnitude of the frequency change? (In a flute, the frequencies after and before the leap are approximately related by an integer-number ratio, i.e., 2:1, 3:2, 4:3, etc. What is the ratio in the vocal folds?)

A voice maneuver was utilized in which chest-falsetto pitch jumps were elicited by smoothly increasing the phonatory airflow while slightly abducting the vocal folds. The magnitudes of pitch jumps were measured and documented throughout the whole frequency range in a normal male subject.

Besides chest-falsetto jumps, also production of an \( F_0/2 \) subharmonic frequency (sounding an octave below the original tone) was observed in the experiment. The occurrence of a subharmonic frequency evokes a question on how the subharmonic phonation is created in the vocal folds? Most often it has been assumed that such a vibratory pattern results from desynchronization of the oscillations of the left and right vocal folds, especially in pathological cases [69; 70; 77; 110; 122; 123]. Here, however, the subharmonic frequency arose in non-pathologic vocal folds in which no large asymmetry is presumed. Models predicted that the subharmonic pattern might also have other origins than asymmetry and could arise with both the vocal folds synchronized [18; 54]. Information on the oscillation of true, non-pathological vocal folds responsible for such a phonation has been missing, however. One of the main reasons for the lack of information have been the difficulties of routinely available videostroboscopic systems with investigating phonations deviating from a simple periodic vibratory pattern (see Section II, below).

Chapter 3 describes the phonatory maneuver, designed in chapter 2, in more detail and devotes the attention to the behavior of the vocal folds during the subharmonic phonation. In order to provide the complete, detailed description of the subharmonic vibratory pattern of the vocal folds, a video-laryngostroboscopic setup was modified by constructing a special electronic divider which allowed to track the subharmonic frequency. Laryngostroboscopic images were obtained, documenting the shapes of the vocal folds during the subharmonic vibratory cycle in detail. Besides the laryngostroboscopic images, the vibratory pattern of the vocal folds was documented also by means of electroglottography and photoglottography and the mean airflow rate values were measured via pneumotachography.

**Theory of nonlinear dynamics and bifurcation phenomena**

In 1990s, the theory of nonlinear dynamics was introduced in voice physiology/pathology and applied to explain phenomena related to irregularities, subharmonic oscillations and sudden changes in vocal fold behavior [1; 4; 6; 7; 30; 47; 48; 54; 92; 123]. It has been realized that the voice source presents a highly nonlinear vibratory system. Nonlinearity has been found, e.g., in elastic properties of the vocal-fold tissues (stress-strain characteristics [25; 57; 71; 123; 124]), in the pressure-flow relation in the glottis [68; 123] or in collision of the vocal folds during their vibration [68]. It has been shown that voice source exhibits phenomena that are similar to effects known from the theory of nonlinear dynamics [47; 52; 54; 69; 70; 92; 110]. The theory also introduced new methods for analysis of the vocal fold vibration [6; 8; 9; 46; 49–51; 89; 123].

One of the typical effects known from the theory of nonlinear dynamics is termed a “bifurcation.” This term designates a sudden qualitative change in the behavior of a nonlinear dynamic system induced by a gradual, smooth change of an input parameter [16; 96; 123]. Studies with vocal-fold models have already indicated that various register transitions might be explained as bifurcations [47; 88]. Also, experiments with excised canine larynges indicate the bifurcation origin of the spontaneous register transitions [19;107].

Chapter 4 explores a bifurcation hypothesis on the mechanism of chest-falsetto jump, which presents an alternative to the Titze’s hypothesis of maximum active thyroarytenoid stress: the abrupt chest-falsetto transition can arise spontaneously, without any necessary sudden change in adjustment of the laryngeal muscles.

Data from the van den Berg instructional film *The Vibrating Larynx* [15], showing abrupt chest-falsetto transitions in an excised human larynx, were analyzed. The film demonstrates some experiments on excised human larynges carried at the University of Groningen in the late 1950s by van den Berg and Tan [10; 12–15; 115]. In their pilot experiments, the abrupt register transitions were noticed, but not analyzed in detail.

Besides the excised larynx, the chapter investigates the chest-falsetto leaps in three singers (one female and two male) and returns to the question of the magnitude of the frequency leap during the chest-falsetto transition. Differences in the magnitudes are studied among the three singers. The chapter offers a new approach of quantifying the chest-falsetto...
Frontal section of the vocal folds during a phonatory cycle

Laryngostroboscopy

Fig. 2. Schematical illustration of a normal cycle of the vocal fold vibration. The oscillating vocal folds modulate a stream of air coming from the lungs and trachea, and determine the primary voice signal. Note that the vibration of the vocal folds is not purely opening-closing, but incorporates differences along the vertical dimension of the vocal folds (the lower part of vocal folds opens and closes earlier than the upper part; a phenomenon called “vertical phase difference”). See also Fig. 1 in Chapter 7 and Fig. 4 in Chapter 9 for more details.
of today which also promises to provide an insight into the basic mechanism of voice registers [17; 18; 53].

Chapter 5 designs an experiment for the investigation of the eigenmodes and eigenfrequencies in living vocal folds by means of laryngoscopy. A resonance approach known from technical studies of vibration of complex structures [2; 101], previously utilized by Kaneko [72–75] for the measurement of resonance frequencies of the vocal folds, has been employed and modified for a laryngoscopic setup. The eigenmodes/eigenfrequencies were identified as resonance modes/resonance frequencies of the vocal folds. The vocal-fold oscillations were excited externally at various frequencies using a shaker placed on a neck of a living male subject (the same subject as investigated in Chapters 2 and 3). The vibratory shapes of the vocal folds (i.e., the mode shapes) were examined laryngoscopically in stroboscopic light.

An original method called videokymography, newly developed by the author for examination of the vocal-fold vibration (see Section II), was employed for examination of the resonance frequencies of the vocal folds. The experiment allowed, for the first time, to visualize the characteristic modes of vibration in living vocal folds and to relate these modes to the specific resonance frequencies of the vocal folds.

SECTION II: Development and application of videokymography

Voice irregularities, diplophonia, subharmonic phonation, or abrupt register transitions – information on vibration of the vocal folds in these cases has been to a large extent missing. One of the fundamental reasons for the lack of information is that the routinely available methods of the laryngeal examination which provide direct view of the vocal folds, such as videolaryngoscopy and videolaryngostroboscopy, are not able to capture the fast changes of the vocal-fold vibration in these cases (e.g., [61], see also below). On the other hand, there exist very powerful high-speed cinematographic systems [28; 58; 63; 97; 105; 116; 135] and high-speed digital imaging systems [45; 55; 64; 66; 78; 79; 81; 85; 136] which are capable of capturing the irregularities of the vocal-fold vibration; these systems remain, however, very expensive and are inaccessible for most voice laboratories and clinics.

Gall et al. [37] introduced a method “photokymography,” which was capable of investigating irregular oscillations of the vocal folds and which was based on a different principle (Fig. 5). Although the images from photokymography appeared very promising for a more detailed investigation of the vocal-fold vibration [33–39; 42; 43], the system
encountered technical problems and has never developed into a commercially available form. There has been a need for a new cost-friendly method which would enable the observation of all kinds of the vocal-fold oscillation not limited to periodic or slow-changing oscillations of the vocal folds. In Fig. 6 a short explanation of the differences among the currently available optical methods is given.

Chapter 6 introduces a new examination method “videokymography,” which was originally designed by the author in Groningen in 1994 and developed together with Prof. Schutte and the Lambert Instruments BV company (Leutingewolde, the Netherlands) into a practical system. The videokymographic system was designed as a cost-friendly, simple alternative of a high-speed imaging system suitable for the examination of vocal-fold vibrations. The paper describes the principle of the method and presents the very first videokymographic images of the vibrating vocal folds obtained from 2 normal male subjects.

Chapter 7 brings the first results of clinical application of videokymography. In the first part, videokymographic images of a normal subject are related to the stroboscopic images. In the second part, the first videokymographic images of vocal folds in patients with selected voice disorders (unilateral vocal fold paralysis, vocal fold edema, vocal fold polyp, partial cordectomy) are shown. Videokymography is presented as a complementary method to video-laryngostroboscopy. Laryngoscopic, laryngostroboscopic and videokymographic images of a single patient are composed together making it possible to effectively document the most important laryngeal findings. It is
shown how the method of composition of such different images can be helpful in revealing the mechanism of a voice disorder in more detail.

Chapter 8 pays attention to the variability of vibration of normal vocal folds as seen in videokymography. Understanding the factors of variability of normal vocal folds is highly important for the interpretation of videokymographic findings, for further analysis and quantification of the observed vibratory pattern, and for distinguishing normal findings from pathological ones. The chapter describes basic factors which need to be taken into account when carrying out a videokymographic examination and which influence the resulting videokymographic vibratory pattern of vocal folds.

Chapter 9 presents the state of art of videokymography in 1999 seen from the clinical perspective. (The chapter presents a paper originally published in Czech language, which is intended to serve as an introduction to the videokymographic method for the otolaryngologists and phoniatricians). The principle of the method is reviewed, characteristic videokymographic features of the vocal-fold vibration are related to the characteristic features known from videolaryngostroboscopy. Various pathologic findings (glottal hyperadduction, sulcus glottidis, vocal fold scar combined with ankylosis of the cricoarytenoid joint, and ventricular voice after cordectomy) are demonstrated by means of compositions of laryngoscopic, laryngostroboscopic and videokymographic images.

Chapter 10 provides some additional data to Chapters 2–5 on dynamic behavior of the vocal folds and shows how videokymography can contribute to explaining the basic mechanism of the chest-falsetto transition. Also, an example of videokymographic and stroboscopic findings in a patient with mutational voice disorder is given here and the possible contribution of the resonance modes to the occurrence of chest-falsetto jumps is discussed.

Videokymography, validated as a very useful method and showing its clinical value, as described in the Chapters 6–9, can become an important tool for studying the register-related phenomena in more detail in the future. Information on the fast transitions, as described in Chapters 2–5, will be clarified in studies in excised human larynges (now in progress), as well as contribute to the improvement of numerical modeling. This all contributes to our knowledge of the biomechanical properties of the human vocal folds.

REFERENCE LIST


