When the Clarinet Sounds Bad

Identification study

A T H A N A S I A   Z L A T I N T S I

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When the Clarinet Sounds Bad

Identification study

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När klarinetten låter illa - En identifikationsstudie

Sammanfattning

I blåsinstrument är tonkvaliteten en viktig ljudaspekt som är starkt beroende av spelaren. Målet med denna studie var att undersöka perceptuellt när en klarinetton låter illa, hur den låter, och vad det beror på.

Analyser av klarinettinspelningar, intervjuer och ett lyssningstest gav inblick i de vanligaste felen och dess orsaker. Resultaten visar att professionella klarinettister och lärare ganska säkert kan identifiera den troliga orsaken till en dålig ton. Ett antal vanliga metoder för att undvika typiska sådana misstag har sammanställts.

Kännetecken i spektrum för dåliga klarinettoner analyserades. Det var inte alltid möjligt att finna gemensamma särdrag för en särskild felkategori, men några tendenser och indikationer som särskiljer olika kategorier av dåliga toner har hittats och diskuteras. Algoritmiska beskrivningar för att kunna särskilja sådana toner kompilerades för att automatiskt kunna finna dåliga toner i en inspelning. Detta är ett viktigt område för datorstödd inlärning, särskilt för nybörjare.

When clarinet sounds bad – Identification study

Abstract

In wind instruments, tone quality is an important sound feature which strongly depends on the player. The subject of this study was to examine perceptually when a clarinet tone sounds bad, how it sounds, and what this depends on.

Analysis of clarinet recordings, interviews, and a listening test gave insights into the most common mistakes and their causes. The results show that professional clarinetists and teachers can identify the possible cause of a bad tone quite reliably. Also, a number of common methods for avoiding typical playing errors were acquired.

Spectrum characteristics of bad clarinet tones were analyzed. It was not always feasible to find common characteristics for a certain error category, but some tendencies and cues that distinguish between categories of bad tones have been found and are discussed. Algorithmic descriptions for differentiation of bad tones were compiled with the purpose of finding bad tones in a recording automatically. This is an important issue in computer-aided learning, especially for beginners.

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Athanasia Zlatintsi

Table of contents

1 Introduction

1.1 The Vemus project

In wind instruments, like in most other musical instruments, tone quality is a main feature of the sound. The tone quality is strongly dependent on the player and how she controls air flow, embouchure (the conditioning of the lips and support of the reed), and the coordination with the fíngering. It is very important that the young student is taught the right techniques already in the first years. The main teaching resource nowadays is the teacher who meets the student during short lessons, typically once a week. It would be desirable, however, to be able to offer the young students help while practicing alone at home as well.

In an ongoing EU-project VEMUS (Virtual European MUsic School) a virtual practicing environment for wind instruments such as the recorder, flute, clarinet, saxophone, and trumpet is being developed. The target user group is woodwind instrument students during their first 4 -5 years of playing. VEMUS could be thought of as virtual assistant teacher who guides the student while practicing.

VEMUS records the audio signal while the student is practicing a melody and analyses and evaluates the performance by comparing it with the musical score. Following, feedback is given to the student about the mistakes she did and how to correct them. This feedback is limited to a couple of items and based on pedagogical considerations. In order to be able to give feedback on bad tone quality, i.e. to identify and give advice on how to correct such mistakes, it is important to be able to distinguish a good-quality tone from a bad one, and further to be able to recognize and tell apart different categories of bad-quality tones. This requires an understanding of the acoustical characteristics of each specific type of tone quality.

1.2 Aim of the thesis

The purpose of this thesis is to gain an understanding of bad clarinet tones, i.e. to be able to identify a bad clarinet tone and describe how it sounds in perceptual and acoustical terms. Different reasons which can make a tone sound bad will be taken under consideration, including the quality of the reed, breathing technique, embouchure, fingering, and the quality and condition of the instrument. The approach will be to examine recorded clarinet tones from three aspects, perceptual, pedagogical and acoustical.

Published studies mostly deal with factors and techniques that influence the ‘perfect’ tone, not including conditions when the tone is incorrect. From such research the studies by Fritz et al [1, 2] about the effects of the player’s vocal tract and its influence on the tone can be mentioned, as well as Mukai’s study on the effect of the larynx on the tone quality [3]. Regarding the properties of the instrument, Thompson [4] has shown how the reed resonance can stabilize the loudness, pitch and tone color. Due to the lack of research on bad clarinet tones, the study was designed to examine when a tone sounds bad from a perceptual and acoustical point of view, describe how exactly it sounds, and give plausible suggestions to which the causes are.

The study will be limited to the clarinet. One reason is that the clarinet is among the most popular woodwind instruments and all single-reed woodwinds will likely share many characteristics with the clarinet, as discussed below. A second reason is that it gives a reasonable limitation of the study. The design of the clarinet and how it affects the sound will only be discussed briefly. The focus will be on why a tone sounds bad, how the sound can be described in acoustical and perceptual terms, not including what can be done in order to avoid the errors.

The study is divided in two main parts. The first part deals with the identification of bad clarinet tones, how they can be described perceptually, and suggestions for discriminating between the causes for each type of bad tone. Analysis of collected clarinet recordings for the VEMUS project, interviews with clarinet teachers, and a listening test give insights into the most common mistakes by young clarinet students, the produced bad tones, and their causes. In the second part, a recording session of clarinet tones was performed, based on the knowledge and results of the previous identification part. These recordings were analyzed using spectrograms and long-time average spectra and the spectrum characteristics of each type of bad tone quality were identified. Finally, algorithmic descriptions for the differentiation of bad tones were compiled with the purpose of finding bad tones in student recordings automatically.

1.3 Bad tones

Five basic bad-tone categories which were found during the analysis of the clarinet recordings and which were repeatedly produced by students will be presented in the following. It is important to mention that some of the terms used to describe the tones may not be in common use. Certain terms are even introduced especially for the purpose of this report, such as “double tones,” based on the way those tones sounded.

1. Squeaks
Squeaks usually have a metallic, harsh and piercing sound quality at a pitch much higher than the following actual tone. Squeaks are caused by poor control of embouchure or air flow, or leakage in the instrument (covering of finger holes).

2. Whistling tones
Whistling tones are another kind of squeak, also characterized by a harsh and metallic sound, but they do not last as long as the squeaks and do not need to have as high pitch as well.

3. Unstable tones
Unstable tones do not possess stable pitch over time and are in a way out of tune. They are usually caused by unsteady embouchure or unsteady air pressure. Tones that suffer from this kind of problem are often long tones that occur at the end of a phrase.

4. Hollow/empty tones
Hollow or empty tones are characterized as having no shape, body, brilliance or depth. They

can be caused by a broken and possible dry reed, insufficient lip pressure and lip contact with the reed and mouthpiece, loose embouchure or too soft attacks. The hollow tones can also be perceived as weak, in both loudness and content.

5. Double tones
Double tones are perceived as having two pitches, the first weaker than the second intended pitch. Double tones are produced when the player does not manage to play the right tone from the beginning, e.g. due to problems with the coordination of fingering.

2 Background

The background material shortly presented in the following is based on scientific papers which describe the woodwind instruments, and particularly the acoustics of the clarinet. Educational material gave an insight into playing techniques and common mistakes.

2.1 Wind instruments

Wind instruments contain a resonator (usually a tube), in which a column of air is set into vibration by the player, usually through a mouthpiece. The pitch produced is determined by the length of the tube and by manual modifications of the effective length of the vibrating air column. There are two main types of wind instruments, brass and woodwind instruments. Brass instruments are usually made of brass and woodwinds were originally of wood, but the material is not the determining property. For instance, the saxophone is made of brass but yet it belongs to the woodwind instruments because it uses a reed in order to produce sound. In woodwind instruments, of which there are three kinds, the sound is produced either by (1) a vibrating single reed (clarinet, saxophone) or (2) double reed (oboe, bassoon), or (3) by blowing against an edge or fipple (recorder) or the edge of an open hole (flute) [6]. In contrast, the cornetto, which is made out of wood, belongs to the brass instruments because the sound is produced by an interaction of the lips of the player (supported by the rim of the mouthpiece) and the vibrating air column in the same way as in a trumpet or trombone [5].

2.2 The clarinet and clarinet acoustics

2.2.1 Construction

The B^b clarinet is almost cylindrical and made up of five parts, see Figure 1:

The *mouthpiece*, to which the *reed* is attached by the ligature, is the top part of the clarinet which is held in the player’s mouth. The reed is attached at the bottom side of the mouthpiece and supported by the lower lip, while the upper teeth and lip have contact with the mouthpiece. The player’s formation of the mouth around the mouthpiece and the support of the reed is called the *embouchure*.

Figure 1: The five clarinet parts.

Below the mouthpiece is a short barrel that joins the mouthpiece with the main body of the clarinet. This connecting device is used for fine-tuning of the clarinet. Increasing the length by pulling out the barrel lowers the intonation.

The main body of the clarinet contains the *upper joint* which is operated by the left hand, and the *lower joint* operated by the right hand. There are seven *tone holes* closed by the fingers, six on the front and one at the back of the upper joint. Furthermore, the clarinet has additional tone holes operated by keys, which enable to play chromatically and use alternative fingerings. The three middle fingers of both hands usually operate the tone holes and the little fingers the keys. The right thumb supports the instrument and holds it in position behind the lower joint on the *thumb-rest* while the left thumb operates both a *tone hole* and the *register key*.

The last part is the *bell,* which seemingly has the function of helping the sound waves in the bore to radiate from the instrument. However, almost all sound radiation takes place through the open tone holes. Without the bell, the tones in the lowest register, which are played with just a few or no holes open, would have a noticeably different timbre[1] [7]. For the higher

[1] A ‘tone’ is here considered a sounding representation of a musical event, while a ‘note’ is an abstraction or graphical representation of the same event.

tones, the sound is radiated almost entirely through the 2- 3 first open tone holes and only the highest spectral components pass through the bell.

The lowest tone is associated with the lowest normal mode of vibration of the complete air column, thus it is produced by having all tone holes closed. A chromatic scale is played by opening the tone holes one by one, shortening the effective length of the vibrating air column. By opening a tone hole the pitch raises by a semitone, which requires a pipe that is about 6% shorter. At an octave and fifth (duodecima) above the lowest tone, corresponding to a frequency ratio 3:1, the fundamental frequency (lowest mode) of the shortened tube is the same as the frequency of the second mode of the complete tube with all tone holes closed [8]. At this point the first mode of the complete tube is suppressed by opening a register hole (overblowing), and the next tone in the chromatic scale is played with all tone holes closed.

2.2.2 The clarinet registers

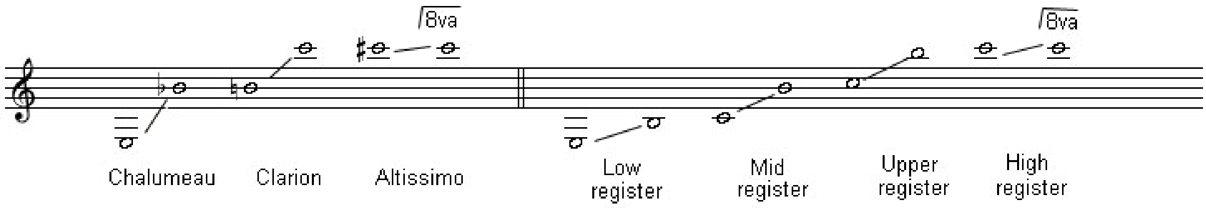


Figure 2: The different clarinet registers.

The clarinet has three main registers according to Pino [9] (see Figure 2):

- The *chalumeau* (low) covers the written range from E_3 to Bb_4. In this range the fundamental frequency is controlled by the lowest mode of vibration of the air column defined by the effective length of the bore.
- The *clarion* or *clarino* (middle), played by overblowing to the second mode of vibration of the air column (see Sect. 2.3), covers the range from B_4 to C_6 .
- The *altissimo* register, played by overblowing to the third mode of vibration of the air column, covers the range from $C_6^{\#}$ to approximately C_7.

2.2.3 Clarinet acoustics

All musical sounds consist of *partials*. The actual pitch that we hear corresponds to the frequency of the lowest partial (the *fundamental frequency*), but we never hear the fundamental alone as a *pure* tone; it is colored by the other spectral components called *overtones*. In the following, the fundamental frequency will be denoted by f_0, and the overtones f_1, f_2, f_3, … If the frequencies of the partials (fundamental + overtones) form a harmonic series (1:2:3…) the term *harmonics* is often used. The geometry of the bore of different instruments promotes different sets of overtones and gives them a characteristic timbre. For the clarinet (cylindrical bore) there are some particularities that will make a distinctive sound, and the sound cannot be mistaken for that of a saxophone (conical bore). One characteristic of the cylindrical bore closed at one end is that it produces in principle only odd-numbered partials (the spectrum consists of the first, third, fifth, etc partials, in our notation f_0, f_2, f_4, f_6 ….), see Figure 3. This approximation is valid in the lowest range of the clarinet.

Sound is produced by an oscillating motion of the reed which modulates the steady airflow, supplied by the player. The reed, in cooperation with the resonances of the bore, produces an oscillating component of both flow and pressure. The air column in the clarinet resonates at certain frequencies, which also determine the playing frequency and thus the pitch. Specific lengths of the air column, and thereby the tuned musical pitches, are achieved by combinations of keys [10]. When the air column in the tube is vibrating, a small fraction of the acoustical energy is radiated as sound from the bell and the open tone holes.

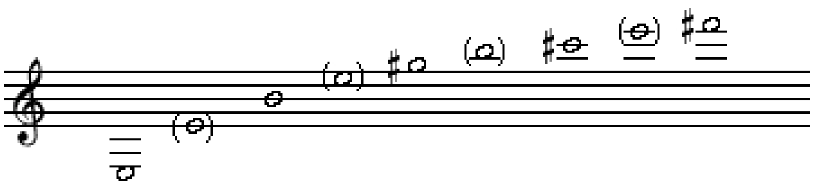


Figure 3: Harmonics of the lowest note on a clarinet.

2.2.4 Reed vibrations

The reed of a clarinet has its own set of modes of vibrations (resonances). These correspond to the frequencies heard when a squeak is produced. When playing a normal clarinet tone, the lower lip, which supports the reed, damps the reed vibrations and the oscillating frequency of the reed is controlled by the lowest mode frequency of the air column. The reed vibrations feed energy to both odd and even modes of the air column, but in the *chalumeau* register only the odd harmonics set up in the sound spectra as the even modes of the air column are very weak. Consequently, the sound spectrum in that register has strong first and third harmonics, but weak second and fourth [11].

The frequencies of the air column resonances are lowered compared to a completely closed tube because of the periodic variation in volume flow through the reed opening. This means that a soft reed lowers the playing frequency more than a hard reed as soft reeds move more than hard ones. This effect is comparatively greater at high pitches than at low.

When the pressure inside the mouthpiece drops the reed tends to close and allows less air in, and when the pressure goes up the reed opens and allows more air in (‘inward beating reed’). When playing louder, the driving pressure increases and the opening and closing occurs faster This is reflected as steeper slopes and more angularity in the flow waveform, corresponding to stronger higher harmonics in the spectra. Blowing harder thus makes the sound both louder and brighter. When even more pressure is added by blowing harder, the reed closes completely during a part of the fundamental period, resulting in a rich spectrum (‘beating reed'). In order to retain a non-beating reed condition at hard blowing, a harder (stiffer) reed can be used.

The embouchure and the effective length of the reed are important factors for the reed vibrations. The position of the lower lip and the bite force on the reed affect the vibrating length and hence the effective stiffness of the reed.

2.2.5 Different reeds and mouthpieces

The most common characteristic for reeds is their 'strength,' although, a reed is not only characterized by this feature. There are different kinds of brands, and each one is suited for a specific purpose. It is not unusual that professional players use certain reeds for certain musical styles. Concerning the strength, there are five sizes (1-5). Beginners most often start out with a 1.5 or 2, which are soft, and quickly move to size 2.5 which is medium soft. Softer reeds are best for mouthpieces with open facings, while a closer tip opening acquires a harder reed. In other words, it is important to match the mouthpiece with the best fitted reed.

There are several types of mouthpieces, and choosing the right one is important for the best possible tonal result. A good mouthpiece can clearly improve the qualities of the instrument, but the choice is a matter of personal preferences, experience and style.

2.3 Differences between woodwind instruments

There are three basic prototypes of air columns in woodwind instruments (see Figure 4): (a) open-open cylinder like the flute, (b) closed-open cylinder like the clarinet, and (c) conical bore like the saxophone, see Figure 4. The main differences between them are that the closed-open cylinder (the clarinet) defines a series of modes of vibration which includes odd multiples of the fundamental only, and that the fundamental frequency is on octave lower than that of an open-open cylinder of the same length (the flute). The saxophone, though closed-open like the clarinet but conical, contains a complete harmonic series of modes. This is because the mode shapes do not form half wavelengths of sinusoids (see Fig. 4).

The length of the air column determines the pitch, thus the lowest frequency is achieved by playing the full length of the tube. For the flute, the longest wavelength is twice the length of the open-open cylinder, for the clarinet, four times the open length of the closed-open cylinder, and for the saxophone twice the length of the cone. In other words when a flute or saxophone plays a tone using almost the whole length of the instrument, the clarinet produces the same tone with just half the length of the instrument.

Further, as the two lowest modes of the clarinet forms a frequency ration of 1:3, the clarinet will not overblow in an octave like the flute, but in an octave and a fifth. This leads to more difficult playing technique as the fingering is not maintained between octaves as for the flute and saxophone.

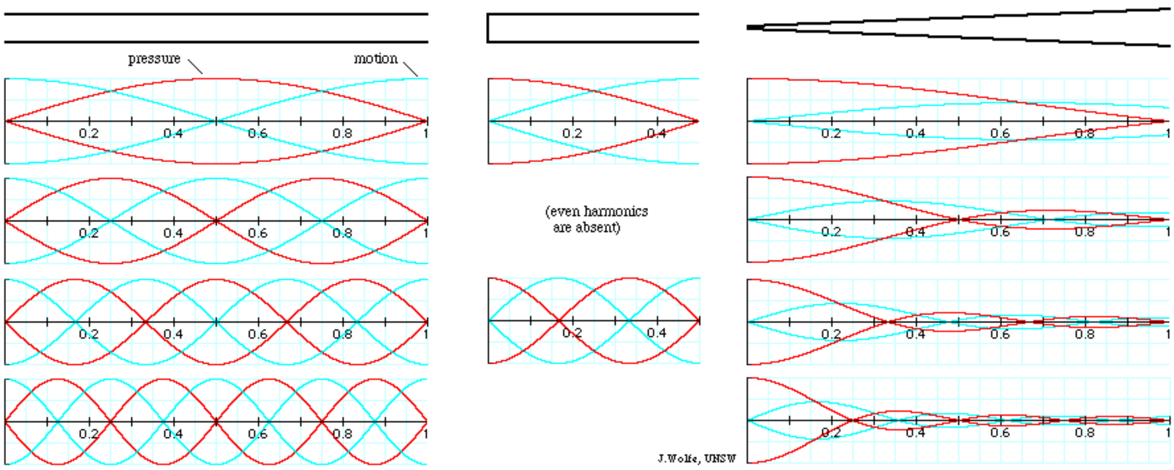


Figure 4: Lowest modes of the three prototype air columns for wind instruments: open-open cylinder, closed-open cylinder and complete cone. The red line (bold) represents sound pressure, which is zero at the open end and maximum at the closed end and the blue line represents the amount of air vibration From Wolfe, J. [10].

In flute instruments the necessary conditions to overblow an octave and change register is controlled by the way the player blows across the embouchure hole, forming the shape and velocity of the air jet. In reed instruments there is a register hole to facilitate overblowing. The purpose of the register hole(s) is to suppress the lowest mode of the air column by open up to atmospheric pressure at one of the points where the second mode has a pressure node but not the first. For the clarinet this occurs at a third of the distance from the closed end (see Fig. 4).

Tones can be overblown without using the register key by changing the embouchure and the blowing pressure. When tones are played in this manner the pitches are successively flatter than the harmonic frequencies. This is due to effects of the reed and the bell [10].

It is important to mention that the bore of the clarinet is not a perfect cylinder. If it was, the registers would be out of tune, and the intervals would be too wide. This effect is eliminated by small perturbations of the cylindrical shape, including also the shape of the mouthpiece, an expanding of the upper region of the bore, and a gradual flare in the bottom half of the instrument [11].

For many wind instruments it is important to distinguish between the *written note* in the score and the *sounding note*. Clarinets come in different sizes and pitch ranges. The family of clarinets are transposing instruments, in other words a certain note in the score calls for the same fingering and basic embouchure, regardless of whether the composer desires a high-pitched note from a soprano clarinet, or a low one from a large bass clarinet [15]. The sounding pitch is, however, different from the written note. For the Bb clarinet, the most common instrument in the clarinet family, all notes sound two semitones lower than the written note. For instance the clarinet's $\mathbf{F}^{\mathbf{Low}}$ sounds like an Eb_3 (155 Hz) as played on the piano. Some of the notes used in the following experiments are indicated in Table A showing the names, sounding note, and actual fundamental frequency. In the following, the notes will be referred to with their written names.

Table A: Written notes and the corresponding sounding notes on the Bb clarinet and their fundamental frequencies at nominal tuning reference A_4 = 440 Hz.

Written notes	Sounding notes	Fundamental frequency
F^{Low}	Eb_3	155.6 Hz
G^{Mid}	F_4	349.2 Hz
B^{Mid}	A_4	440.0 Hz
A^{Up}	G_5	784.0 Hz

2.4 Tone quality in general

Tone quality, or timbre, can be described by the balance between spectral components; the overtone composition. Both the amount and variety of overtones added to the fundamental affect the tone's quality, brilliance and intensity. For a strictly periodic sound the above offers a complete description of the quasi-stationary part of the tone. But all tones are not periodic. In some tones there are spectral components which are not part of the true harmonic series of the tone and in some way affect tone quality. Those other overtones can be produced in many different ways. When they occur a 'bad sound' is produced. The acoustical description of such bad tones is the main subject of this study, including typical examples as 'squeaks' or 'hollow tones.'

The intruding frequencies can be produced during the attack or decay of the tone. Their transient parts broaden and shape the peaks of the spectrum, bringing forward other nearby partials. Due to this interference the perception of tone quality for the whole tone is affected.

In wind instruments the higher modes of the air column may not be harmonic, meaning that they are not related by integer multiples to the fundamental because of variations in the effective length of the tube (due to the open end) [12]. This reduces the spectral amplitudes in the high-frequency end of the spectrum when a normal tone with harmonic overtones is produced. During transients inharmonic partials may be heard before the oscillations have locked to the intended playing frequency, defined by the effective length of the tube. Noise is produced by the reed vibrations and strong air flow through the narrow tone holes causing turbulence. Noise is characterized by a large number of spectral components of nearly the same amplitude over a large range of frequencies and it can have a prominent effect on tone quality.

Some quantitative indicators of tone quality are [13]:

- Spectral centroid: Correlated to perceived 'brightness'; measures the frequency at which the energy of the sound is centered.
- Inharmonicity: Plays an important role in identification of sound: measures the degree to which partials are exact harmonics.
- Irregularity: The variation in energy between partials.
- Odd and even: The ratio between odd and even harmonics

- Roughness: A measure of the degree of perceptual annoyance caused by the presence of several partials in each critical band.

2.5 Earlier studies

In 1979, Thompson [4] published the results of a study on the effect of the reed resonance on woodwind tone production. An important conclusions was that by tightening or loosening their embouchure clarinet players can change the natural frequency of the reed by ± 15% (250 cents), and thus the frequency of the tones in the *clarion* register by ± 0.6% (± 10 cents). Additionally, the second register oscillations can be stabilized when the reed resonance is set near to a low-order harmonic of the playing frequency. This condition also produces a good tone quality in this register of the clarinet, because of the stabilizations of loudness and pitch. Although, he emphasizes that such spectrum changes are not the only reasons for good-quality tones.

Fritz et al. investigated in different studies how the vocal tract of clarinetists influenced the frequency of the tone. In their latest study from 2005 [1, 2] they experimented with two vocal tract configurations, “ee” [iː] and “aw” [ɔː]. They concluded that different configurations are used for special effects, such as slurs across registers or pitch bend (by i.e. lowering the tongue). Moreover, some tones can only be produced with a specific configuration of the vocal tract. The results of their experiment were in agreement with musicians’ opinions about the effects of different configurations. Therefore the authors suggest that the effect of the vocal tract should not be neglected as it has a large influence on the sound. Still the configurations used can vary largely among professional clarinet players.

Mukai, 1992 [3] concluded in a study on laryngeal movement while playing wind instruments that the larynx plays an important role in the production of tones. The results were based on observations of the laryngeal movements of three groups of players with laryngo-fiberscope; experts, amateurs and beginners. Experts produced tones with controlled laryngeal apertures, while no such difference in openings could be observed for beginners. That is probably the reason why beginners have difficulties in producing differences in loudness. The cooperation of the respiratory muscles and the larynx were considered important for producing differences in loudness properly. Beginners cannot complete phrases in one breath and their tones contain much noise. Mukai concluded that tones with good tone quality cannot be produced if the larynx does not regulate the airflow.

3 Methods

The methods used in this study were (a) interviews with three clarinet teachers, (b) a field observation, (c) a listening test, and (d) acoustical analysis of recordings of clarinet tones.

Interviews with woodwind instruments teachers were done during the first part of the thesis. The aim was to establish which issues music teachers usually remark on in the performances of young students, to get an insight in which the most common errors/mistakes are and their causes.

A field observation during a music lesson was made in order to gain better understanding about the mistakes in an authentic teaching situation. Unfortunately, this method turned out to be less useful for the purposes of this study, since several pupils took part in the lesson. This made it difficult to understand who made a mistake and furthermore to recognize the cause. In addition it became clear that the teacher did not usually remark on mistakes on how a bad tone was produced during a lesson, or what should be done in order to correct the specific mistake. Instead exercises complemented with instructions may be given so that the student gets sufficient practice to learn the necessary corrections.

Following, a listening test was arranged in order to establish what makes a bad tone sound "bad" and what is generally considered a bad tone. In addition, we wanted to see if experienced clarinetists could recognize and agree on which tones are bad in selected sequences´. At the same time, this selection would create a database of 'verified' bad tones for the following acoustical study. The listening test was based on existing recordings of clarinet students made for the VEMUS project. The test was arranged as a web form and sent to clarinet teachers and concert players with many years of experience.

Finally, new material was recorded by a professional clarinet player while experimenting with the clarinet and some already known causes for bad-sounding tones. The purpose of this recording was to try to produce bad sounds, using for instance wrong fingering or a broken reed and then try to identify the bad tones in listening experiments. Analysis of the spectra was done in order to see how different kinds of bad tones could be distinguished. Based on these analyses, algorithmic descriptions of how to find bad-quality tones in student performances automatically were compiled. These condensed algorithmic descriptions are a set of instructions for finding bad tones, but do not include complete mathematical or programming procedures.

4 Interviews

The interviews were undertaken in order to get a basic understanding of the factors that influence clarinet tone quality and how they should be controlled in order to avoid bad tones. More specifically, the interviews dealt with (a) the causes for different categories of bad-quality tones, (b) which factors the students do not pay sufficient attention to with regard to tone quality, and (c) what the students' main difficulties are in obtaining an acceptable tone quality during their first years of study.

The first interview took place in Stockholm, with a clarinet teacher involved in the VEMUS project. This gave a good basis for understanding how the clarinet works and what the main difficulties are for clarinet students in the specific ages (9 – 14 years). The second interview took place in Thessaloniki, Greece, with an experienced clarinet teacher and soloist, and gave a deeper insight into the causes for particular categories of bad-quality tones. During the third interview, which took place at the Royal College of Music in Stockholm, also with an experienced clarinet teacher and soloist, the statements earlier acquired were confirmed. The interviews were used to define the characteristics of five categories of bad-quality tones described below: *squeaks*, *whistling sounds*, *blow sounds*, *unstable tones,* and *double tones*.

4.1 Squeaks

The causes for the characteristic clarinet ‘squeaks’ can be various. One major cause is when saliva gets into the clarinet mouthpiece, or when the reed has become calcified from saliva deposits. This gives the tone a harsh metallic quality, which causes a “bubbling” or “frying” sound [14]. Further, the young students have the tendency to press and bite the reed which can prevent the reed from vibrating freely. This can also be caused by sudden fluctuations of lip pressure [14], as well as when the student tighten up the mouth. The conditions mentioned above are the main causes for squeaks. A relaxed conditioning of the mouth, a firm embouchure, and focus on a steady air pressure and supply of air into the clarinet is the general recipe for avoiding squeaks. Tones in the upper register are prone to squeaks and need good support with stable and sufficient air pressure.

4.2 Whistling sounds

The sound described as a ‘whistling sound’ is actually a short, low intensity squeak. A whistling sound can occur when the airflow too high, or when the coordination of the fingers is bad. Whistling sounds may often occur in the first tone of a phrase since the young students use to have a tighter embouchure in the beginning of the phrase and are not relaxed around the lips. Students often tend to bite the reed, which prevents it from vibrating freely. Also with too loose embouchure the reed is allowed to vibrate uncontrollable, causing a whistling sound. The exact position where the tongue hits the reed is important too, and thus the right holding position of the clarinet is essential. Further, wrong placement of the barrel can have an effect on the sound; it can actually cause a whistling in some tones. This is, however, not considered as a main cause, since the students learn early how to assemble their instrument correctly.

4.3 Blow sounds

During the analyses of the VEMUS recordings it became clear that sometimes a blow or breath sound could be heard, either during the whole song or at specific phrases. This sound is produced by leaking air at the sides of the mouth when the student does not have a firm grip of the mouthpiece with the lips.

4.4 Unstable tones

The last tone of a phrase or a musical piece can often be unstable; such long duration tones seem to be problematic for the young student. Long tones need to be planned well ahead before they should be played, including the support of the air by the diaphragm. It is important to not allow the breath support to gradually become limp during tonal release (along with the reduction in air flow), or the tone will lose body and texture [14].

Moreover, the tone must be maintained with stable air pressure during the whole duration, or the pitch can fall and the loudness can decrease. In such cases the students usually compensate the flattening by (incorrectly) biting the reed which sharpens the pitch. Another reason for an unstable tone can be insufficient amount of air for the specific tone, in other words a disproportional air flow for the active length of the clarinet. Unstable tones can be also caused by the embouchure not being firm enough, or when air is kept inside the cheeks and not directly blown into the clarinet.

It is also important to mention here that there is just one size of clarinet mouthpieces, independent of the age of the player. For this reason it is necessary to find the right place for the mouthpiece to lean towards the mouth and lips. If the position is not right then the player will have difficulty in controlling the reed.

The open G ($\mathbf{G^{Mid}}$) is a tone which often causes problems with stability, since the player does not support the clarinet except by the mouth and the right thumb (all tone holes open). If the embouchure is not firm, the mouthpiece can change position in the mouth which may cause a bad tone. This can possibly occur for tones with just one finger hole closed as well, such as $\mathbf{F^{Mid}}$, $\mathbf{F^{\#Up}}$, $\mathbf{G^{\#Up}}$, $\mathbf{A^{Up}}$, and $\mathbf{C^{Hi}}$. Correct holding of the instrument and body posture are of course a necessary prerequisite for maintaining stability.

4.5 Double tones

Double tones are usually caused by bad fingering, which means that the student does not close all tone holes properly at the beginning of the tone. This usually occurs when there is a difficult motoric task involved in the change of fingering between two tones, or at register shifts. In particular, register shifts from high to low register are prone to double tones.

4.6 Discussion

How to avoid bad-quality tones is not always obvious because of the many possible causes for them. Still there are some general suggestions which may help.

Squeaks can be avoided by keeping a constant airflow. In addition, supporting the supply of air with the diaphragm is important, which explains why students have to learn early how to use the right breathing technique, and how to find the right amount of air flow for each tone. The problem which arises when supporting the air supply with the lungs is that an uncontrolled amount of air flows into the instrument under high pressure, and consequently breathing sounds or whistling sounds can be heard. Hyperventilation is another effect of controlling breathing with the lungs. Furthermore, to avoid whistling sounds the student has to prepare the tone in advance and imagine how it is going to sound before the tone is played. A good practice is to support the supply of air for the note already before it is played.

A stable and firm embouchure is crucial, and to achieve this, the clarinet must be held in a stable position. The thumb of the right hand should always push the instrument upwards and the lips should hold the clarinet so firmly that it will not be easy to pull it out of the mouth. The embouchure should, however, not be too tight.

4.7 Conclusions

From the interviews we learn that the most essential factors for obtaining a good tone quality in general, and avoiding bad tones in particular, are the embouchure and the breathing technique. The reed can have an influence too, either because of the quality or because it is affected by factors such as the embouchure and air flow. Bad coordination of fingering can also explain deviating tone quality. In reality, often a combination of all these factors contributes to bad-quality tones.

This ranking could be compared to Pino's order of priority; relaxation, airflow, embouchure, technique, and articulation [9]. Whether one of these is not controlled properly by the student, a bad-quality tone can occur. Pino´s prioritized list include the same components as found in the interviews, but the two first, embouchure and breathing technique (airflow), follow in switched order.

In conclusion, we see that it is especially important to control the embouchure, avoiding any sudden relaxation or tensioning of the lip muscles around the reed and mouthpiece. Furthermore, a continuous support of the tone by controlled air flow and pressure and motoric skills in fingering will prevent tones of bad quality.

A concluding citation from Stein (1958):

> *It is not enough to play from the lowest depths of the lungs into the mouthpiece, but equally essential to play the air stream (which results in tone) completely "on through" the full length of the clarinet. Depth of sound, tonal body, richness, and evenness of quality result from combining imagination with reality in blowing the air column on through the clarinet (p. 22)* [14].

5 Listening test

5.1 Method

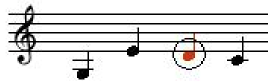
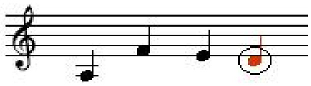
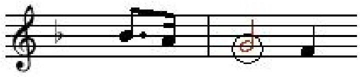
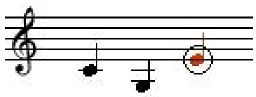
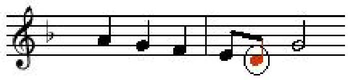
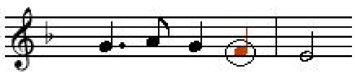
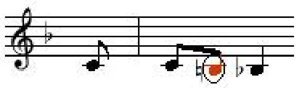
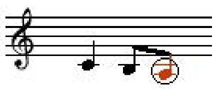
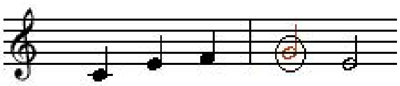
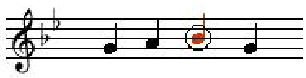
In order to determine the reasons to why bad tones are produced, a listening test was arranged. The material for the test was selected on the basis of analyses of VEMUS recordings of clarinet students. The aim was to find out what kind of bad tones students in the specific ages usually produce. After listening to 63 performances, 25 were selected for a more detailed analysis. During the selection process it became clear that similar mistakes, or in other words, specific categories of "bad" tones, were produced by many students. It was obvious that difficulties in the control of air flow and fingering caused significant problems for most young students. Five major categories of bad tones were chosen to be included in the test.

- Squeaks
- Unstable and out-of-tune tones
- Hollow tones that have no power and content
- Double tones, where the pitch changed during the duration of the tone.

- The open G (**G^{Mid}**) which is played with all the tone holes open and with no support from the fingers except the right thumb.

Ten short sequences were selected from the analyzed performances in which one of the tones belonged to one of the categories above, see Table 1. The sequences were uncompressed

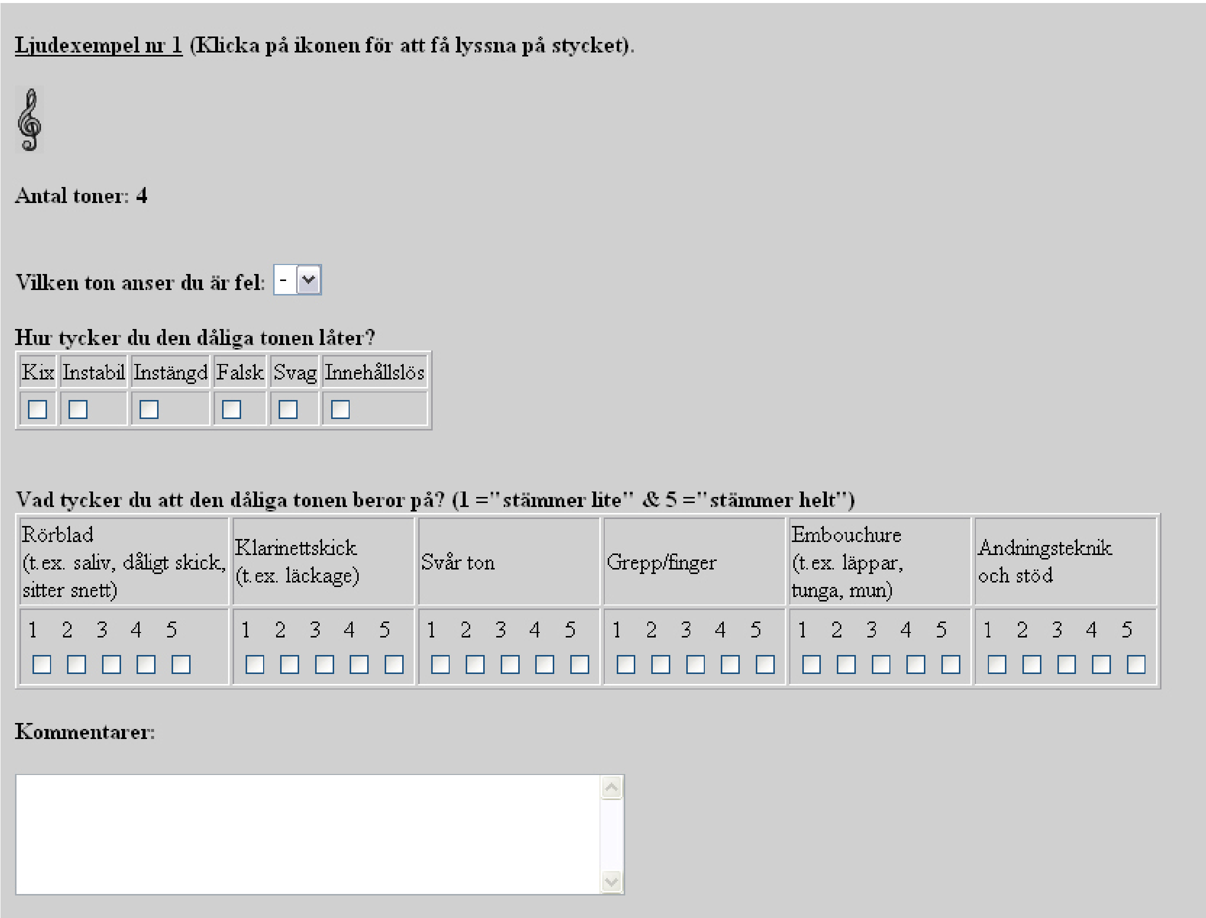
Table 1: Examples 1-10 with sequences including one bad note (encircled). The reason why the indicated note was considered bad is indicated.

Example	Note examples	Reason the note was chosen	Affected note
Example 1		Unstable, out of tune	D^{Mid}
Example 2		Squeak	D^{Mid}
Example 3		Unstable - open G	G^{Mid}
Example 4		Double tone	E^{Mid}
Example 5		Out of tune, hollow	D^{Mid}
Example 6		Double tone, hollow	F^{Mid}
Example 7		Squeak	B^{Low}
Example 8		Unstable	A^{Low}
Example 9		Unstable - open G	G^{Mid}
Example 10		Squeak	B^{bMid}

audio files. A clarinet teacher with 30 years of experience was consulted in order to find probable causes for these particular mistakes. This was done by playing and "imitating" student mistakes, and by testing different combinations of playing techniques, clarinets and reeds.

The intentions with the listening test were to see if different clarinet players categorized the bad tones in the same way, i.e. to see if they perceived the bad tones similarly. Moreover, we wanted to see if they agreed on the causes for the bad tones and if it is possible to make a one-to-one connection between a bad tone, for instance a squeak, and its cause(s). In order to get as accurate answers as possible, the test was given to clarinet teachers and professional and advanced amateur clarinet players.

The listening test was arranged as a web-based test in order to be able to reach as many subjects as possible, see *Figure 5*. The test was written in Swedish for the convenience of the participants. The subjects could listen to the sequences, as many times they wished. The


Ljudexempel nr 1 (Klicka på ikonen för att få lyssna på stycket).

Antal toner: 4

Vilken ton anser du är fel: -

Hur tycker du den dåliga tonen låter?

Kix	Instabil	Instängd	Falsk	Svag	Innehållslös
☐	☐	☐	☐	☐	☐

Vad tycker du att den dåliga tonen beror på? (1 ="stämmer lite" & 5 ="stämmer helt")

Rörblad (t.ex. saliv, dåligt skick, sitter snett)	Klarinettskick (t.ex. läckage)	Svår ton	Grepp/finger	Embouchure (t.ex. läppar, tunga, mun)	Andningsteknik och stöd
1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐

Kommentarer:

Figure 5: The web-based listening test. The subjects could click on the treble clef icon to listen to the sequence. The second field informs about the number of the tones in the specific sequence. In the third field, the subjects selected the one of the tones with bad quality. In the fourth field the subject indicates the category of the bad tone. In the fifth field the subjects are asked about the causes of the bad tone (more than one cause could be indicated). In the sixth field the subjects could write free comments about the selected bad tone.

number of tones for each of the ten sequences was given in advance. The subjects were first asked to identify which one of the tones in the sequence was the bad tone. After that the subjects could choose to categorize the selected tone according to one of the following six types:

- Squeak
- Unstable
- Hollow
- Out of tune
- Weak
- Without content

It was possible to choose more than one category for the selected tone. Following, the subjects were asked about the probable causes of the bad tone, and to rank to what extent the causes matched the sound on a scale from 1 (agrees little) to 5 (totally agrees). There were six causes to choose between:

- Reed (for instance saliva, bad condition, badly placed)
- Clarinet condition (leaking)
- Difficult note
- Difficult fingering
- Embouchure (lips, tongue, mouth)
- Breathing technique and support

The subjects also had the possibility to write comments about each tone to clarify their answers.

5.2 Results

Seventeen clarinet players with different amount of experience responded to the test. The subject with shortest professional experience had played the clarinet for 7 years, and those with longest experience for 40 years. The average was 22 years of playing, which promised confidence in the accuracy of the results. The results were compiled in the following manner:

Firstly, the indicated tone was checked to see if it matched the tone defined as the bad one, see Table 2 (column 3 “Right tone”). Secondly, the category of the bad tone was checked to see if the subjects agreed on the presumed category. In this way, all answers about the different reasons, causing the specific bad tone, could be compared (column 4-9). Valuable information for the summary was acquired from the subjects’ free comments.

The answers were grouped together with respect to categories, in order to see if the responses to expected causes were consistent between subjects.

Table 2 shows that in all examples except one (Example 4), the subjects quite accurately choose the tone defined as the bad one. Squeaks and Unstable open-G were particularly easy to identify. The low identification of the right tone in Example 4 was due to the fact that the note preceding the indicated bad note also could be considered as bad.

Table 2: Results of the listening test. The column named "Right tone" shows the portion of the 17 subjects who chose the tone defined as bad tone. The following columns show how the categorization of the answers was divided between the 6 categories. As more than one categorization could be given for each example the sum of each example may exceed 100%. Numbers in bold indicate categories which correspond with the definition of the bad tone.

Example	Definition of the bad tone	Right tone	Squeak	Unstable	Hollow	Out of tune	Weak	Without content
Example 1	Unstable Out of tune	94%	0	**73%**	33%	**53%**	20%	27%
Example 2	Squeak	100%	**100%**	6%	0	12%	0	0
Example 3	Unstable Open G	70%	0	**100%**	9%	28%	9%	18%
Example 4	Double tone	50%	13%	**88%**	25%	25%	25%	13%
Example 5	Out of tune Hollow	70%	0	64%	**45%**	**37%**	73%	73%
Example 6	Double tone Hollow	100%	0	**88%**	**19%**	13%	0	6%
Example 7	Squeak	100%	**93%**	37%	12%	12%	12%	12%
Example 8	Unstable	94%	20%	**74%**	40%	27%	40%	27%
Example 9	Unstable Open G	75%	0	**92%**	17%	67%	0	17%
Example 10	Squeak	100%	**100%**	12%	6%	0	0	6%

Also with regard to categorization, the subjects accurately choose the expected categories. Example 5 shows the largest spread. This is explained by the fact that it belonged to two categories, Out of tune and Hollow. Further Hollow quality can well be described as Without content. The tones characterized as Double tone (Example 4 and 6) had no corresponding alternative in the answer fields. As mentioned in section 1.3 the category Double tones was defined in this study and is not a common term among clarinet players. The alternative answer Unstable was used frequently which is an appropriate description of the tone quality Double tones.

5.2.1 Squeaks

Table 3 sums up results of the squeaks. The embouchure seems to be the main cause of a squeak in combination with breathing technique (airflow). Other causes which are important are the reed (the reed is in bad condition), and the fingering (the player does not cover the holes in a proper way). Squeaks due to fingering causes can be explained by a coordination difficulty in covering the right combination of tone holes or by register change. The leakage caused by bad finger coordination can also occur because of a leakage in the instrument, as for instance damaged pads. A bad reed can almost always be compensated for if the player has good control of embouchure and breathing technique.

Table 3: Summary of the main causes for squeaks. The causes are listed in descending order of answer frequency and rating of how well the causes described the tone-quality.

Example	Note	Cause 1	Cause 2	Cause 3
Example 2	**D^{Mid}**	Embouchure	Airflow	Reed/Fingering
Example 7	**B^{Low}**	Embouchure/Reed	Airflow	Fingering/Clarinet condition
Example 10	**B^{bMid}**	Embouchure	Airflow	Fingering/Difficult note

For Example 2, the answers were distributed rather evenly among several causes. However, the combination of comments and answers indicate that the main expected causes for the squeak are in descending order; embouchure, breathing technique, reed, and fingering. According to one comment, the fingering cause in this example can also mean a leakage in a malfunctioning instrument.

For Example 7 we see again that the main cause is the embouchure but in this case both the subjects' answers and their comments show that another main factor of equal importance is the reed. That implies that the reed was either too stiff for the student or vibrated in the wrong way. Furthermore, the breathing technique and a leakage of air, either because of the fingering or in the clarinet, were chosen as reasons for this specific squeak.

In Example 10, all subjects except one assumed that besides the embouchure and the airflow, it is a difficult tone and the fingering could have been a cause for the squeak. It is commented on that a register change can be confusing for a young clarinetist, who has to think about controlling many factors at the same time (fingering, airflow, support, and embouchure).

5.2.2 Unstable tones

Table 4: Summary of the main causes for Unstable open G. The causes are listed in descending order of answer frequency and rating of how well the causes described the tone-quality.

Example	Note	Described as	Cause 1	Cause 2
Example 3	Open **G**	Unstable	Embouchure	Airflow
Example 9	Open **G**	Unstable/Out of tune	Embouchure	Airflow

Both Examples 3 and 9 had an open G that was Unstable. Most of the subjects recognized this tone as the bad tone and categorized it as Unstable in Example 3, and Unstable and Out of tune in Example 9. The reason why the notes sound unstable in both examples is assumed to be the embouchure and the breathing technique, see *Table 4*. For Example 9, some of the subjects have commented on that this Unstable tone could be caused by a bad reed.

The conclusions from these two examples are that the open G can really be a problem for a young student, which is overcome when she develops a firm embouchure and good breathing technique.

5.2.3 Double tones

Table 5: Summary of the main causes for Double tones. The causes are listed in descending order of answer frequency and rating of how well the causes described the tone-quality.

Example	Note	use 1	Cause 2
Example 4	E^{Mid}	ering	Embouchure/Airflow
Example 6	F^{Mid}	ering	Embouchure/Airflow

In both Examples 4 and 6 the indicated cause for the double tone was bad finger coordination, see *Table 5*. Double tones are tones that the player do not manage to play right from the beginning, and is perceived as two different pitches, the first being weaker than the following intended pitch. The results for Example 4 were not very convincing since just 50% of the subjects chose this double tone as the bad one (see *Table 2*). The other 50% chose the tone before the bad tone, which they considered as Out of tune and with embouchure and airflow as main reasons why it sounded bad[2].

5.2.4 Leaking

Table 6: Summary of the results for Examples 1, 8 and 5. The causes are listed in descending order of answer frequency and rating of how well the causes described the tone-quality.

Example	Note	Described as	Cause 1	Cause 2	Cause 3
Example 1	D^{Mid}	Unstable/Out of tune/ Hollow	Fingering	Embouchure/ Airflow	
Example 8	A^{Low}	Unstable/Hollow/ Out of tune	Airflow/ Fingering	Embouchure/ Reed	Clarinet condition
Example 5	D^{Mid}	Weak/Without content/Unstable/Hollow/ Out of tune	Airflow	Embouchure	

In both Examples 1 and 8, just above 70% of the subjects categorized the tone as Unstable and in second place Out of tune or Hollow (see *Table 2*). For both examples, the subjects' comments showed that leaking was the probable reason. For Example 1 the causes were bad finger coordination in the first place, followed by embouchure and airflow. For Example 8, airflow and fingering comes first, secondly embouchure and reed and then the condition of clarinet, which in this case is an indication of leaking.

[2] Further analysis did confirm that indeed this tone was Out of tune. This unexpected result is in correspondence with the reasons predicted for Unstable tones.

In Example 5, 73% answered that the tone sounds weak and without content, 64% answered unstable, 45% answered hollow, and 37% found the tone to be out of tune. Here the reasons are suspected to be breathing technique (airflow) and embouchure. Some subjects suggesed that this sound can be caused by the large interval after the bad tone. The student concentrates on hitting the next note and stops focusing on the note she plays at the moment. The subjects emphasize the fact that too low airflow will generally cause a bad-quality tone.

5.3 Discussion

The results of the listening test indicates that it is not straight-forward to identify the exact cause of a bad tone. In general, however, it seems possible for professional clarinet players to identify and agree on which tones are bad, and to recognize the major causes and suggest how a student could avoid them. A bad tone is often a combination of different causes, but in many cases some causes are more prominent than others.

For squeaks the main causes are embouchure and airflow, or a hard or broken reed, or a leaking instrument. Leaking can either be caused by bad finger coordination or a defect instrument. One comment from a subject on a squeak example gives valuable insight:

> *"The squeak could be caused by leakage in the instrument, by a bad reed with a split in it, or by fingers not covering the holes properly. The squeak would have been less extreme if the embouchure and breathing had been correct in the first place."*

It seems that problems with squeaks can be overcome if the student has developed a firm embouchure and a good breathing technique, even if she plays a malfunctioning instrument or does not cover the holes properly.

For unstable tones occurring for the open G, embouchure and breathing technique are regarded as the main causes. Also the unexpected result in Example 4, in which the tone before the indicated tone was considered bad and considered as Out of tune, shows the same causes as the Unstable tones.

For the other unstable tones the subjects suggested leaking as the most possible reason, with embouchure and breathing technique following. Some comments on one of the unstable tones were that although the tone sounded more like a genuine leakage in the instrument, as for instance a leaking pad, it could equally well be that the student did not got the fingers down properly. These comments raise the question if it is possible to tell apart such differences by computer analysis without watching the player, as it is apparently not possible even for very experienced clarinet players to do so. Once again the subjects emphasize that it is possible to avoid unstable tones with good embouchure and airflow.

The main reason for the double tones is bad finger coordination, a result of a difficult tone or register change. Regarding leaking tones, the subjects agree on that the reason is probably the embouchure and breathing technique. Hollow and Out of tune tones are suggested to be caused by a following large interval. Further, the subjects point out that lack of sufficient airflow into the clarinet is common cause of hollow tones.

The following statement from Stein [14] underlines how important a steady and relaxed embouchure is:

> *Air leakage from the lips and nostrils weaken tone quality, cuts down power, shortens endurance and the audible sound detracts greatly from the intended tonal beauty. Players usually lay the blame on weak lips and consequently tighten them up even more. This simply adds fuel to the fire, since their real trouble is most often caused by over-tensed lip muscles. The true remedy lies in learning to ease the embouchure muscles into a plastic and flexible wrapping around the mouthpiece (p.48).*

6 Acoustical analysis

6.1 Methods

6.1.1 Description of the task

The audio material used for the analysis was produced by a professional clarinet teacher, who had played the clarinet for 25 years. A professional, Buffet RC Prestige Bb clarinet with a Vandoren B45 mouthpiece and reeds of varying strength (3 and 4) were used during the recording process. Reeds of varying quality were used in order to imitate typical playing conditions for students (good condition, too dry, and cracked). The recording took place in a semi-anechoic room. The player was standing in the middle of the room with the microphone positioned at about 1.5 m distance from the bell. The sound was recorded using a JJ LABS Sweden ND6000 microphone and a MOTU soundcard.

A representative set of tones with bad or deviating tone qualities were recorded. The selection was based on the previous analysis of VEMUS recordings (see Section 5), which were analyzed in order to find out which categories of bad tones students in the specific ages typically produce. The listening test also helped in determining the reason why these tones were produced. Based on this knowledge, the player was asked to produce seven categories of tone quality:

- good-quality tones
- squeaks caused by bad fingering or a bad reed
- double tones, usually caused because of bad fingering
- unstable tones which are usually caused by the embouchure, the breathing
- technique and the fingering
- hollow/empty tones
- squeaks of different durations

The decision on which tones (pitches) to include was based on two considerations; (a) different registers should be analyzed, and (b) students have difficulties with certain tones. After discussions with the player, a set of four notes were selected. Those were the *written notes*, $\mathbf{F}^{\mathbf{Low}}$ for the low register, $\mathbf{G}^{\mathbf{Mid}}$ (open G) and $\mathbf{B}^{\mathbf{Mid}}$ for the mid register, and $\mathbf{A}^{\mathbf{Up}}$ for the upper register. During the session, additional notes were included, in order to collect examples of squeaks of different durations.

The player was asked to perform at *mezzo forte* level, defined as the level at which the reed just fails to beat against the mouthpiece facing. This is very easily recognized as the level just short of change of feel and sound. Mezzo forte level is easily reproduced by clarinet players as a specific musical task irrespective of any reasonable variations in reed stiffness or alternations in the playing characteristics of the instrument [16].

6.1.2 Recording

Each note was played for a few seconds depending on the effect that was intended to be achieved. The next note was played after a short rest. Three conditions of the reed were used; normal, dry, and split.

Normal reed

- Chromatic scales in all three clarinet registers were played in order to obtain a reference of good-quality tones at *mf*.
- Four good-quality tones were played at *mf* level and then at *piano* level in order to examine how the spectra normally changes due to level differences.
- Two types of squeaks were produced, first with a bad reed and then with bad finger coordination. It was noted that $\mathbf{G}^{\mathbf{Mid}}$ had a special kind of squeak since it is played with all the tone holes open.
- Double tones were tried, unfortunately with no success. It was concluded that it was too difficult for the professional teacher to produce double tones, which are typical of young students.
- Unstable tones were recorded.

Dry reed

The reed was changed in order to produce hollow tones. Students have a tendency to not wet the reed enough and this has consequences for empty and hollow tones.

- Hollow tones were produced in two ways. First with loose embouchure and without a strong attack, and secondly with less lip pressure and less lip contact with the reed and mouthpiece.
- More squeaks were produced for the examination of short-long squeaks at pitches corresponding to the following written notes: $\mathbf{E}^{\mathbf{Mid}}$, $\mathbf{B}^{\mathbf{Mid}}$ and $\mathbf{B}^{\mathbf{Up}}$. The reason why additional tones were chosen for this purpose was that it turned out to be easier to produce squeaks of varying duration at these pitches.

Split reed

- The reed was changed once more and physically altered (introducing cracks) in order to obtain more pronounced examples of squeaks. The played notes were $\mathbf{B}^{\mathbf{Mid}}$, $\mathbf{B}^{\mathbf{Up}}$ and $\mathbf{C}^{\mathbf{Up}}$. (With this reed it was actually possible for the teacher to produce some double tones.)
- Even more characteristic hollow tones were recorded with the split reed, since it was noted that the tone quality obtained with this reed was even closer to the expected hollow quality.

6.1.3 Analysis

The recorded tones were analyzed with respect to evolution of the harmonics over time and their average spectral content. The analysis was performed using a sound file editor (Soundswell ®) using spectrograms and line spectra. In the following analyses of the four bad tone categories - squeaks, double tones, hollow/empty tones, unstable tones - the results were consistently compared with the normal, good-quality *mf* tones. The first analysis deals with the changes in tone quality with dynamic level for normal tones.

6.2 Results

6.2.1 Dynamic level - *mf* vs. *p*

Spectrogram analysis

For professionals, playing softly or loudly does not change the pitch, so the frequencies of the harmonics are constant. In tones played softly the fundamental is strong and the higher harmonics are weak, which gives rise to a mellow timbre. When the player successively increases the dynamic level as in a crescendo, the power of all harmonics increases faster than the fundamental and the sound becomes louder since more harmonics are added. The higher harmonics increase much more in amplitude than the lower (see Fig. 6 – 8), and because the higher harmonics fall in the frequency range where our hearing is most sensitive, this makes the timbre 'brassier' or brighter, at the same time it makes the tone louder [11].

When comparing the spectrograms in Figures 6 - 8, it should be observed that they do not have the same grey scale (amplitude). The strength of the harmonics can thus not be compared between the *mf* note and *p* note in each pair, but only across the four *mf* notes and *p* tones, respectively.

For all tones the *mf* tone has much higher overtone content than the *piano* tone as expected.

For $\mathbf{F}^{\mathbf{Low}}$ (*Figure 6*) the *mf* tone has overtone activity up to about 6.9 kHz (more than 40 harmonics), compact up to 4.2 kHz, while for the *piano* tone only f_0 and f_2 are visible during the whole duration and f_4 just at the end of the tone.

F^Low

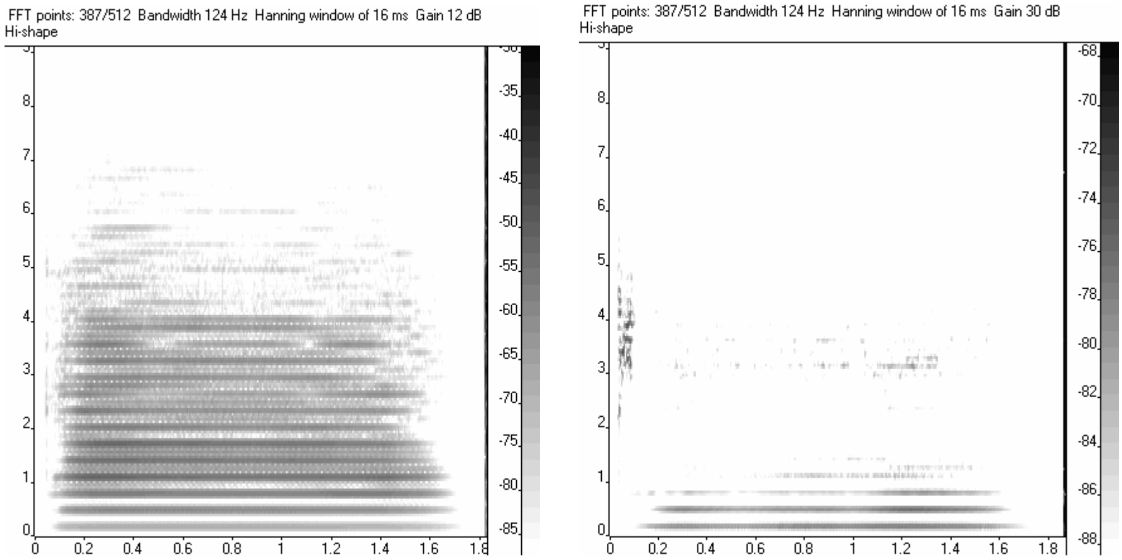


Figure 6: Spectrograms for F^Low *mf* and *piano*

G^Mid

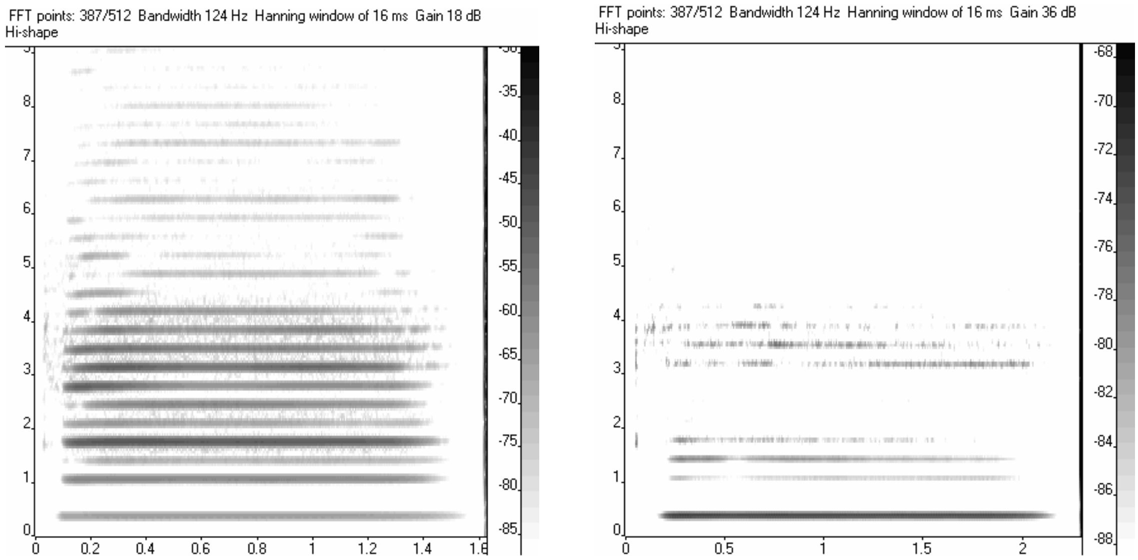


Figure 7: Spectrograms for G^Mid *mf* and *piano*

***B**^{Mid}*

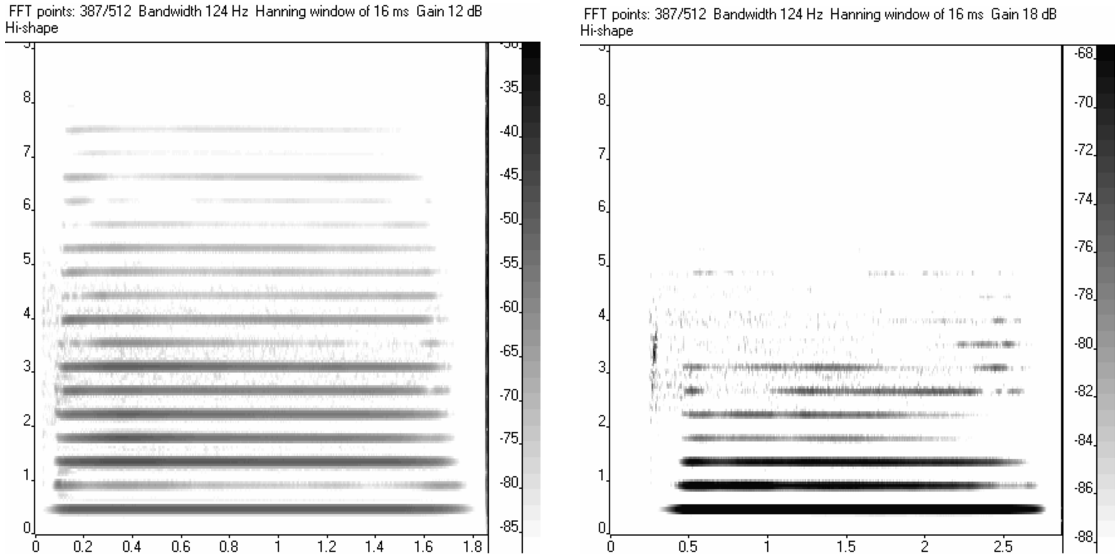


Figure 8: Spectrograms for B^{Mid} *mf* and *piano*

***A**^{Up}*

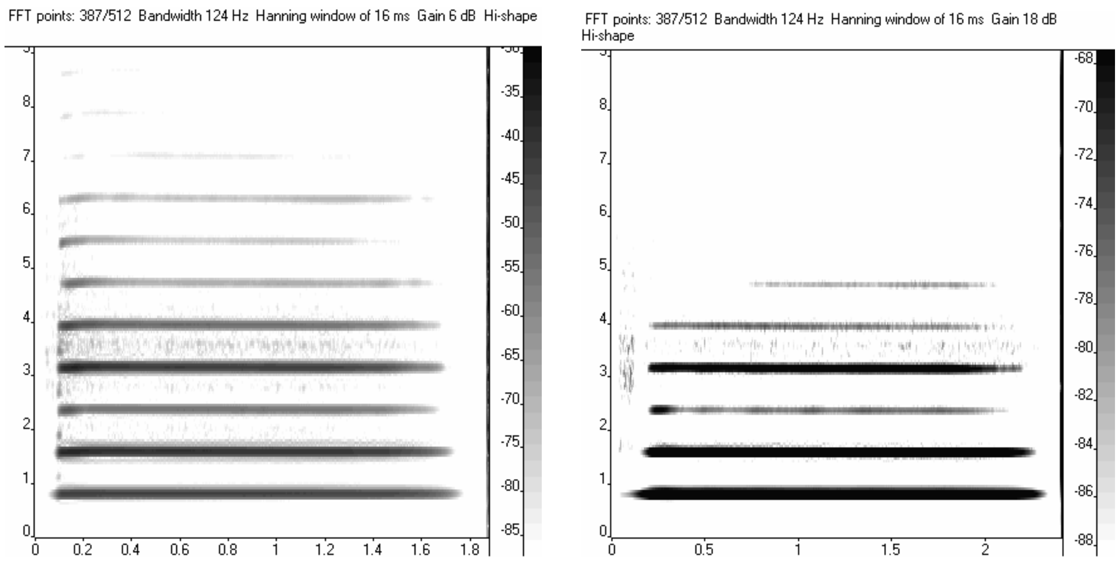


Figure 9: Spectrograms for A^{Up} mf *and piano*

For **G^{Mid}** (*Figure 7*) the *mf* tone has overtone activity, up to 8.2 kHz (about 20 harmonics), compact up to 4.4 kHz. In contrast for the *piano* tone just f_0 is clearly visible. Above that there are only traces of overtones, which do not even extend over the whole duration of the tone.

B^{Mid} *mf* (*Figure 8*) has compact overtone activity up to 3.3 kHz and spurious partials up to 7.6 kHz. For the *piano* tone only f_0, f_1 and f_2 are clearly visible. The fundamental f_0 is much stronger than f_1 and f_2 in the *piano* tone compared to the *mf* tone.

For **A^{Up}** *mf* (*Figure 9*) the overtone activity is as high up to 6.5 kHz (8 harmonics), while for the *piano* tone the overtone activity goes up to 4.1 kHz. In the *piano* tone the second overtone f_2 is very weak compared to f_0 and f_1 in comparison with the *mf* tone. Further, the *mf* tone has much more noise in between the first four harmonics, something which is not visible in the *piano* tone.

6.2.2 Squeaks

Spectrogram analysis

The two types of squeaks, fingering and reed squeak (see Sect 5.2.1) are both represented at the start of the tone **F^{Low}** (see *Figure 10* b, c),. The squeak caused by bad fingering lasts longer the one caused by a bad reed. The squeaks have a harsh and metallic sound. During parts of the squeaks there is clearly an absence of the fundamental frequency f_0 and first overtone f_1. This occurs at the beginning of the bad reed squeak, and in the middle of the squeak for the tone caused by bad fingering. For both types of squeaks the spectra is filled with energy between the partials corresponding to the following part of the tone with good quality.

The squeaks have a completely different pitch than the following good part of the tone (see the Line spectra analysis below). Moreover, the two types of squeaks have a quite different timbre; the squeak caused by a bad reed is not only shorter but much duller, sounding more like a short whistling. Further, the reed squeak has not as high overtone content, up to 7 kHz, while the spectrum for the squeak caused by bad fingering extends up to 8 kHz.

The duration of the fingering squeak was 250 ms and for the reed squeak 130 ms, approximately. It can be observed that the fundamental for the bad reed squeak is not missing as long as for the fingering squeak, 40 ms compared to 100 ms. This difference in absence of lower harmonics is probably an important contribution to the timbre difference between the two types of squeaks.

The good-quality part of both squeak tones sound quite good, almost as the normal *mf* tone. The spectrograms show only weak traces of harmonics above 4 kHz, specifically for the squeak tone produced with a bad reed.

Only one example of **F^{Low}** squeaks has been analyzed.

F^Low

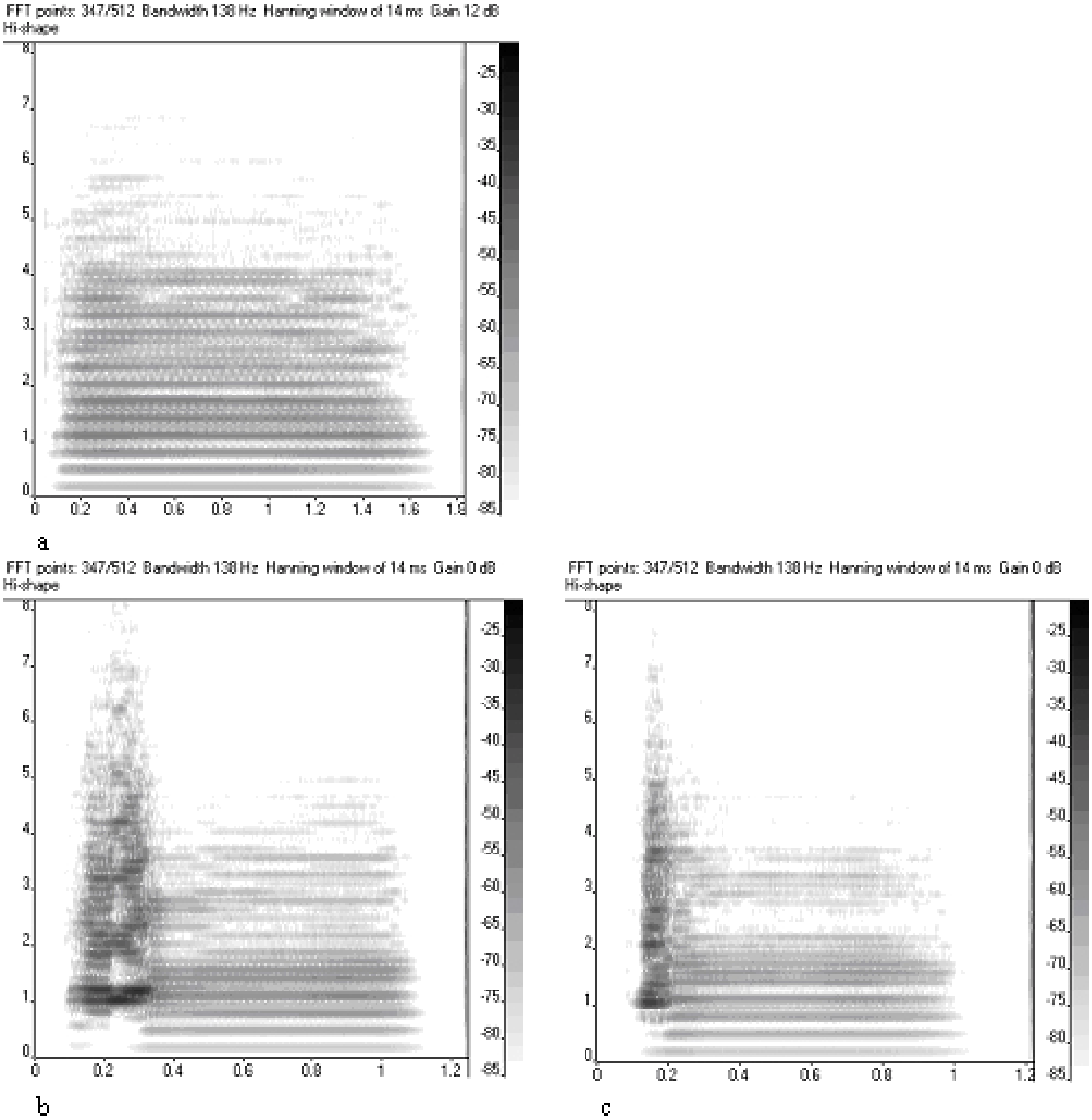


Figure 10: Spectrograms for a) F^{Low} normal mf, b) F^{Low} fingering squeak and c) F^{Low} reed squeak.

In the case of $\mathbf{G^{Mid}}$, there are no squeaks caused by bad finger coordination, as it is played with all tone holes open. Here the bad reed squeak comes at the end of the tone after about 500 ms of normal tone quality (see *Figure 11* b). The squeak sounds high, hollow and harsh. In the squeak part, a clear change in the spectrum is observed. During the squeak the fundamental frequency switches to one octave and fifth above the normal fundamental, 987 Hz (corresponding to overblowing 1:3). In the beginning of the pitch change (for the about 50 ms), all previous harmonics exist although they gradually decay in level.

G^Mid

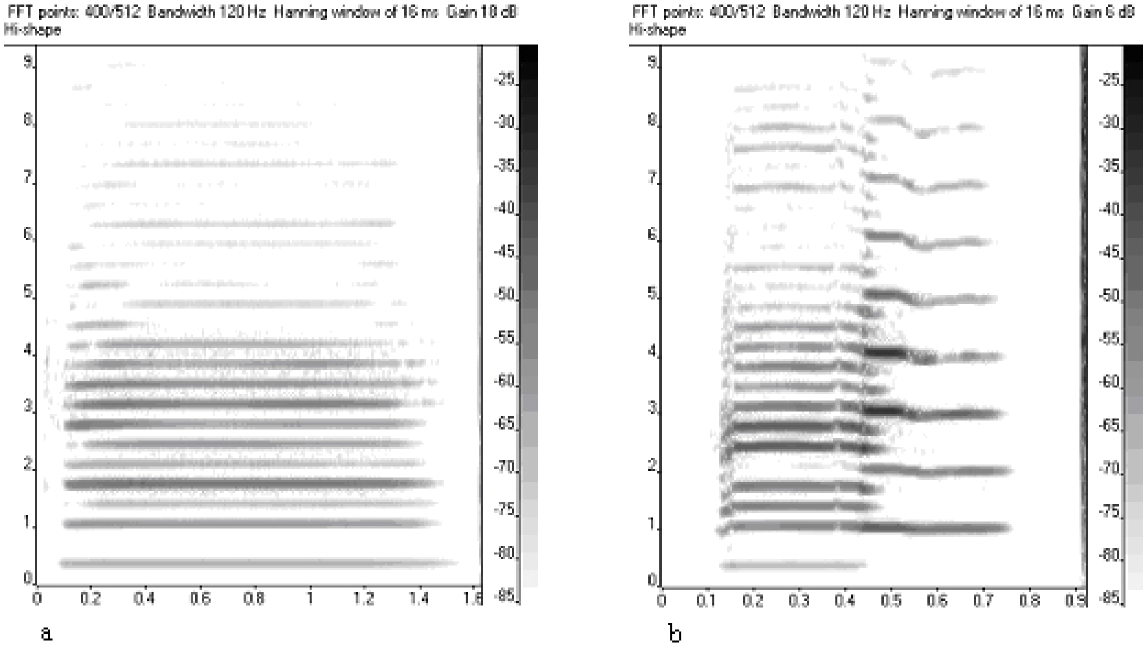


Figure 11: Spectrograms for a) G^{Mid} *normal mf and b)* G^{Mid} *reed squeak*

The good part of the tone in the beginning is similar to the normal *mf* tone, although the overtone content is slightly higher.

Analysis of another two $\mathbf{G^{Mid}}$ squeak tones gave exactly the same characteristics.

For the $\mathbf{B^{Mid}}$ squeak caused by bad finger coordination (see Figure 12 b) it can be observed that although some traces of a harmonic structure including the fundamental is visible there are no clear and separated overtones during the entire duration of the tone. This tone could definitely not be recognized as a $\mathbf{B^{Mid}}$. The tone was perceived as just a harsh metallic timbre and did actually not resemble a good tone in any respect. The spectrum contains energy up to 7 kHz including high noise levels between the harmonics.

For the squeak caused by a bad reed (see Figure 12 c), the spectrogram proved to be more normal. The squeak appears in the beginning of the tone, lasting about 200 ms. The fundamental is present also during the squeak. The higher overtones are shifted slightly upwards, and much noise is added in between. The noise content extends up to 7 kHz, while the highest clear overtone for the good part is found at about 4 kHz. Traces of individual, weaker overtones can be seen up to 7 kHz.

Analysis of another two $\mathbf{B^{Mid}}$ tones of each squeak type gave exactly the same characteristics.

B^{Mid}

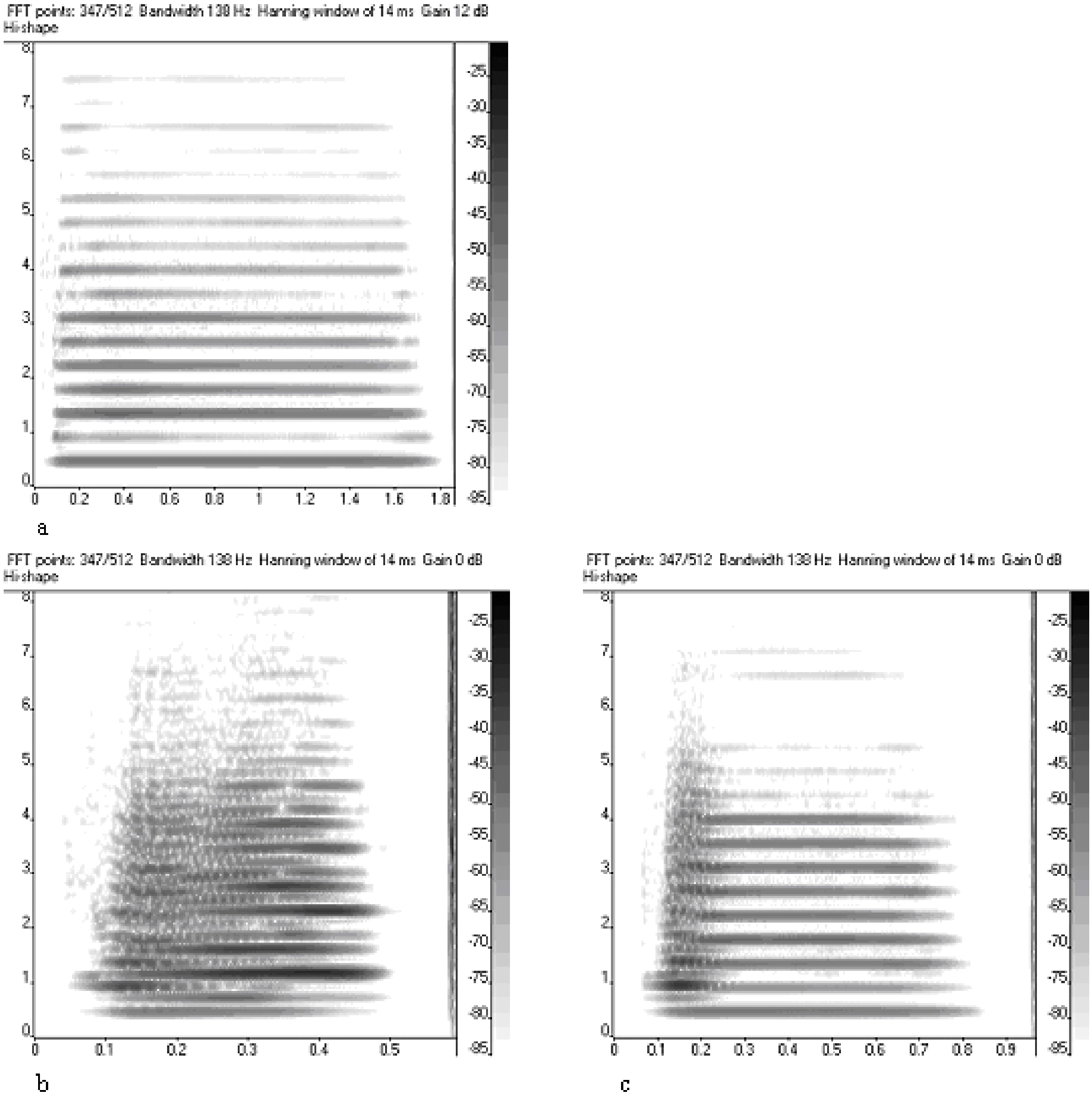


Figure 12: Spectrograms for a) B^{Mid} normal mf, b) B^{Mid} fingering squeak and c) B^{Mid} reed squeak.

A^{Up}

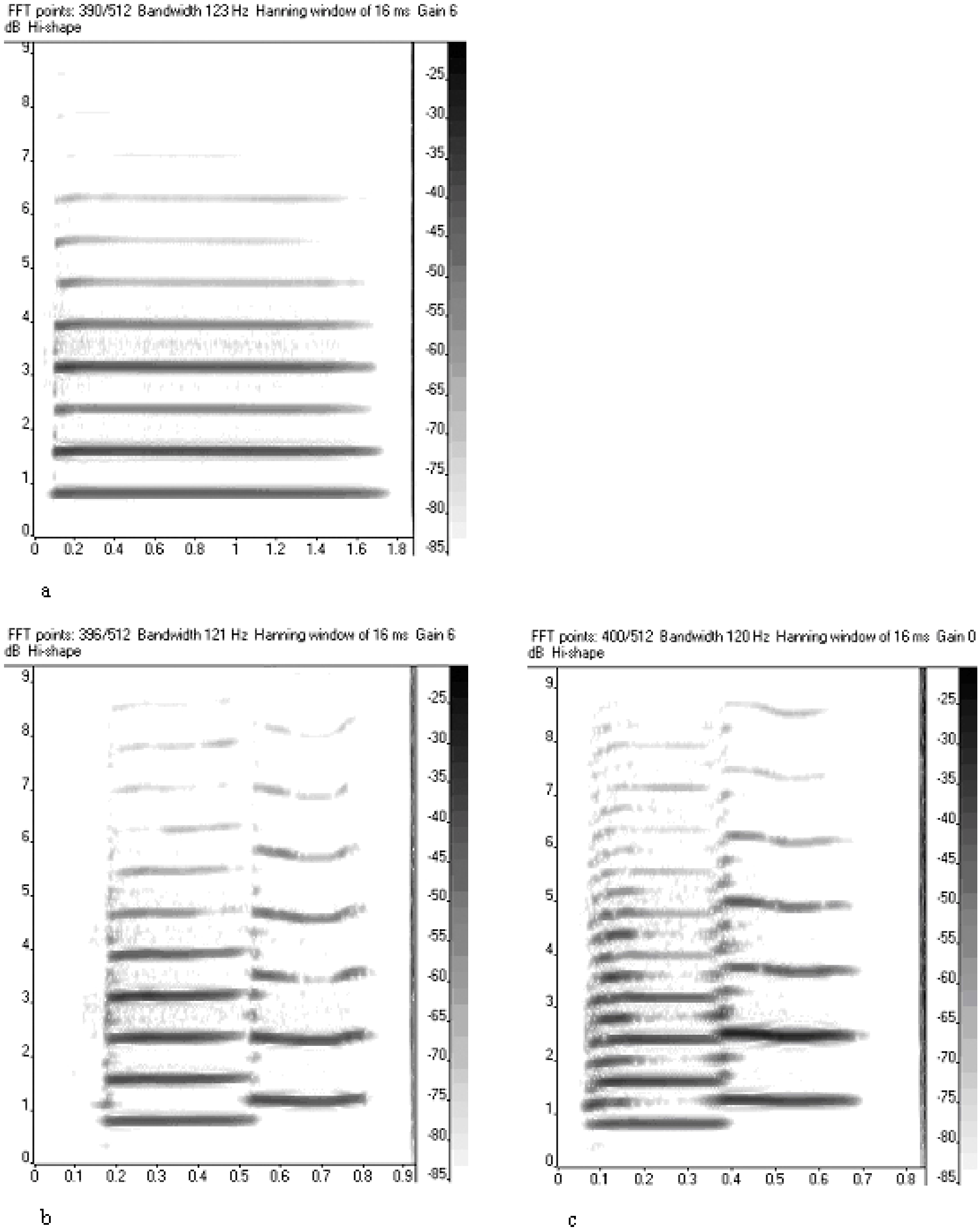


Figure 13: Spectrograms for a) A^{Up} normal mf, b) A^{Up} fingering squeak and c) A^{Up} reed squeak.

Both examples of squeaks for $\mathbf{A^{Up}}$ set in at the middle of the notes, lasting for more than 400 ms (see Figure 13). Perceptually, the squeak caused by a bad reed sounds louder than the one caused by bad finger coordination. This is probably due to the pitch change due to the squeak, which for the fingering squeak is a fifth above the fundamental at a frequency of around 1.2 kHz. For the reed squeak the pitch shift is slightly larger and none of the shifted partials match the frequency of the initial good part of the tone. Further, none of the squeaks show traces of the original fundamental frequency of $\mathbf{A^{Up}}$.

The frequencies of the partials of the squeak caused by bad fingering tend to decrease in the middle of the squeak; then they go up again and end even above the frequency they started on. The overtones of the squeak caused by a bad reed are more stable for the lower harmonics, but above 5 kHz they start showing the same kind of decrease/increase as the fingering squeak.

Concerning the good part of the squeak caused by bad finger coordination we see that it is similar to the good-quality tone except that initially there is a bit more noise between individual overtones. For the reed squeak tone, there is a striking difference during the first 100 ms up to the middle of the tone where the squeak starts. Additional subharmonics corresponding to a missing fundamental an octave below the actual one fill the spaces between the normal $\mathbf{A}^{\mathbf{Up}}$ overtones and create a dense spectrum.

Analysis of another $\mathbf{A}^{\mathbf{Up}}$ tones of each squeak type gave the same characteristics.

Line spectra analysis

F^{Low} Squeak

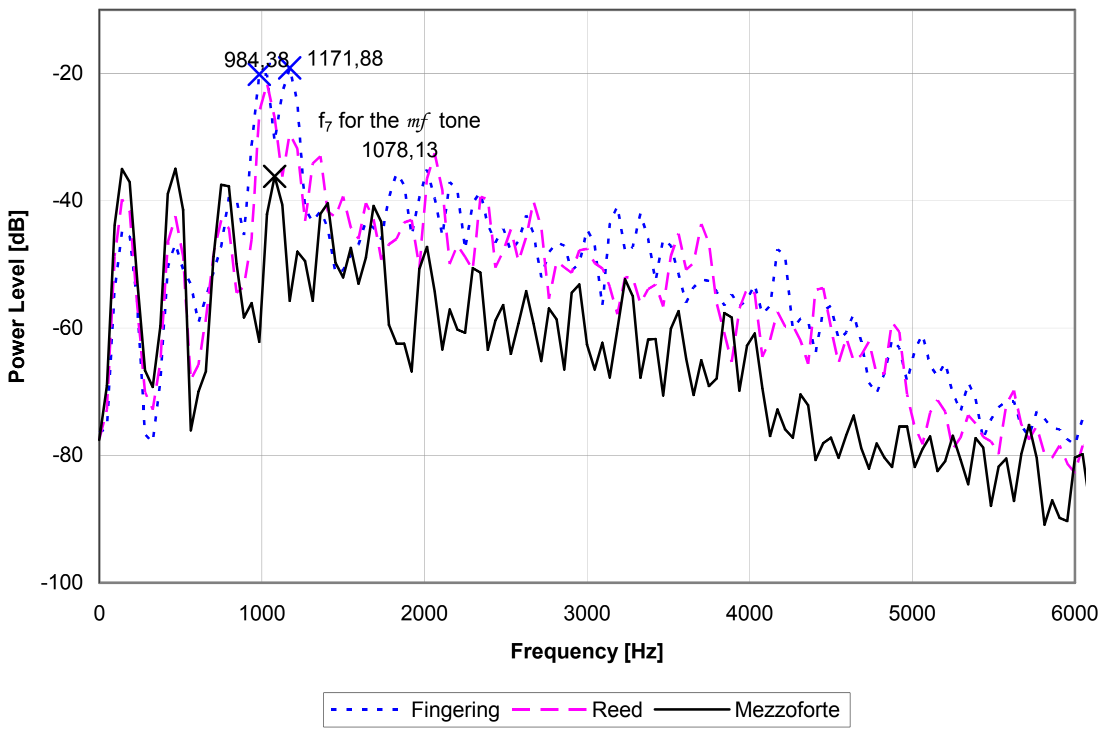


Figure 14: Averaged line spectra for the tone F^{Low} normal mf and the squeak part of F^{Low} squeak tone caused by bad reed and by bad fingering, respectively.

The spectra for the squeak parts of the tones are compared with the normal *mf* tone in *Figure 14*. Interestingly, the squeak spectra share many characteristics with the normal *mf* tone. The harmonics f_0, f_2 and f_4 for both squeaks have only slightly lower level than the *mf* tone, and the average level above 1500 Hz is somewhat higher. The low, even harmonics are missing in both cases as expected.

The squeaks correspond to two high spectral peaks at about 1000-1200 Hz. This region corresponds to the frequencies around f_6 of the normal $\mathbf{F}^{\mathbf{Low}}$. These high-intensity peaks can be heard as the characteristic harsh and metallic tone quality of squeak tones.

The tone caused by bad finger coordination shows two peaks in the 1000-1200 Hz range, which gives an impression of a double tone.

F^{Low} *Good Part (Squeak)*

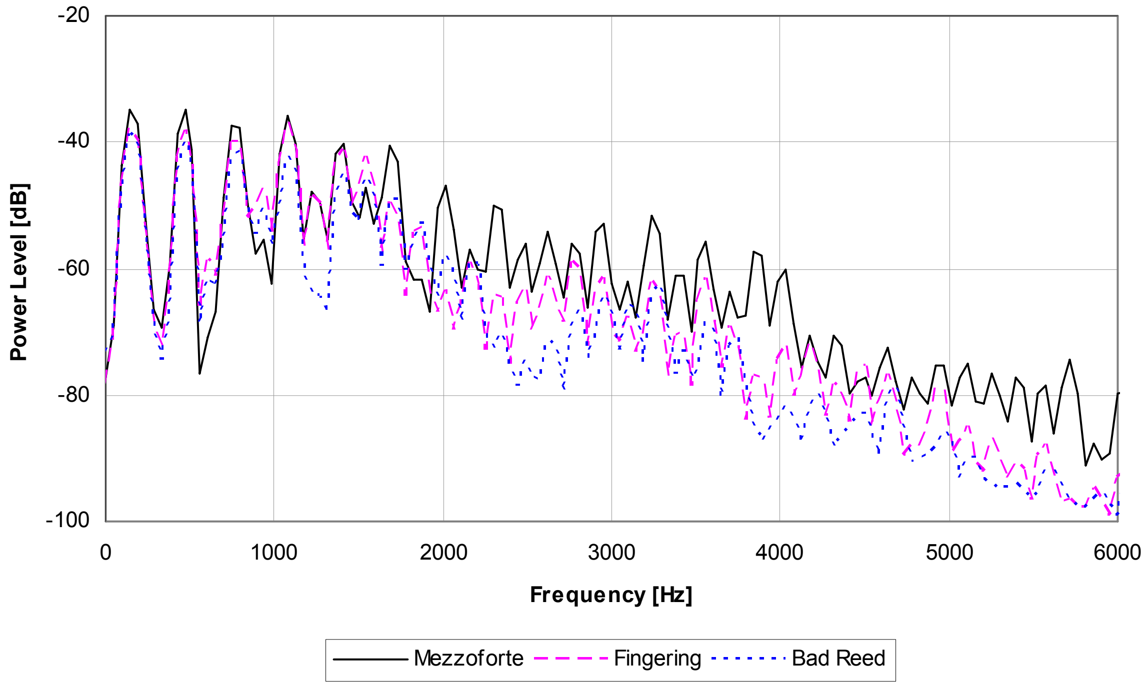


Figure 15: Averaged spectrum for F^{Low} normal mf and the good part of the F^{Low} squeak tone caused by bad reed and by bad fingering.

Comparing normal *mf* tones and the good part of the squeak tones, no clear differences for the first harmonics can be seen (see Figure 15). More noteworthy differences can be seen above f_{11} at about 1800 Hz, where the spectra for both squeak tones start to fall below the normal tone. At higher frequencies, above 3000 Hz, the squeak-tone level decreases even more. Those differences, which occur quite high in frequency, contribute to the perception of the *mf* tone as brighter and having more depth.

The spectra for the $\mathbf{G}^{\mathbf{Mid}}$ squeaks supports the observations made from the spectrograms in *Figure 11*. The division of the squeaks in two phases is apparent. The spectrum for the start of the squeak shows that all $\mathbf{G}^{\mathbf{Mid}}$ harmonics exist, but with slightly down-shifted frequencies. Also, the levels at the start of the squeak are much higher compared to the normal *mf* note, except for the fundamental. The spectrum for the end of the squeak shows how the $\mathbf{G}^{\mathbf{Mid}}$ partials, present in the beginning of the squeak, changes to an octave and fifth higher.

G^{Mid} Squeak

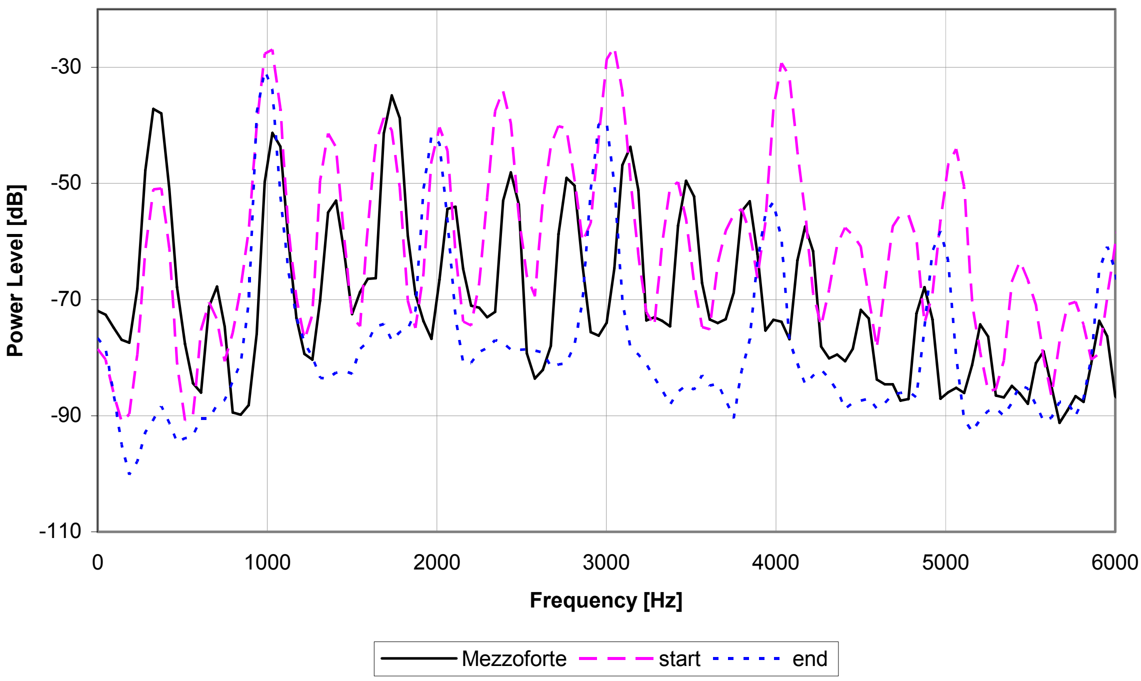


Figure 16: Averaged spectra of the two different states of the G^{Mid} squeak, taken in the beginning and at the end, compared to the normal mf G^{Mid} tone.

G^{Mid} Good Part (Squeak)

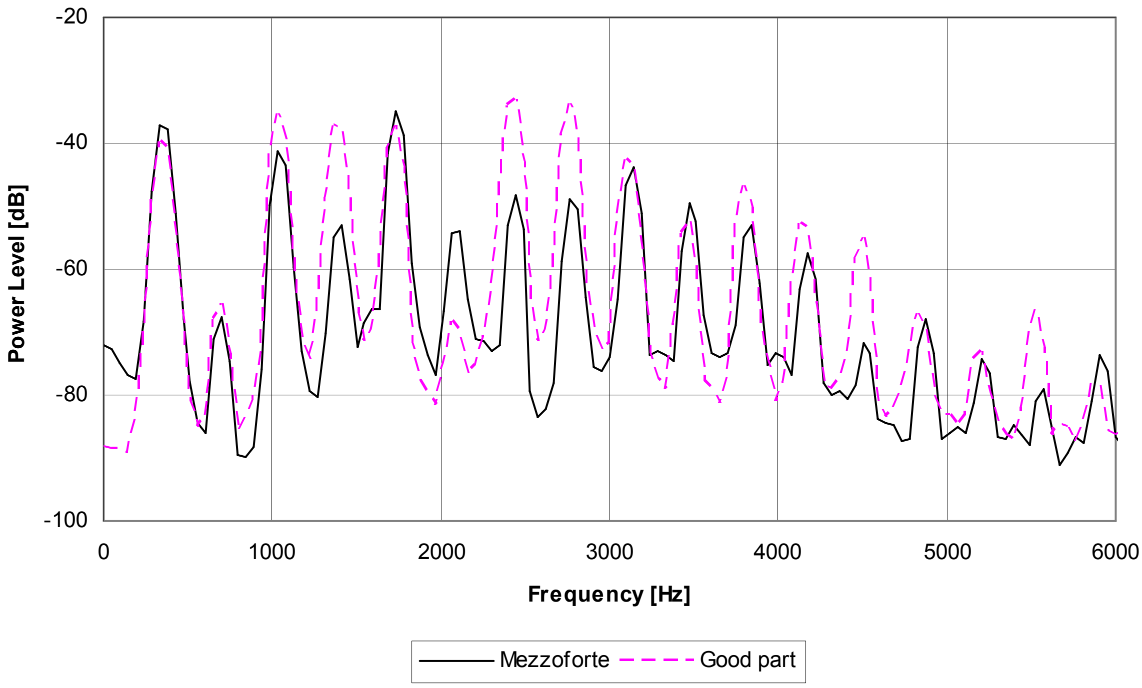


Figure 17: Averaged spectrum for G^{Mid} normal mf and the good part of the G^{Mid} squeak tone caused by bad reed.

The averaged spectra for normal **G^{Mid}** *mf* tone and the good part of the squeak tone are similar (see *Figure 17*). The only difference that can be observed is that individual overtones such as f_2, f_3, f_6 and f_7 are higher in level than those for the normal *mf* tone. These level differences make the tone slightly harsh and brighter in timbre. The observed differences, which give the good part of the tone its coloring and particularity, may be the reason why this part does not sound typical of a **G^{Mid}** note for a clarinet.

B^{Mid} Fingering Squeak

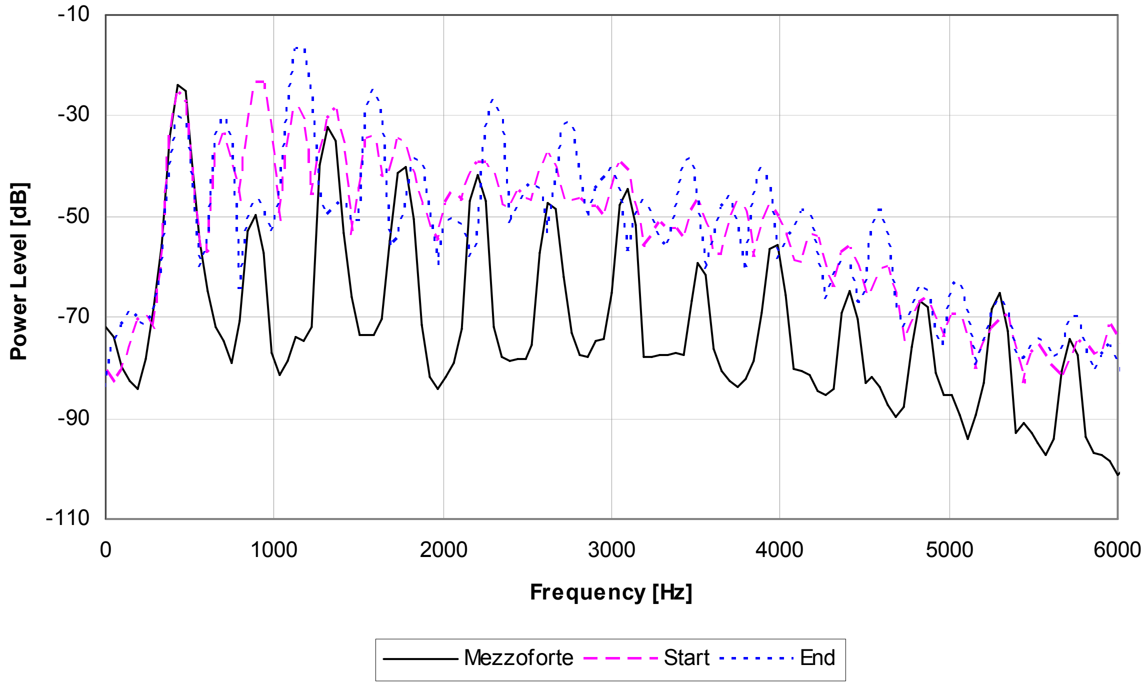


Figure 18: Averaged spectrum for B^{Mid} normal mf and two states of the B^{Mid} squeak tone caused by bad fingering.

In this example the squeak extended for the whole duration of the note. *Figure 18* shows the average spectra. Compared to the normal *mf* tone the squeak contains interleaved partials, corresponding to a missing fundamental one octave below the **B^{Mid}** fundamental. This can explain the fact that this tone could not be recognized as a **B^{Mid}**. However it is interesting to note that the **B^{Mid}** fundamental f_0 exists during the whole duration of the squeak with just a slightly lower level than in the *mf* tone.

The tone had no good part as mentioned, and all repeats gave a similar result. For this reason is not possible to relate the spectrum characteristics of the squeak to the good part of the tone.

B^{Mid} *Reed Squeak and Good Part*

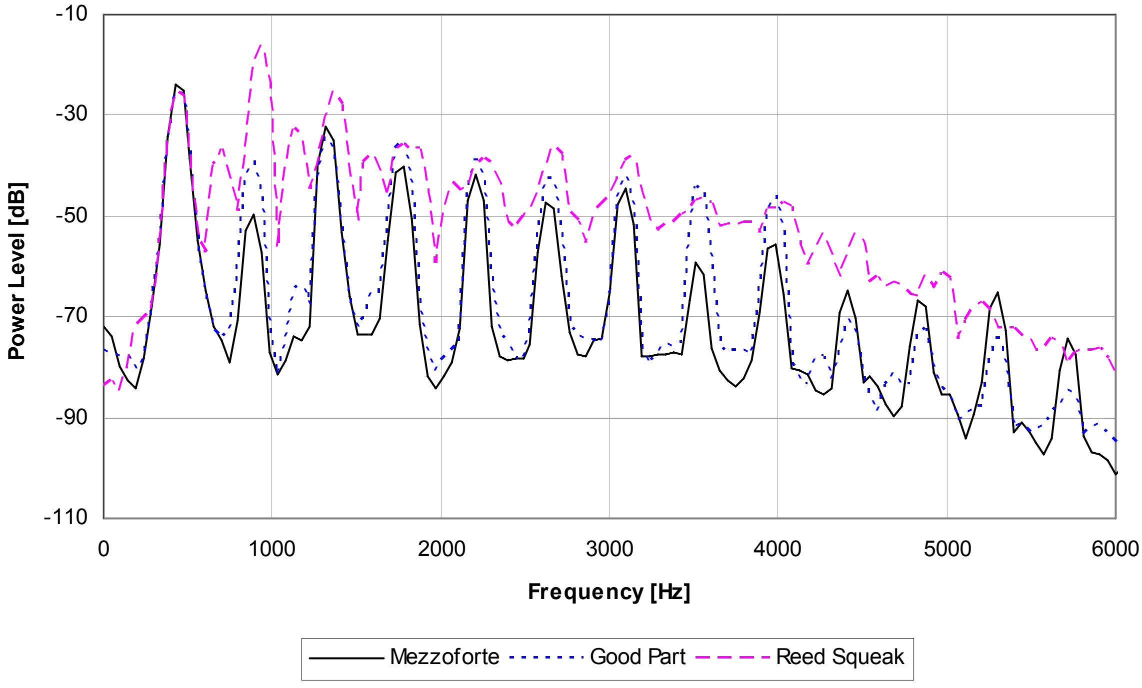


Figure 19: Averaged spectrum for B^{Mid} normal mf, averaged spectrum for the good part B^{Mid} squeak tone and the squeak part caused by bad reed.

The spectrum for the normal $\mathbf{B}^{\mathbf{Mid}}$ *mf* tone and the good part of the squeak tone are almost identical (see *Figure 19*), except that the overtones for the good part are slightly higher in level up to f_8. The fundamentals are equally strong. Perceptually, the good part has less depth than the *mf* tone.

The fundamental of the squeak part is in this case identical to the fundamental of the good part of the tone, both with respect to frequency and amplitude. Again, interleaved partials of the same magnitude as the original partials fill the squeak spectrum. This gives a rather smooth spectral contour which eventually follows the partial peaks of the good part of the tone up to f_6 (3000 Hz), followed by a fall-off towards higher frequencies.

The pitch of the squeak part of $\mathbf{A}^{\mathbf{Up}}$ is shifted up in frequency by approximately a fourth for the fingering squeak and a fifth for the reed squeak, corresponding to about 300 and 400 Hz, respectively (see *Figure 20*). This brings the frequency of the second harmonic of the squeaks close to the third harmonic of the normal tone. Both level and frequencies of the squeak caused by fingering are slightly lower than for the bad reed squeak. This is probably a consequence of the bad finger coordination.

A^{Up} Squeak

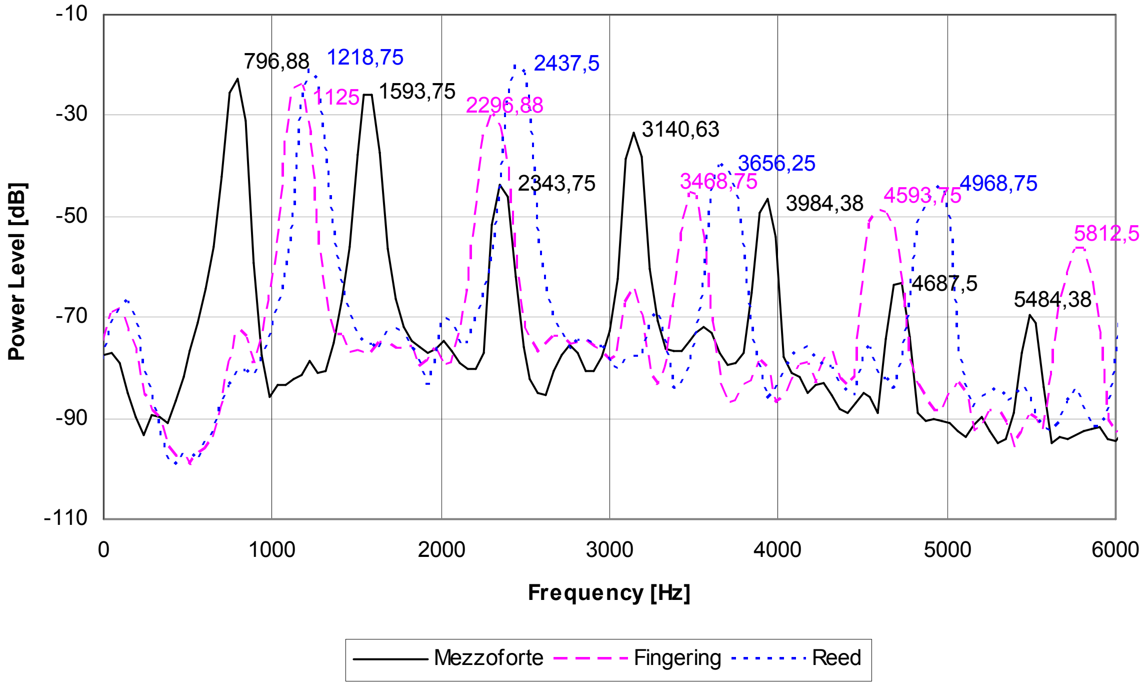


Figure 20: Averaged spectra for the two A^{Up} squeak tones caused by bad reed and bad finger coordination, compared to the A^{Up} normal mf tone.

A^{Up} Good Part (Squeak)

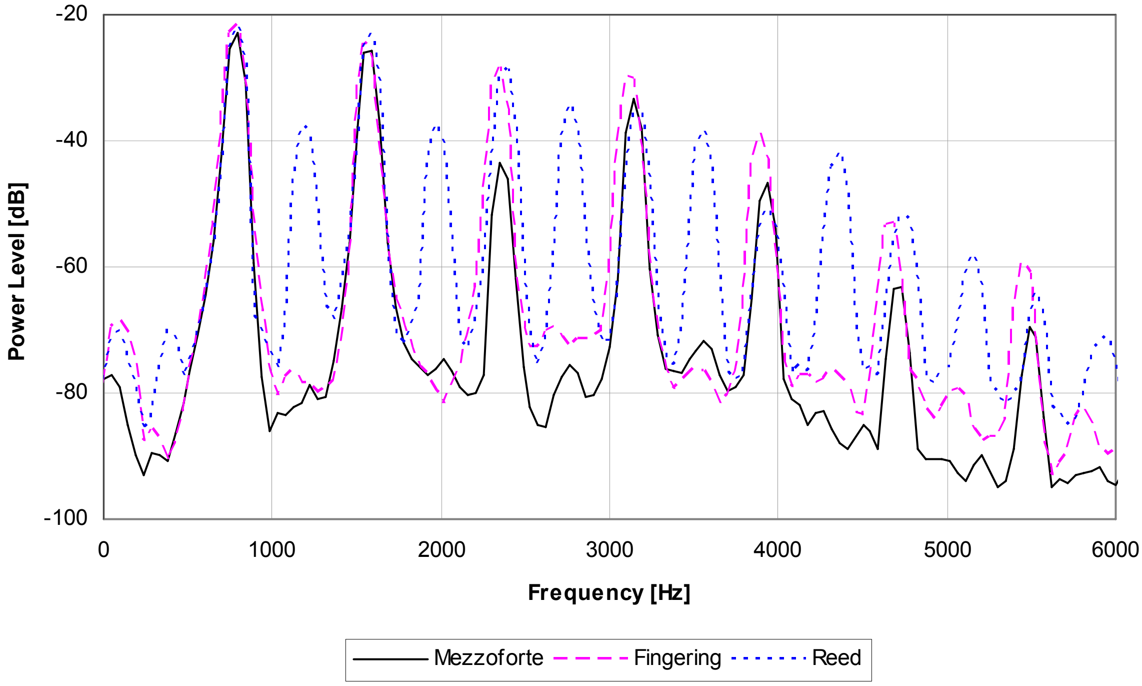


Figure 21: Averaged spectrum for A^{Up} normal mf and the good part of the A^{Up} squeak tone caused by bad reed and bad fingering.

For the good part of the squeak caused by bad fingering there is much similarity with the normal $\mathbf{A}^{\mathbf{Up}}$ *mf* tone. The levels for the peaks of the squeak tone are slightly higher from f_2 and upwards (see *Figure 21*). In contrast, the tone caused by a bad reed has peaks in-between the ordinary harmonics for an $\mathbf{A}^{\mathbf{Up}}$ normal tone. When analyzing the spectra for reed squeak at different moments in time, we could not see large differences for the harmonics which fit to the normal tones $\mathbf{A}^{\mathbf{Up}}$ harmonics. However, the extra overtones, which do exist during the whole duration of the good part of the tone, show largely varying levels (see *Figure 22*).

A^{Up} Good Part (Squeak)

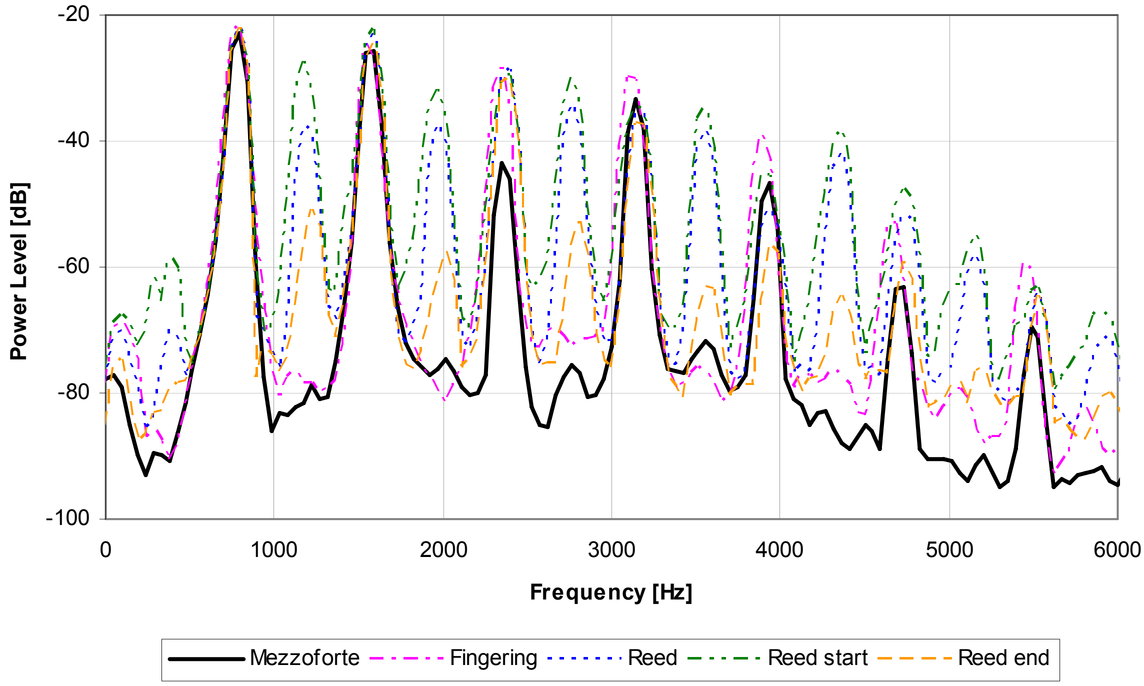


Figure 22: Spectra for the A^{Up} squeak tone caused by bad reed at different time instances (reed = averaged over the good part of the tone, reed start and reed end).

Conclusions

Squeaks can occur at the start of the tone, as for $\mathbf{F}^{\mathbf{Low}}$ and $\mathbf{B}^{\mathbf{Mid}}$ caused by a bad reed in the examples above, and in the end as for $\mathbf{G}^{\mathbf{Mid}}$ and $\mathbf{A}^{\mathbf{Up}}$. There was also the extreme case of $\mathbf{B}^{\mathbf{Mid}}$ caused by bad finger coordination where there was no good part at all to indicate the intended tone.

For the squeaks in the start of the tone it can be concluded that the spectra show much higher maxima at the partial peaks but less pronounced dips in between, giving a compressed spectral variation compared to the good part of the tone. The partials can be shifted in frequency as well. Furthermore, there are peaks in between the actual overtones.

For the squeaks at the end of the tone, the overtone peaks have much higher level than during the good part of the tone, and partials in between the actual overtones can appear. For this type of squeaks the spectral dips are as pronounced as for the good-quality tone. Most importantly, this type of squeaks tends to be perceived as another tone with a new pitch, since the fundamental frequency of the actual tone disappears.

For $\mathbf{G}^{\mathbf{Mid}}$ squeak the new f_0 is one octave and a fifth above, for $\mathbf{A}^{\mathbf{Up}}$ reed squeak a fifth above, while the f_0 for the $\mathbf{A}^{\mathbf{Up}}$ fingering squeak is a fourth above. These observed frequency shifts need to be validated by further experiments before a firm conclusion about the size of the pitch-shift intervals in squeaks can be drawn.

It turned out to be difficult to formulate general features which discriminate between squeaks caused by a bad reed and bad finger coordination, respectively. The squeaks caused by a bad reed at $\mathbf{F}^{\mathbf{Low}}$ and $\mathbf{B}^{\mathbf{Mid}}$, both occurred at the start of the tone, and both were shorter than the squeaks caused by bad fingering. For squeaks occurring at the end of the tones no corresponding conclusion about the duration of the two types of squeaks could be drawn.

The good part of the squeak tones show in most cases a clear resemblance with the good-quality tone. Two exceptions were the $\mathbf{B}^{\mathbf{Mid}}$ squeak tone caused by bad fingering, where there was no good part at all, and the $\mathbf{A}^{\mathbf{Up}}$ squeak tone caused by a bad reed, where in-between partials could be seen. The spectral characteristics of the good part of the squeak tones can be quite different compared to the normal *mf* tone. In some cases the average spectral level was lower compared to the normal tone and in other cases higher. Commonly, more noise could be found in between the overtones in the good part of the squeak tones. Perceptually, the good parts of the squeak tones were close to the normal tones, but not as bright and rich.

Future work should analyze and consider more tones in the same registers to check if they share the characteristics of the analyzed tones. Although $\mathbf{G}^{\mathbf{Mid}}$ and $\mathbf{B}^{\mathbf{Mid}}$ are in the same register, they were not expected to behave in the same way, since $\mathbf{G}^{\mathbf{Mid}}$ is a special tone with regard to fingering. This expectation was confirmed by the result of the analysis. Moreover, it would be beneficial to look into tones such as the $\mathbf{B}^{\mathbf{Mid}}$ caused by bad fingering where there was only a squeak part and no good part at all. Also, further studies should investigate if the two kinds of squeaks can be distinguished with respect to the durations.

Algorithmic description

The analysis did unfortunately not provide means to distinguish squeaks caused by a bad reed from squeaks caused by bad finger coordination. Only a general algorithm for squeaks occurring in the beginning and at the end can be given.

- If there is a marked change in the spectrum of a tone, either in the beginning or at the end, then this change can be a squeak.

- For changes in the beginning of the tone, it should be checked if the spectral content across the unstable part of the tone extends to higher frequencies than expected for the normal tone. Moreover, if the partial peaks are higher and the dips in between are less pronounced compared to the good part of the tone, this indicates a squeak. Another strong indication for a squeak is peaks between the overtones of the normal tone.

- For changes at the end of the tone, it should be checked if the fundamental frequency of the expected tone disappears, and if the overtone structure corresponds to a much higher pitch. In addition, if the partial peaks have higher level than the normal tone, while the spectral dips still are low, this is an additional indication of a squeak. If other partials are present in between the overtones of the normal tone, this is a further indication of a squeak.

6.2.3 Unstable tones

Spectrogram analysis

F^Low

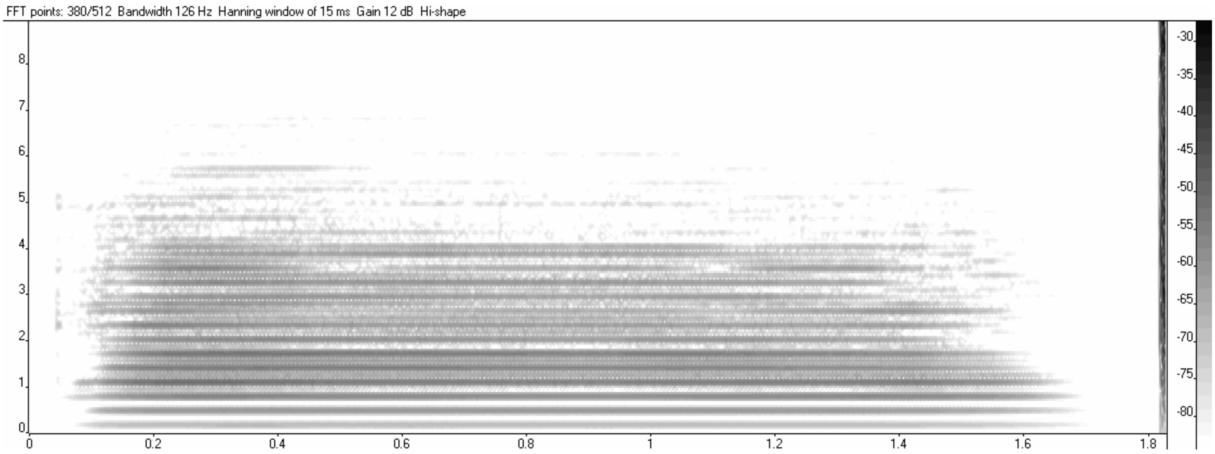


Figure 23: Spectrogram for F^{Low} normal mf

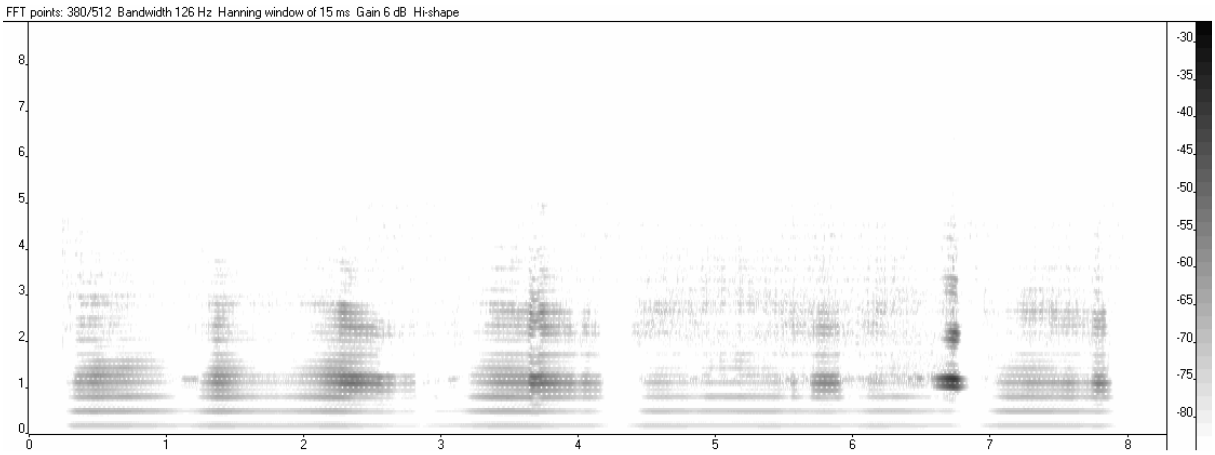


Figure 24: Spectrogram for F^{Low} Unstable

G^{Mid}

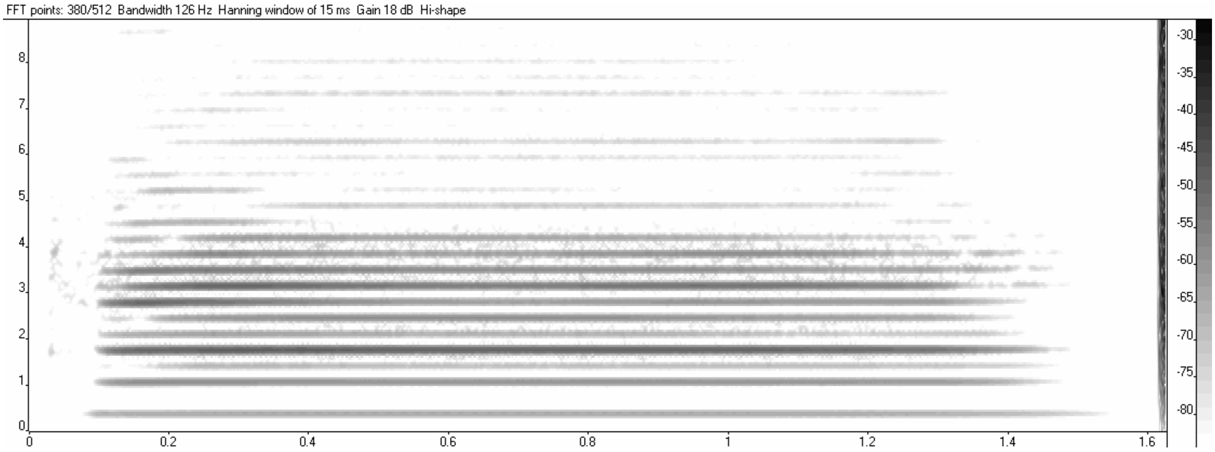


Figure 25: Spectrogram for G^{Mid} normal mf

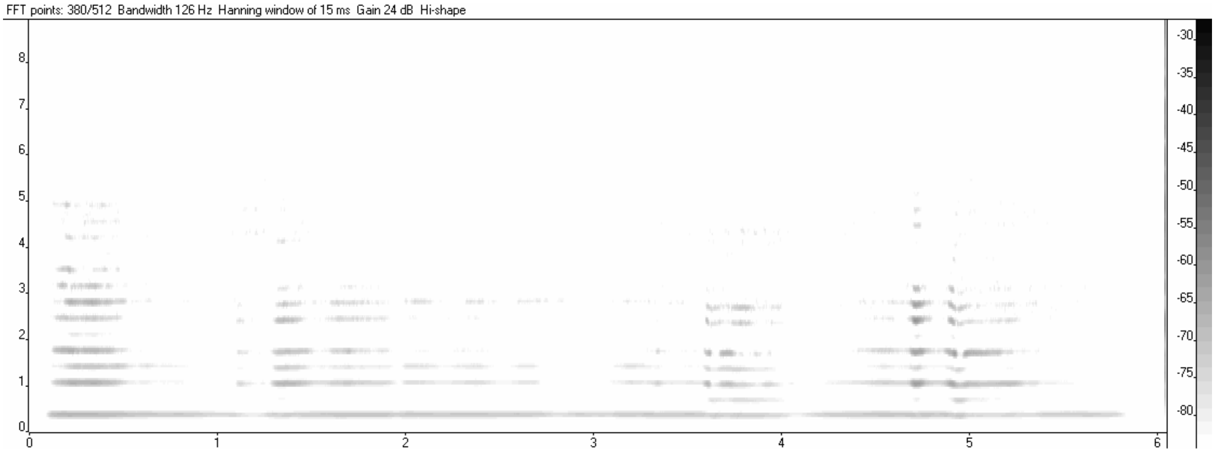


Figure 26: Spectrogram for G^{Mid} Unstable

B^{Mid}

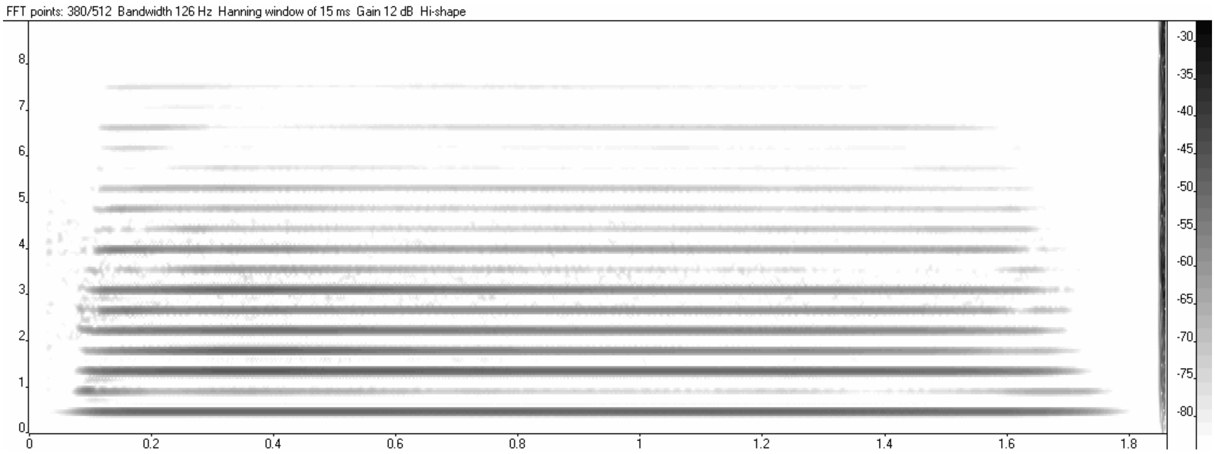


Figure 27: Spectrogram for B^{Mid} normal mf

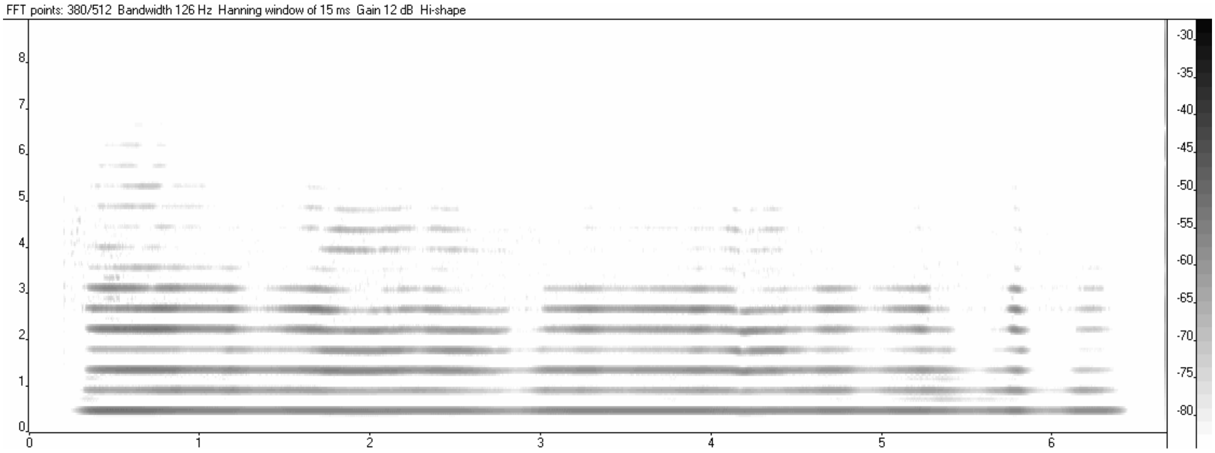


Figure 28: Spectrogram for B^{Mid} Unstable

A^{Up}

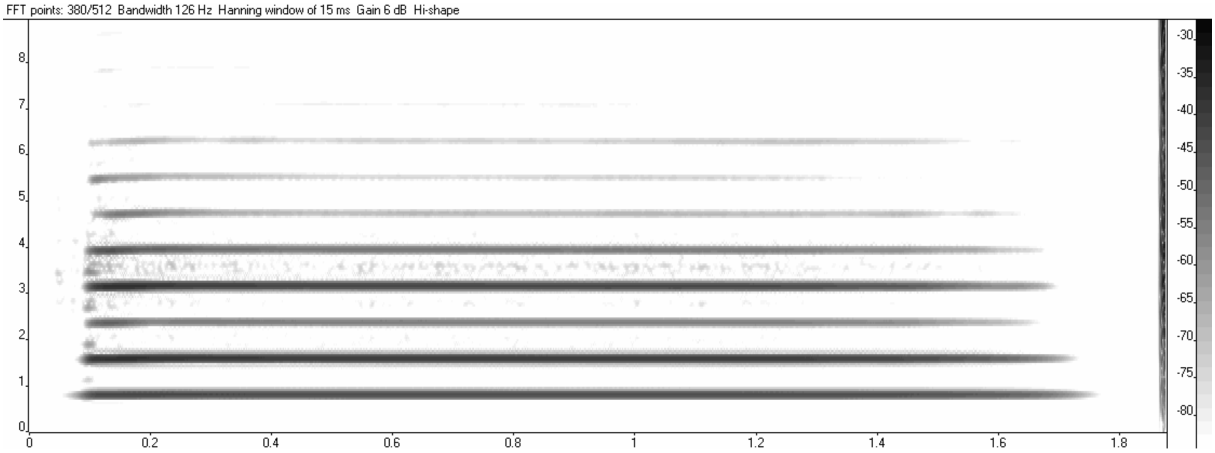


Figure 29: Spectrogram for A^{Up} normal mf

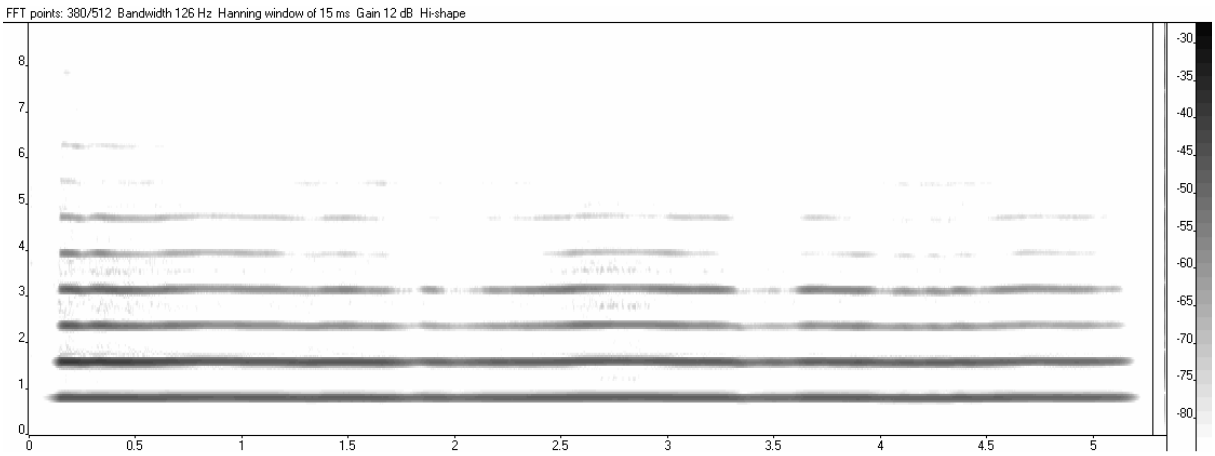


Figure 30: Spectrogram for A^{Up} Unstable

The spectrograms for all four unstable tones $\mathbf{F}^{\mathbf{Low}}$, $\mathbf{G}^{\mathbf{Mid}}$, $\mathbf{B}^{\mathbf{Mid}}$ and $\mathbf{A}^{\mathbf{Up}}$ (Figure 23 – Figure 30) show similarities in the way they develop over the duration of the tone. There are ‘cut-outs’ (cancellations) of varying durations in the harmonics (mostly the higher harmonics for the higher register tones). During those parts of the unstable tones the timbre gets duller, less brilliant and without richness. Perceptually unstable tones are bad in quality during the whole duration, although during these cut-outs they sound even worse.

A comparison of the spectrograms of the unstable tones with the corresponding normal *mf* tones shows that the unstable tones do not have as high overtone content, although f_0 and f_1 exists almost throughout the whole duration of the tone. The exception is $\mathbf{G}^{\mathbf{Mid}}$ (see *Figure 26*), where f_1 is not as strong as in the *mf* tone. In the case of $\mathbf{B}^{\mathbf{Mid}}$ (*Figure 28*) and $\mathbf{A}^{\mathbf{Up}}$ (*Figure 30*) the cut-outs in the overtones start even higher.

Moreover, the existing overtones for all four unstable tones occur at the same frequencies as for the good-quality tones, except from minor displacements where the tone sounds out of tune compared to the normal *mf*.

Line spectra analysis

F^{Low} Unstable Average

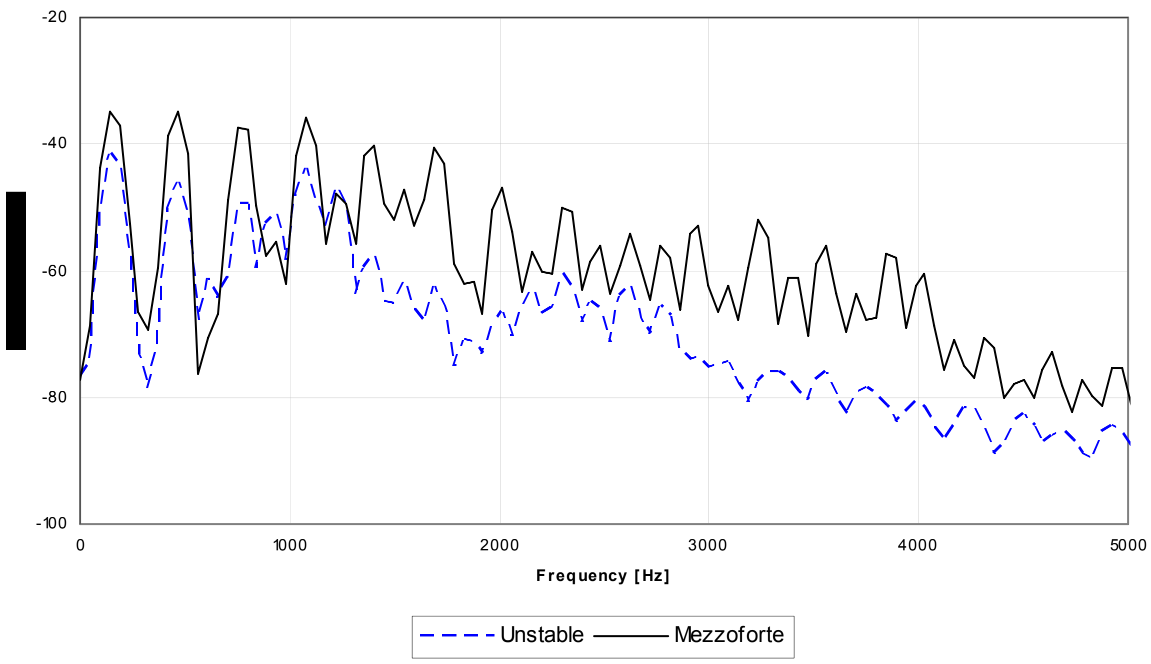


Figure 31: Averaged spectra for the tone F^{Low} unstable and F^{Low} normal mf.

Comparing the line spectra of the normal *mf* tone and the unstable $\mathbf{F}^{\mathbf{Low}}$ tone the same tendencies can be observed up to 1 kHz (see *Figure 31*), although the levels are slightly lower for the unstable tone. A level decrease of an average value of 14 dB can be observed (see Table 7). When normalized to the fundamental the average difference is reduced to 7 dB. This normalization can be motivated by the fact that the fundamental and lower harmonics are dominating in the spectrum and set the measured sound pressure level (SPL) as well as the perceived sound level. At higher frequencies the differences are more apparent and there is no clear overtone content in the unstable tone.

Table 7: Levels for the 7 first odd harmonics for F^{Low} normal mf, F^{Low} unstable average and their differences. Note that as the lowest partial (fundamental) is given index 0 the odd partials correspond to even numbers. The frequencies of the harmonics are approximate, taken as the peak frequencies in the spectra. Due to the relatively short time window (Hanning 15 ms) the frequency resolution is rather coarse (47 Hz).

	Frequency [Hz]	F^{Low} *mf* [dB]	F^{Low} unstable average [dB]	Difference [dB]	Normalized diff. [dB]
f_0	140,6	-35	-42	-7	0
f_2	468,7	-35	-46	-11	-4
f_4	750,0	-37	-50	-13	-6
f_6	1 078	-36	-44	-8	-1
f_8	1 406	-40	-57	-17	-10
f_{10}	1 687	-41	-62	-21	-14
f_{12}	2 015	-47	-67	-20	-13
				Ave ≈ **-14**	**-7**

F^{Low} Unstable

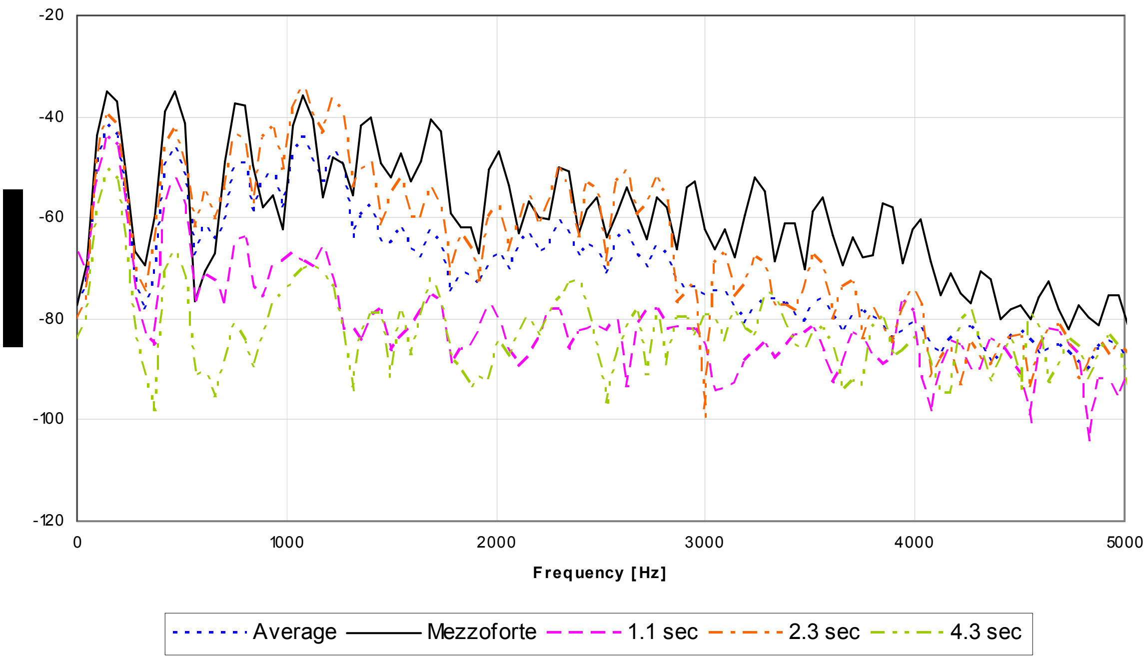


Figure 32: Averaged spectrum for the tone F^{Low} unstable, F^{Low} normal mf tone and spectra for three time instances of the unstable F^{Low} tone at 1.1, 2.3 and 4.3 seconds.

The spectra of the unstable **F^{Low}** tone at different time instances show a striking variation of the spectral content, i.e. the unstable tone is characterized by pronounced fluctuations of the partial levels (see Figure 32). For this reason, the averaged level differences between the two tones, **F^{Low}** unstable averaged and **F^{Low}** normal *mf*, do not give full information (see *Table 8*). Almost all overtones of the unstable tone can 'disappear' for certain moments of time except for the fundamental frequency which is present all the time but with fluctuations in level. When the unstable **F^{Low}** tone gets out of tune, overtones with shifted frequencies compared to the normal *mf* tone can be observed.

Table 8: Level differences for the 7 first odd harmonics for F^{Low} normal mf tone, the averaged unstable tone, and three cases taken at 1.1, 2.3 and 4.3 seconds. A difference of almost 16 dB for f_0 between F^{Low} mf and F^{Low} unstable at 4.3 seconds can be seen, instead of 7 dB which is the case for F^{Low} mf and F^{Low} unstable average. For f_2 the difference gets as high as 31 dB. See also comments to Table 8 for explanations.

	Freq [Hz]	F^{Low} *mf* [dB]	F^{Low} unstable average [dB]	1.1 sec [dB]	2.3 sec [dB]	4.3 sec [dB]	Max dev from F^{Low} unstable aver. [dB]
f_0	140,6	-35	-42	-44	-40	-51	-9
f_2	468,7	-35	-46	-52	-43	-66	-20
f_4	750,0	-37	-50	-65	-44	-81	-31
f_6	1 078	-36	-44	-69	-34	-70	-26
f_8	1 406	-40	-57	-79	-49	-79	-22
f_{10}	1 687	-41	-62	-75	-54	-72	-13
f_{12}	2 015	-47	-67	-80	-57	-84	-17

G^{Mid} *Unstable Average*

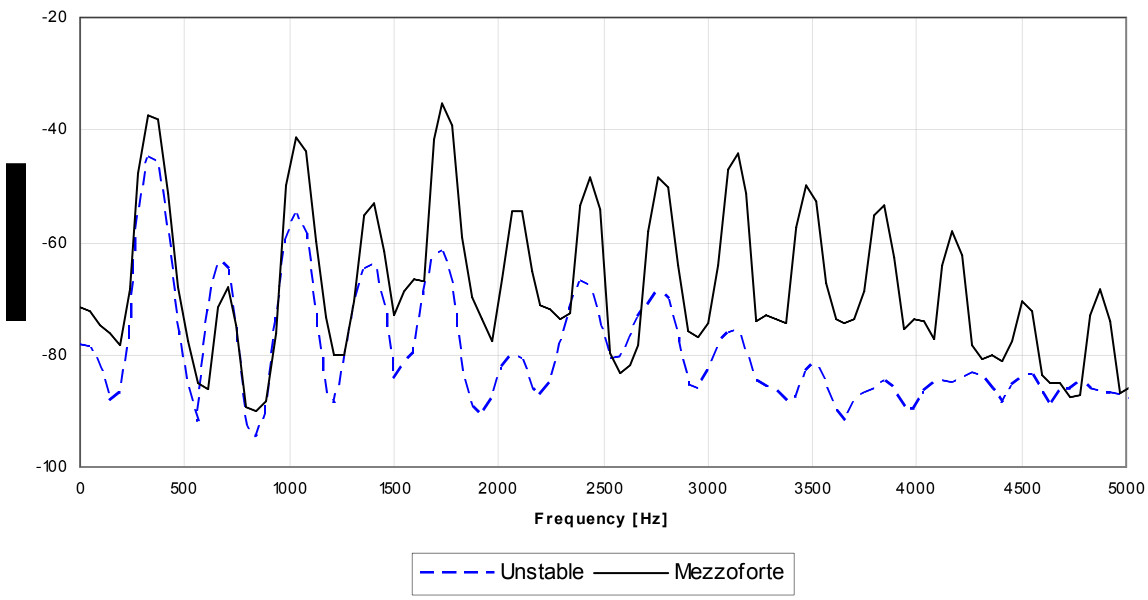


Figure 33: Averaged line spectra for G^{Mid} unstable and G^{Mid} normal mf tone.

Comparing the $\mathbf{G}^{\mathbf{Mid}}$ unstable tone and the normal *mf* tone (see *Figure 33*) the same tendencies as for the $\mathbf{F}^{\mathbf{Low}}$ tone can be seen. The level of all overtones of the unstable tone is 15 dB lower at an average (see *Table 9*), and 7 dB lower when normalized to the fundamental.

Table 9: Level differences for the 8 first overtones for G^{Mid} normal mf and G^{Mid} unstable average.

	Frequency [Hz]	G^{Mid} *mf* [dB]	G^{Mid} unstable aver. [dB]	Difference [dB]	Normalized difference [dB]
f_0	328,1	-37	-45	-8	0
f_1	703,1	-68	-65	3	12
f_2	1 031	-41	-55	-14	-6
f_3	1 406	-53	-64	-11	-3
f_4	1 734	-35	-62	-27	-19
f_5	2 109	-54	-81	-27	-19
f_6	2 437	-49	-68	-19	-11
f_7	2 765	-49	-69	-20	-12
				Ave ≈ **-15**	**-7**

G^{Mid} Unstable

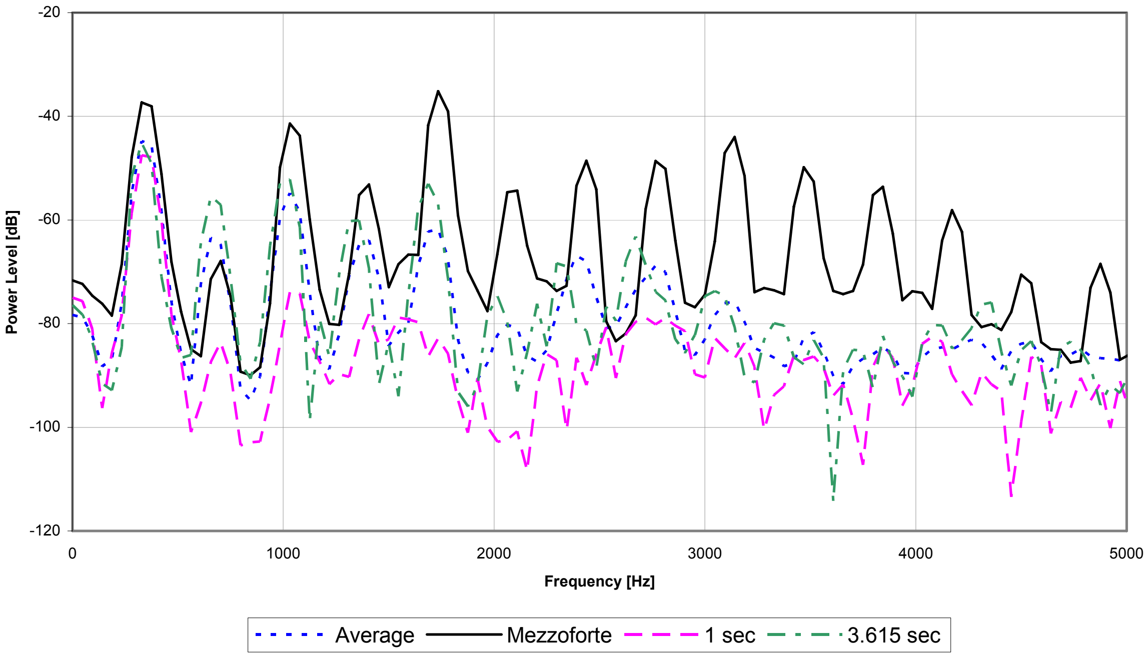


Figure 34: Spectra for the tone G^{Mid} unstable averaged and for two time instances taken at 1 and 3.6 seconds, compared with G^{Mid} normal mf tone.

The same variation in partial levels as for the $\mathbf{F}^{\mathbf{Low}}$ unstable tone can be observed in the spectra for $\mathbf{G}^{\mathbf{Mid}}$ unstable at two time instances, here taken at 1.0 and 3.6 s (see Figure 34). There are striking fluctuations in partial levels (see *Table 10*), especially for the spectrum taken at 1 s. The spectra for the unstable tone show down-shifted frequencies, in particular for the spectrum taken at 3.6 s (of the order of -60 cent). The tone in this case sounds out of tune. Those differences are not visible when comparing the **G^{Mid}** average and **G^{Mid}** normal *mf*.

Table 10: Level differences for the 8 first overtones for G^{Mid} normal mf, G^{Mid} unstable average and G^{Mid} unstable taken at 1 s.

	Frequency [Hz]	G^{Mid} *mf* [dB]	G^{Mid} unstable average [dB]	G^{Mid} unstable 1 s [dB]
f_0	328,1	-37	-45	-48
f_1	703,1	-68	-65	-84
f_2	1 031	-41	-55	-74
f_3	1 406	-53	-64	-78
f_4	1 734	-35	-62	-83
f_5	2 109	-54	-81	-101
f_6	2 437	-49	-68	-92
f_7	2 765	-49	-69	-80

B^{Mid} Unstable Average

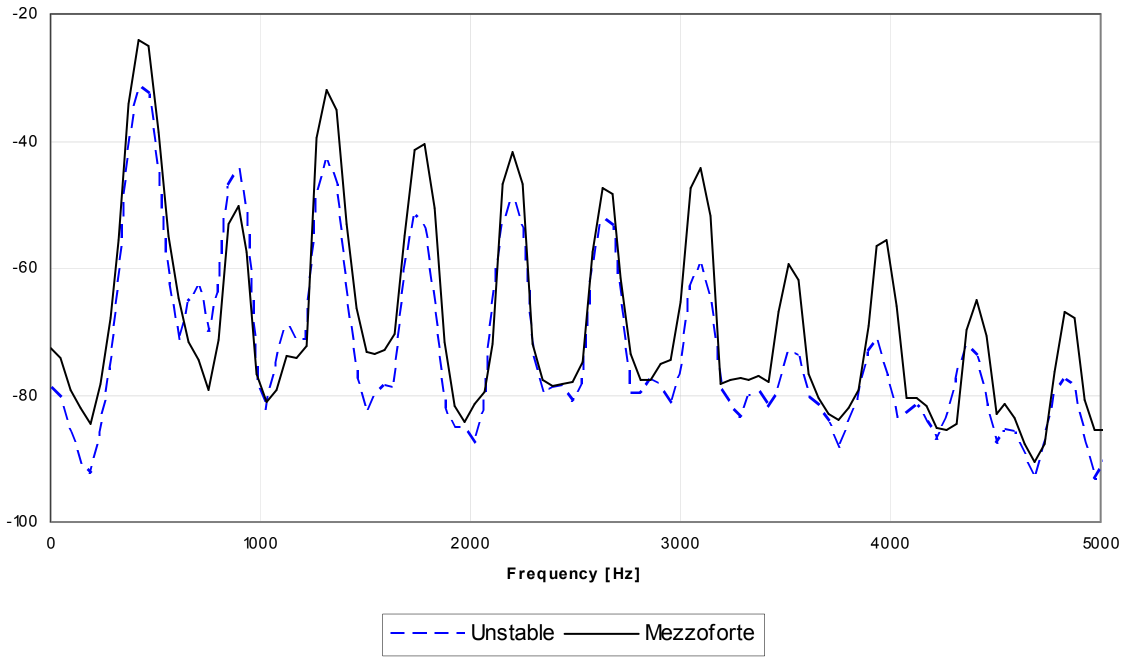


Figure 35: Averaged line spectra for the tone B^{Mid} unstable and B^{Mid} normal mf.

The averaged spectra for the normal *mf* tone and the unstable tone for **B^{Mid}** are rather similar (see *Figure 35*). The first difference observed is that f_1 for the unstable tone is higher in level than in the normal *mf* tone (+13 dB in the normalized difference). Higher overtones decreased in level starting at f_6 (see *Table 11*).

Table 11: Level differences for the 9 first harmonics for B^{Mid} normal mf and B^{Mid} unstable average.

	Frequency [Hz]	B^{Mid} *mf* [dB]	B^{Mid} unstable average [dB]	Difference [dB]	Normalized difference [dB]
f_0	421,8	-24	-31	-7	0
f_1	890,6	-50	-44	6	13
f_2	1 312	-32	-43	-11	-4
f_3	1 781	-40	-54	-14	-7
f_4	2 203	-42	-49	-7	0
f_5	2 625	-47	-52	-5	2
f_6	3 093	-44	-59	-15	-8
f_7	3 515	-59	-73	-14	-7
f_8	3 984	-56	-77	-21	-14
				Ave ≈ **-10**	**-3**

B^{Mid} *Unstable*

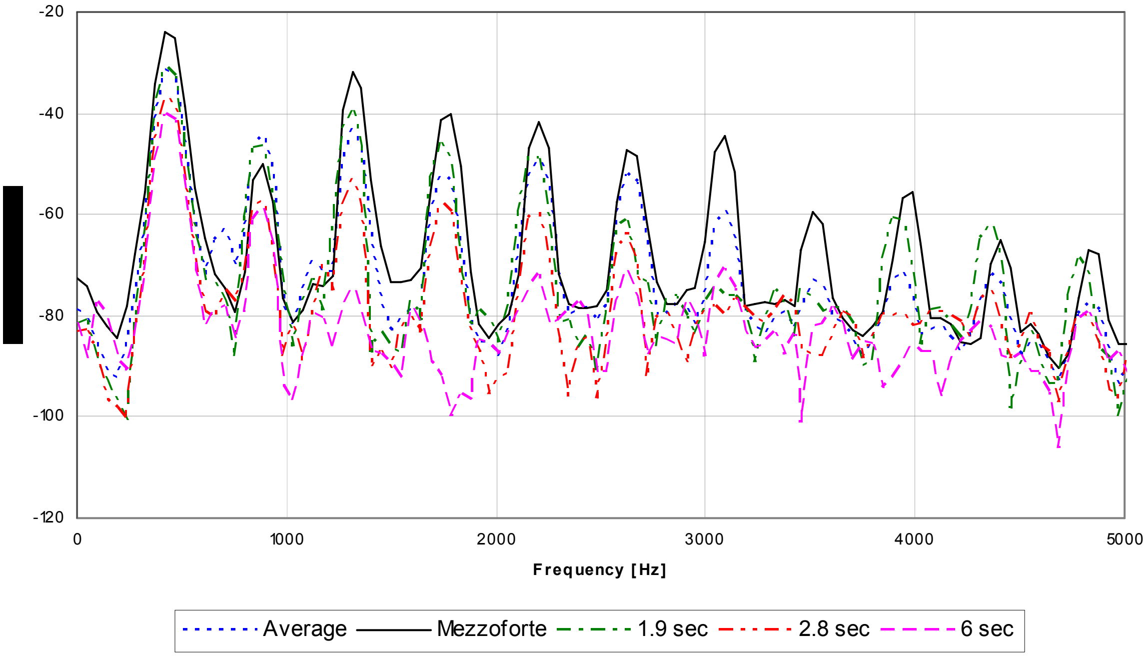


Figure 36: Spectra for the tone B^{Mid} unstable averaged and for three time instances taken at 1.9, 2.8 and 6 s, compared with B^{Mid} normal mf.

In the spectra for $\mathbf{B^{Mid}}$ unstable at different time instances, the same variations as for the two previous tones can be observed (see *Figure 36* and *Table 12*). The spectrum taken at 1.9 s is an illustrative example of shifts in frequency (of the order of 40 cent). In the spectrum taken at 2.8 s, all overtones above 3000 Hz disappear almost completely. The spectrum taken at 6 s is a good example of overtones disappearing already at f_2. The decrease in average level for

B^{Mid} unstable compared to **B^{Mid}** normal *mf* tone is pronounced, with a consequence of poor quality tone.

Table 12: Level differences of the 9 first harmonics for B^{Mid} normal mf, B^{Mid} unstable average and at two instances taken at 2.8 and 6 s.

	Frequency [Hz]	B^{Mid} *mf* [dB]	B^{Mid} unstable average [dB]	2,8 s [dB]	6 s [dB]
f_0	421,9	-24	-31	-36	-40
f_1	890,7	-50	-44	-57	-58
f_2	1 312	-32	-43	-53	-74
f_3	1 781	-40	-54	-59	-100
f_4	2 203	-42	-49	-59	-72
f_5	2 625	-47	-52	-64	-70
f_6	3 094	-44	-59	-80	-70
f_7	3 516	-59	-73	-88	-82
f_8	3 984	-56	-77	-82	-86

A^{Up} Unstable Average

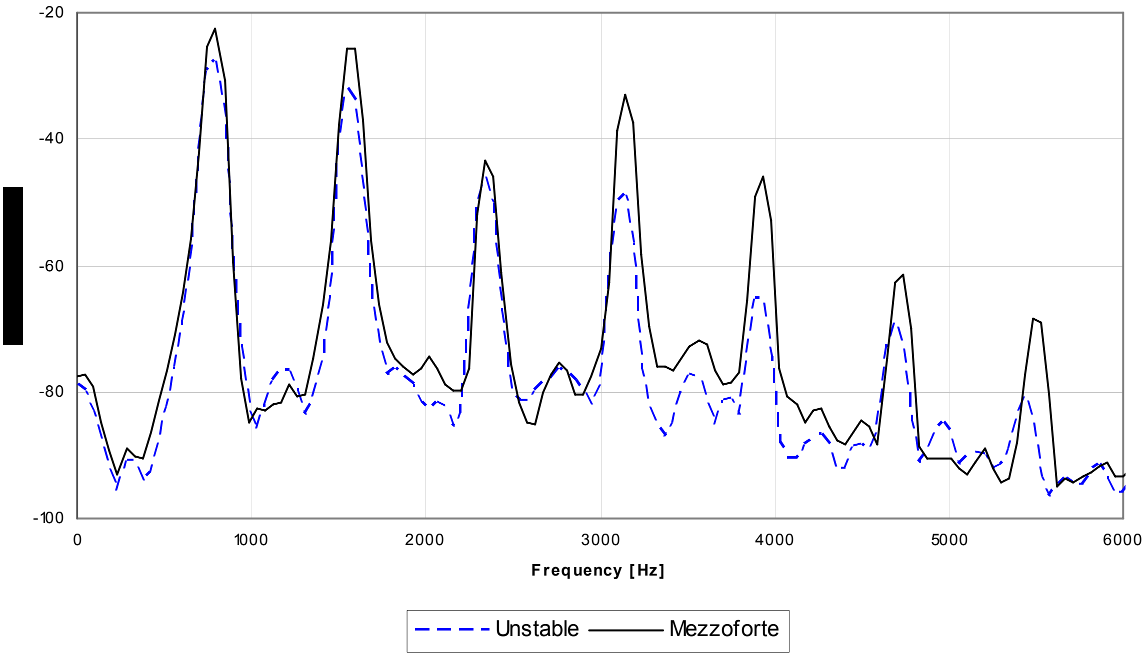


Figure 37: Averaged line spectra for the tone A^{Up} unstable and A^{Up} normal mf.

The level for each of the three first overtones of **A^{Up}** unstable is slightly lower than the corresponding normal *mf* tone (see *Figure 37*). For the higher overtones, the levels start to fall above f_3 and f_4 (see *Table 13*). **A^{Up}** unstable averaged showed an apparent shift in frequencies, clearly visible for the higher overtones.

Table 13: Level differences for the 7 first harmonics for A^{Up} normal mf and A^{Up} unstable average.

	Frequency [Hz]	A^{Up} *mf* [dB]	A^{Up} unstable [dB]	Difference [dB]	Normalized difference [dB]
f_0	796,9	-23	-28	-5	0
f_1	1 594	-26	-34	-8	-3
f_2	2 344	-44	-46	-2	3
f_3	3 141	-33	-49	-16	-11
f_4	3 937	-46	-65	-19	-14
f_5	4 734	-61	-73	-12	-7
f_6	5 531	-69	-93	-24	-19
				Ave ≈ **-12**	**-7**

A^{Up} Unstable

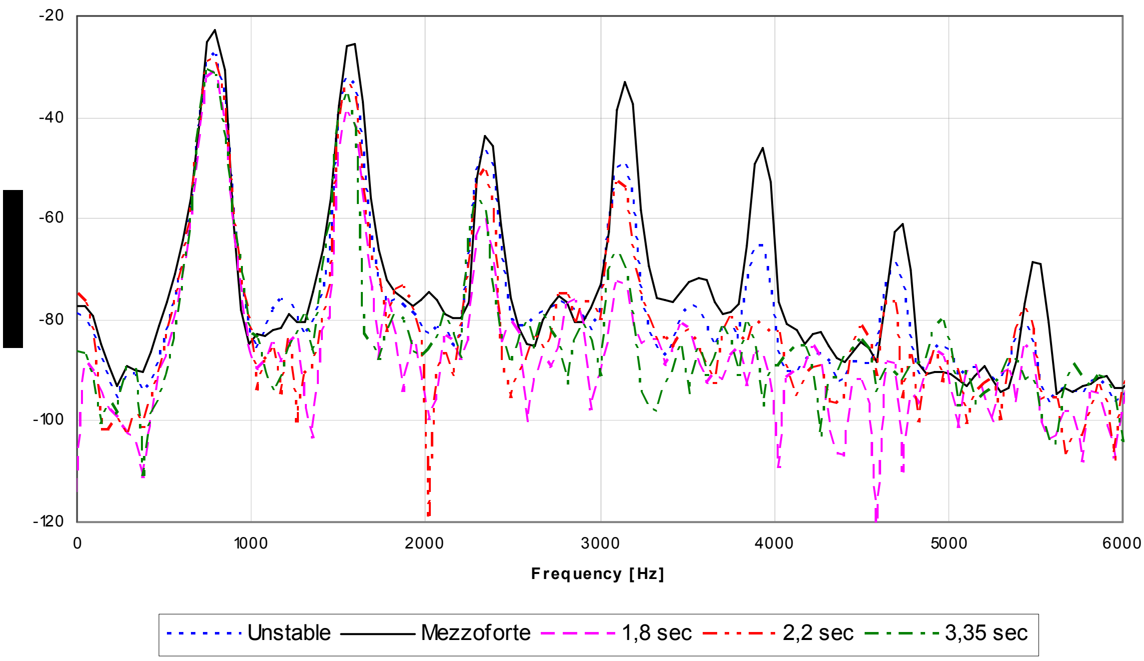


Figure 38: Spectra for the tone A^{Up} unstable average and for three different time states taken at 1.8, 2.2 and 3.35 s, compared with A^{Up} normal mf.

The same variations in the spectra as for the previous tones can be observed for $\mathbf{A^{Up}}$ unstable (see *Figure 38*). Frequency shifts (of the order of 40 cent) can be seen in all three spectra most clearly for the higher overtones. For the spectrum taken at 1.8 s, the overtones above f_2 disappear. The spectrum at 2.2 s shows that f_4 disappears compared to the average across the tone, but that there is activity in the overtones below and above, yet not as high as for the *mf* tone (see Table 14).

Table 14: Level differences of the 7 first harmonics for A^{Up} normal mf, A^{Up} unstable average and A^{Up} unstable at two instances taken at 1.8 and 2.2 s.

	Frequency [Hz]	A^{Up} mf [dB]	A^{Up} Unstable Average [dB]	1,8 s [dB]	2,2 s [dB]
f_0	796,9	-23	-28	-31	-28
f_1	1 594	-26	-34	-42	-36
f_2	2 344	-44	-46	-60	-50
f_3	3 141	-33	-49	-73	-54
f_4	3 937	-46	-65	-86	-81
f_5	4 734	-61	-73	-110	-96
f_6	5 531	-69	-93	-100	-96

Conclusion

The analysis of the four unstable tones for different time instances showed a striking variation in the line spectra. The averaged level differences for the unstable and the normal *mf* tones, calculated across the whole duration of the tones, show large differences compared to the level differences at different time instances. For some of the tones, one or more harmonics disappeared, with a consequence of bad quality. When the partials are shifted in frequency the tones sound out of tune.

It is not easy to arrive at a general conclusion about how individual harmonics behave, in other words, which harmonics disappear or decrease in power level. The four tones that have been analyzed behave differently, but the main characteristics for all of them have been described.

Algorithmic description

In order to be able to recognize unstable tones, the power level of the harmonics and their frequencies should be analyzed. If the power levels of the harmonics fluctuate up and down, or if individual harmonics disappears temporarily, this implies that there is no stability in the tone. Shifts in frequency may occur to such extent that the tone gets out of tune.

6.2.4 Hollow/empty tones

Hollow tones were produced using three conditions: bad reed, less lip pressure, and loose embouchure.

Bad reed

For $\mathbf{F}^{\mathbf{Low}}$ hollow tone produced with bad reed, the spectrogram proves to have the same tendencies as $\mathbf{F}^{\mathbf{Low}}$ normal *mf* tone up to f_4, but already f_5 is not as clear as in the good-quality tone (see *Figure 39* and *Figure 40*). At higher frequencies, individual harmonics disappear and the spectrum is filled with energy. Between 0.7-1.7 s, in the frequencies of about 1.5-2.7 kHz, the spectrogram for the hollow tone shows less overtone content compared to the start and end of the tone. The spectrogram shows overtone content up to 5 kHz.

Less lip pressure

Only the fundamental frequency can be clearly seen in the case of $\mathbf{F}^{\mathbf{Low}}$ hollow produced with less lip pressure (see *Figure 41*). The overtones above f_1 are unclear. It can be observed that there is overtone content up to f_3 at about 1.4 kHz, whereas between 1.4 up to 3.1 kHz there is just noise. The noise content extends up to 5.5 kHz. The tone has similarities with the tone produced with bad reed in the respect of missing overtones above f_3.

Loose embouchure

In *Figure 42* overtones up to f_2 can be clearly seen, but none of them are strong or clear. The spectrogram shows no overtones at higher frequencies, instead there is noise between 3.2 and 5.4 kHz, (where the higher overtone content can also be seen). Up to 2.2 s the tone sounds more hollow than during the last seconds. Between 2.2-2.6 s the tone contains almost only blow sound, explaining the cut-outs in the harmonics.

Summary

Perceptually, the third variant, $\mathbf{F}^{\mathbf{Low}}$ hollow tone produced with loose embouchure is the poorest in tone quality and more empty in sound. This can also be seen in the spectrograms. The other two conditions show more resemblance in tone quality, though the $\mathbf{F}^{\mathbf{Low}}$ produced with bad reed is both louder and has more depth. In general, overtone content is limited, compared to the normal *mf* tone (with overtone activity up to almost 7 kHz).

Spectrogram analysis

F^{Low}

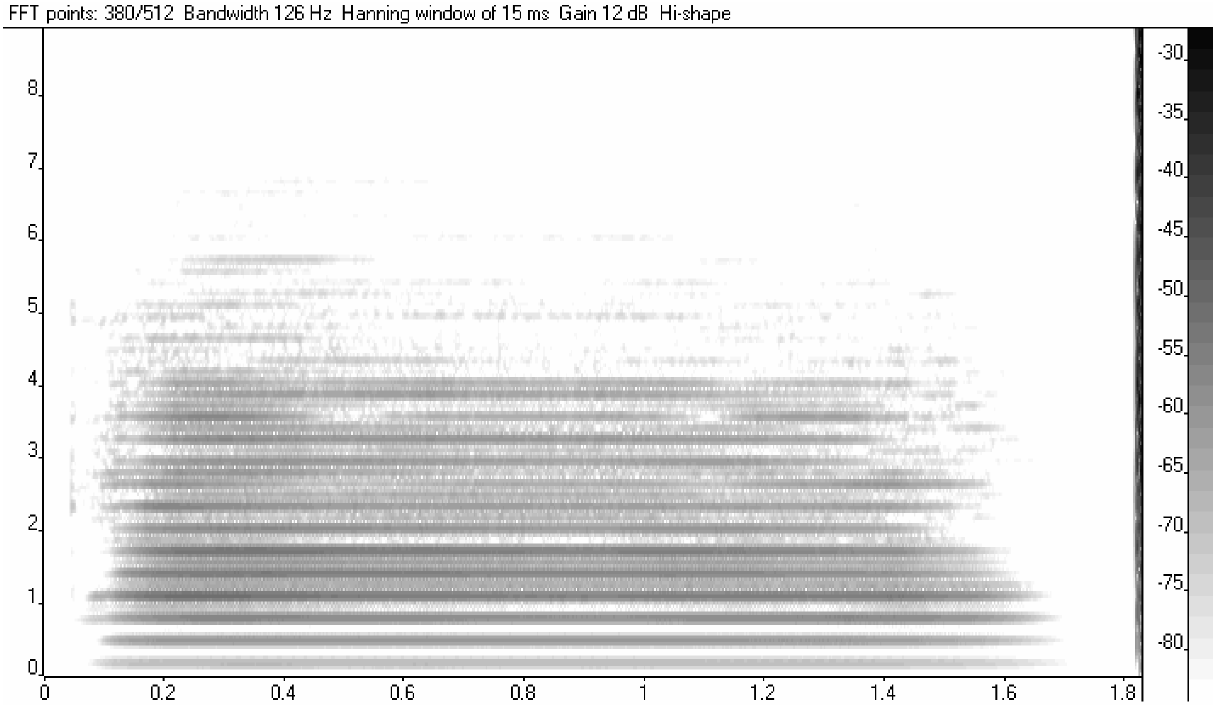


Figure 39: Spectrogram for F^{Low} normal mf tone

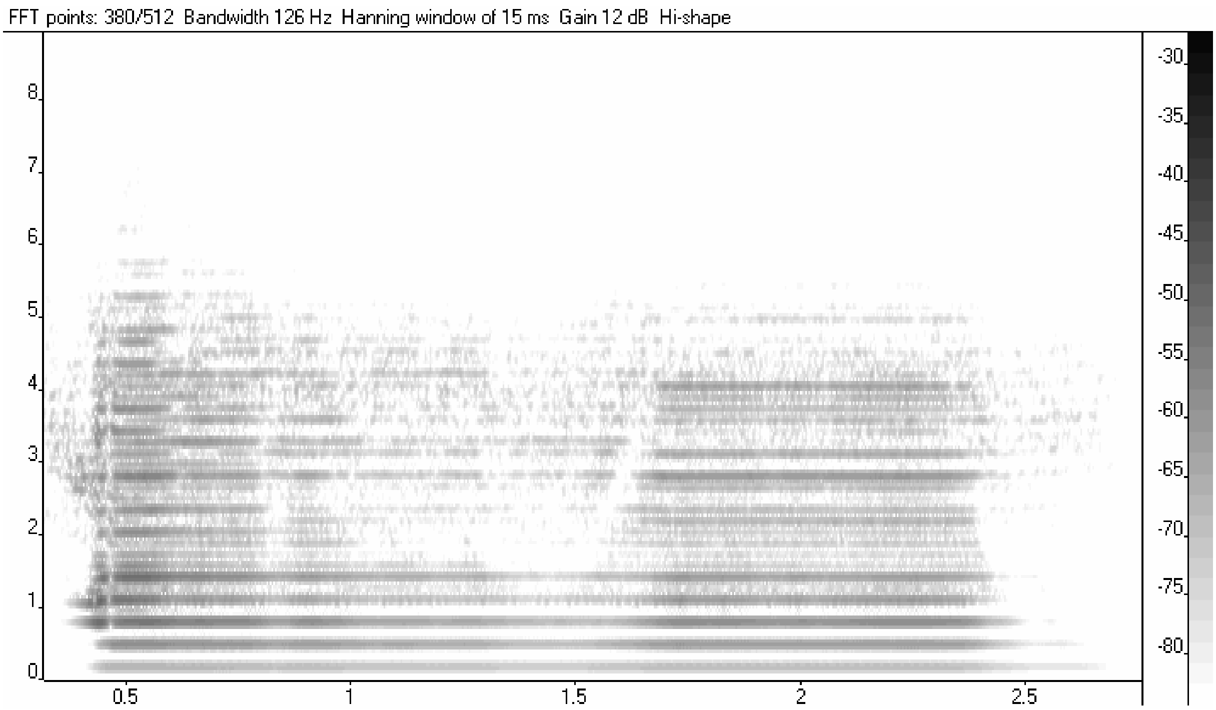


Figure 40: Spectrogram for F^{Low} hollow tone produced with bad reed

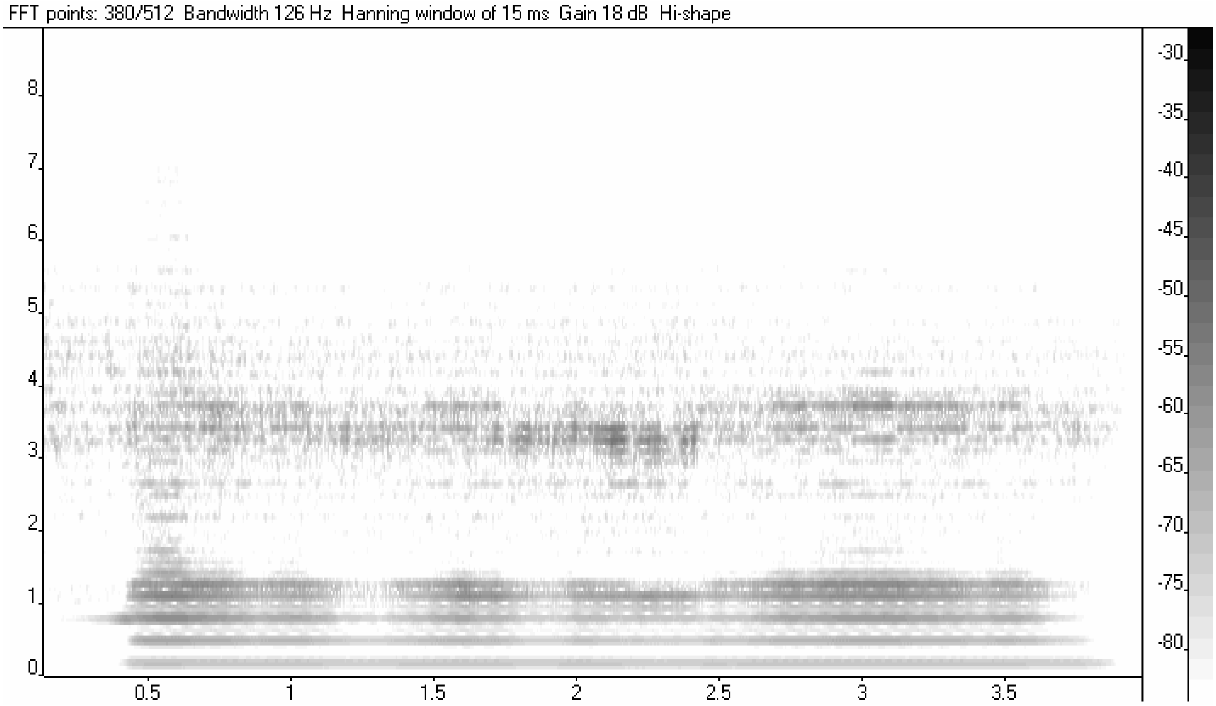


Figure 41: Spectrogram for F^{Low} hollow tone produced with less lip pressure

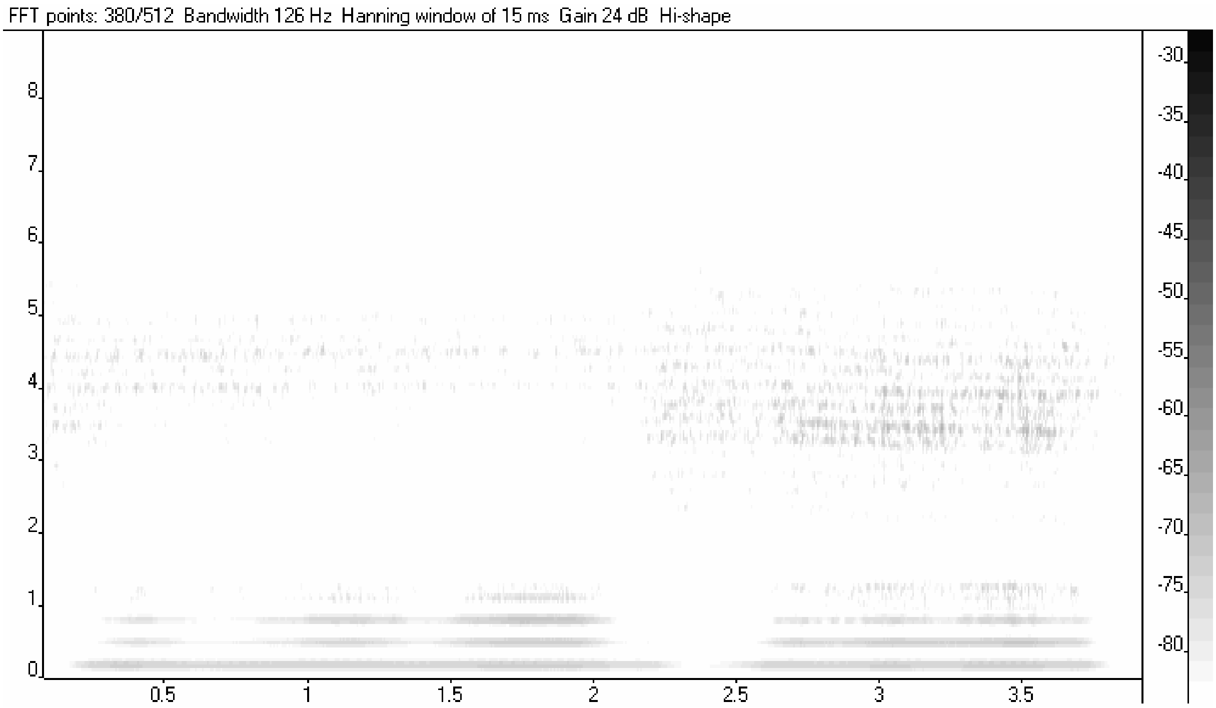


Figure 42: Spectrogram for F^{Low} hollow tone produced with loose embouchure

Bad reed

Starting already at the second overtone, the spectral content of the $\mathbf{G}^{\mathbf{Mid}}$ hollow tone produced with bad reed is not as pronounced as for the $\mathbf{G}^{\mathbf{Mid}}$ normal *mf* tone (see *Figure 43* and *Figure 44*),. Although there is overtone content up to f_3, f_4 disappears completely and f_5 and f_6 are not clear at all. At higher frequencies, the spectrogram shows more noise than overtones. Activity can be seen up to above 5 kHz.

Less lip pressure

Like the tone produced with a bad reed, the $\mathbf{G}^{\mathbf{Mid}}$ hollow produced with less lip pressure has overtone content up to $f_{3,}$ just above 1 kHz (see *Figure 45*). f_4 disappears completely, whereas f_0 is not strong at all. Although, f_5, f_6 and f_7 are visible, there are no overtones in the higher frequencies, just noise. There is activity up to 6 kHz.

Loose embouchure

For the $\mathbf{G}^{\mathbf{Mid}}$ hollow produced with loose embouchure, only the fundamental frequency can be clearly seen, f_1 and f_2 are not clear at all and at higher frequencies just noise can be observed (see Figure 46). The noise content extends up to above 7 kHz.

***G**^{Mid}*

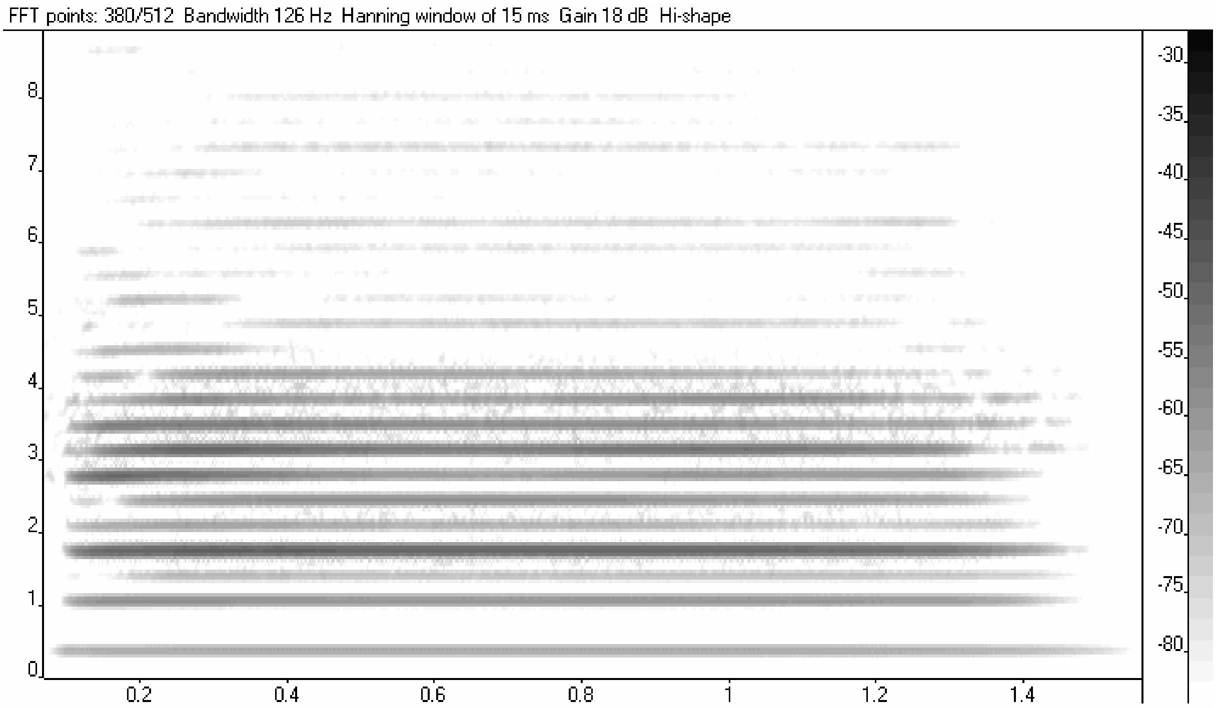


Figure 43: Spectrogram for G^{Mid} normal mf tone

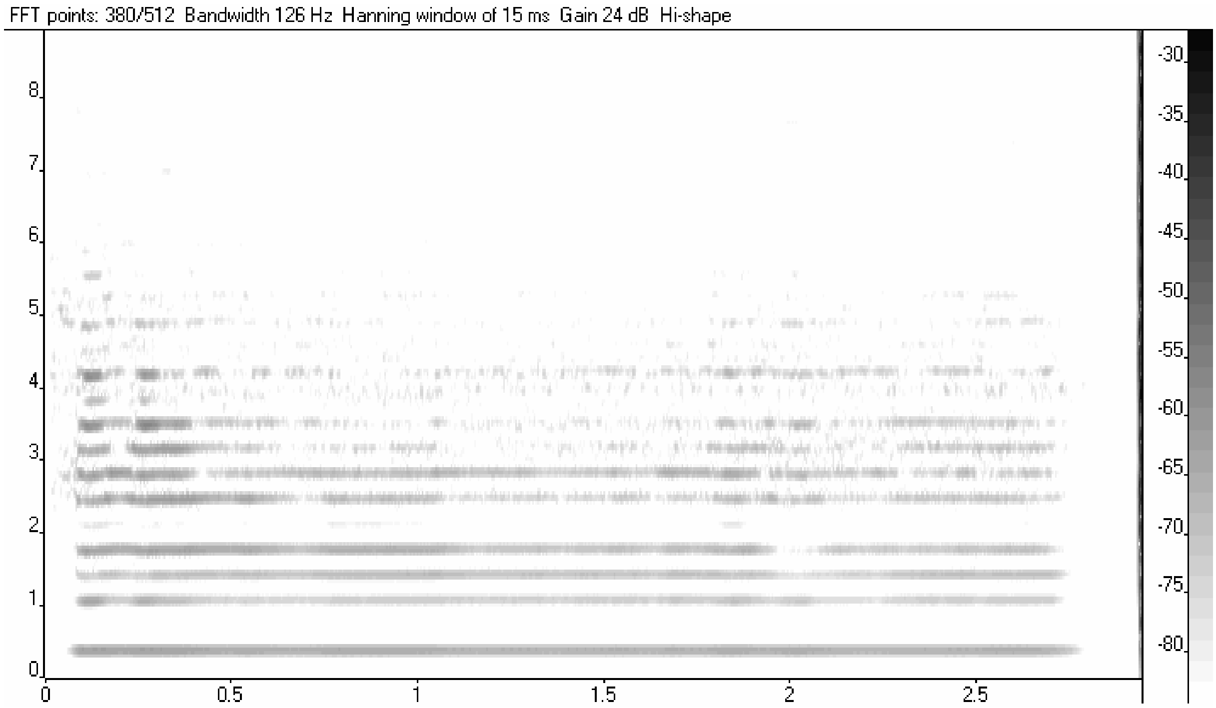


Figure 44: Spectrogram for G^{Mid} hollow tone produced with bad reed

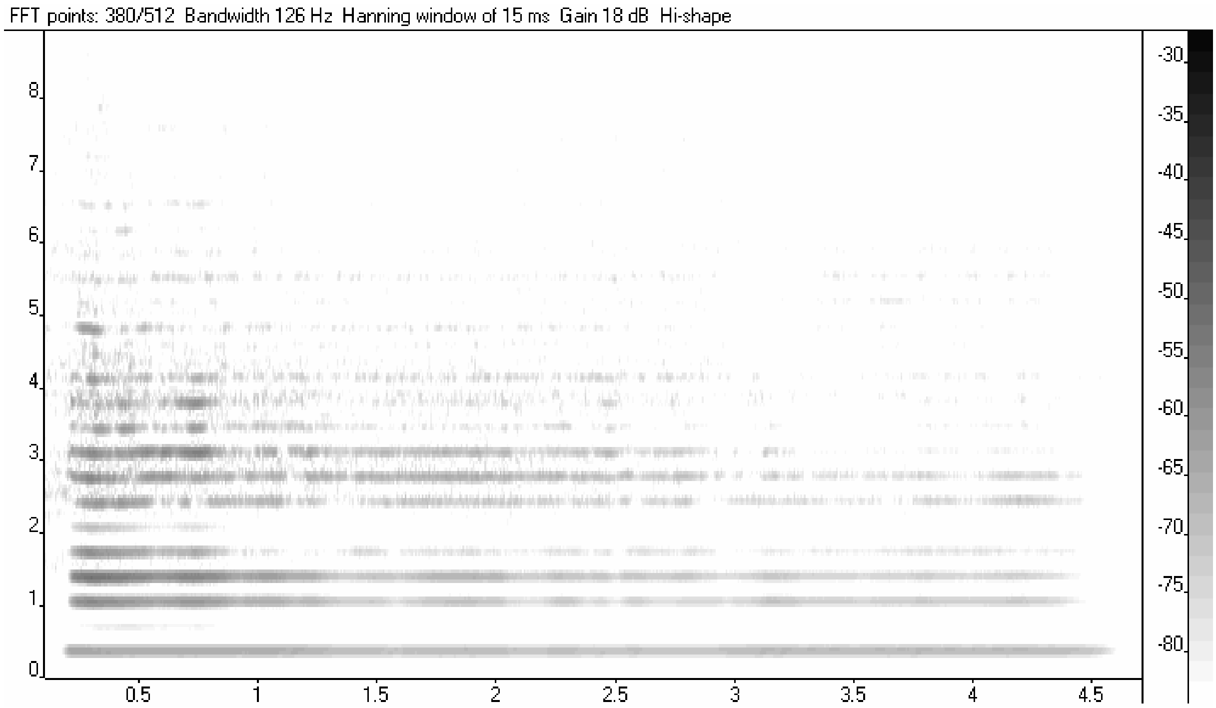


Figure 45: Spectrogram for G^{Mid} hollow tone produced with less lip pressure

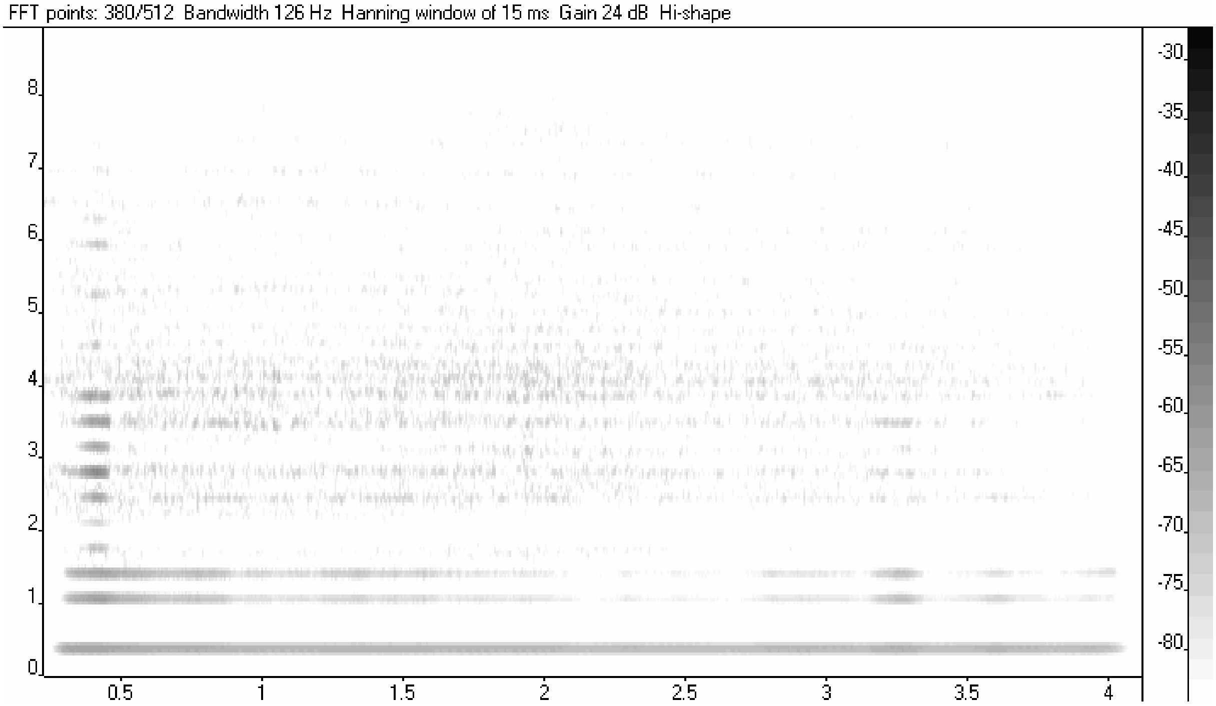


Figure 46: Spectrogram for G^{Mid} hollow tone produced with loose embouchure

Summary

The three conditions for $\mathbf{G^{Mid}}$ hollow tones sounded more similar than in the case of $\mathbf{F^{Low}}$ hollow tones. The $\mathbf{G^{Mid}}$ hollow tone produced with loose embouchure is the poorest in sound quality. A common characteristic for both tones produced with bad reed and with less lip pressure is that f_4 disappears completely. This is actually true for the one produced with loose embouchure too, although this one also misses f_3. Overtone activity is limited compared to the $\mathbf{G^{Mid}}$ normal *mf* tone with overtone content extending up to 8 kHz (but clearly only up to above 4 kHz).

Bad reed

The $\mathbf{B^{Mid}}$ hollow tone shows similarities with the normal *mf* tone up to f_3, although f_3 is not as visible (see Figure 47 and 48). At higher frequencies the spectrogram shows only noise, except of the case of f_6 which is not clear at all. The spectrum is filled with energy up to above 5 kHz, but already at 2 kHz the overtone information gets quite indistinct.

Less lip pressure

The overtones in $\mathbf{B^{Mid}}$ hollow tone produced with less lip pressure are not as clear as in the *mf* tone, but they can all be seen up to the f_6. f_7 disappears, but f_8 and f_9 show up but not so clearly (see Figure 49). The spectrum is filled with energy between the harmonics. The energy extends up to 5.7 kHz.

Loose embouchure

For the **B^{Mid}** tone produced with loose embouchure, the overtone content extends up to f_3, but there are no clear higher harmonics, just noise. This noise content extends as high as 5.3 kHz (*Figure 50*).

Summary

Sounds from blowing explain the noise in the spectrograms before the actual tone starts. The tone produced with loose embouchure is perceptually the poorest of all hollow tones and this can also be seen in the spectrogram. The normal mf tone has overtone content up to 7.5 kHz.

B^{Mid}

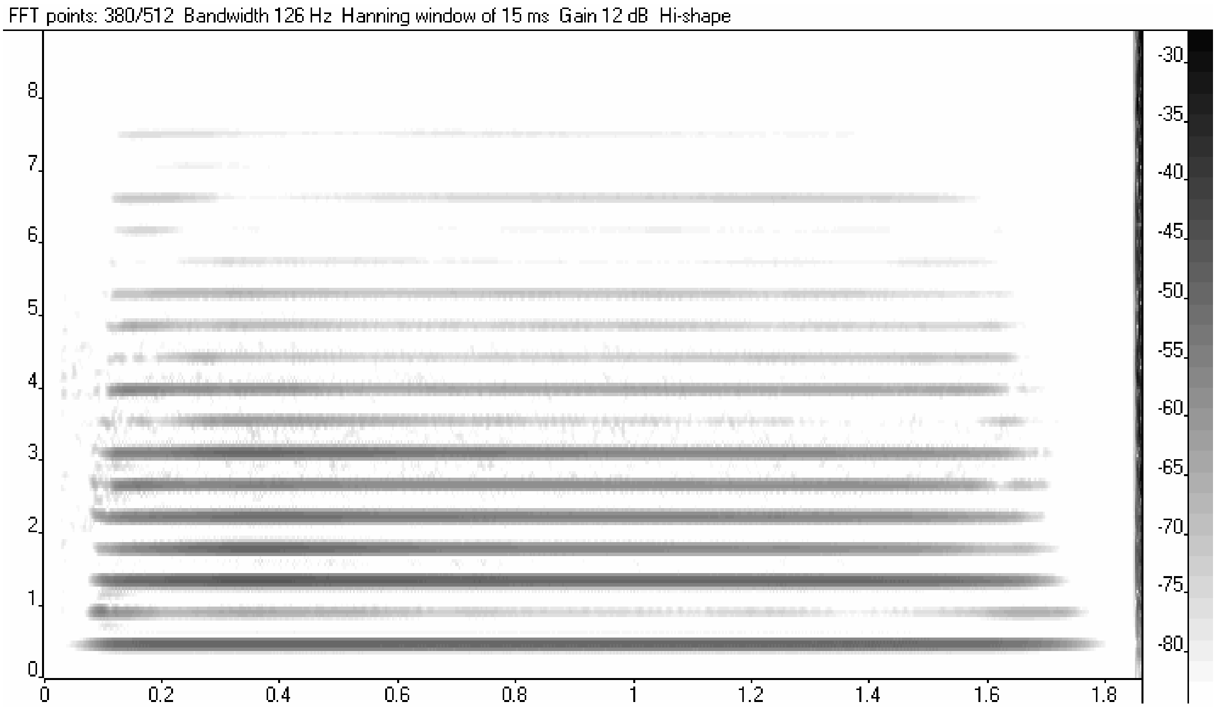


Figure 47: Spectrogram for B^{Mid} normal mf tone

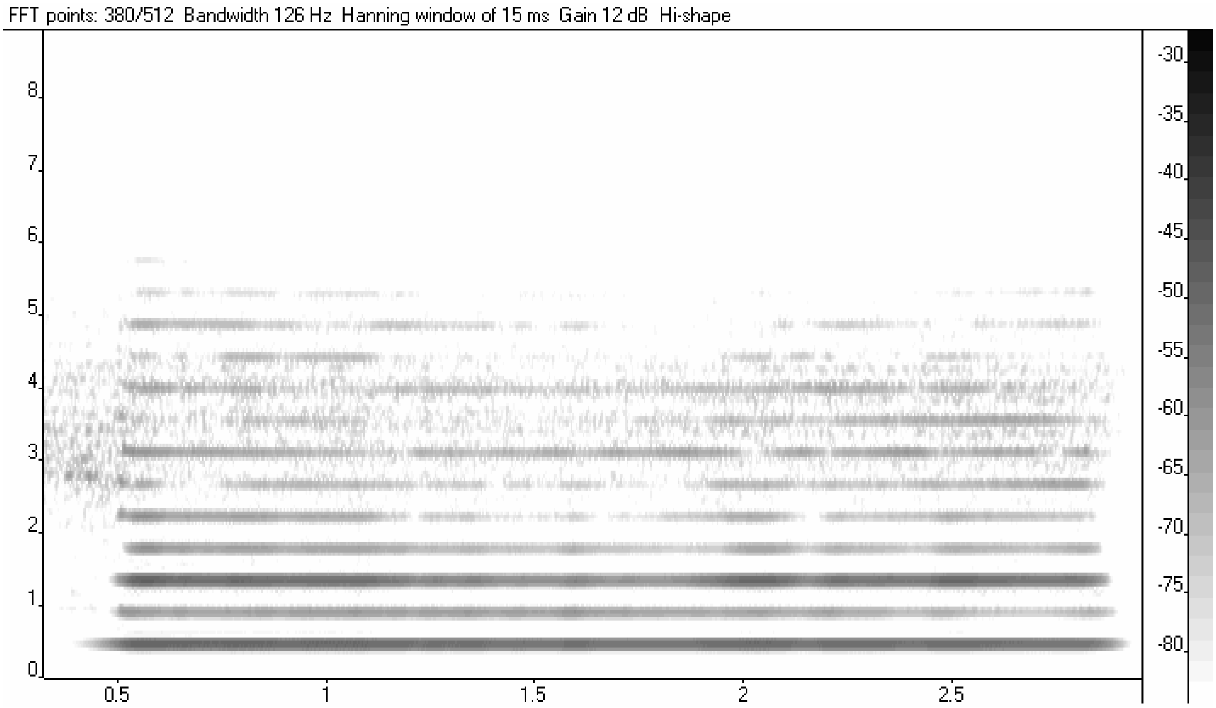


Figure 48: Spectrogram for B^{Mid} hollow tone produced with bad reed

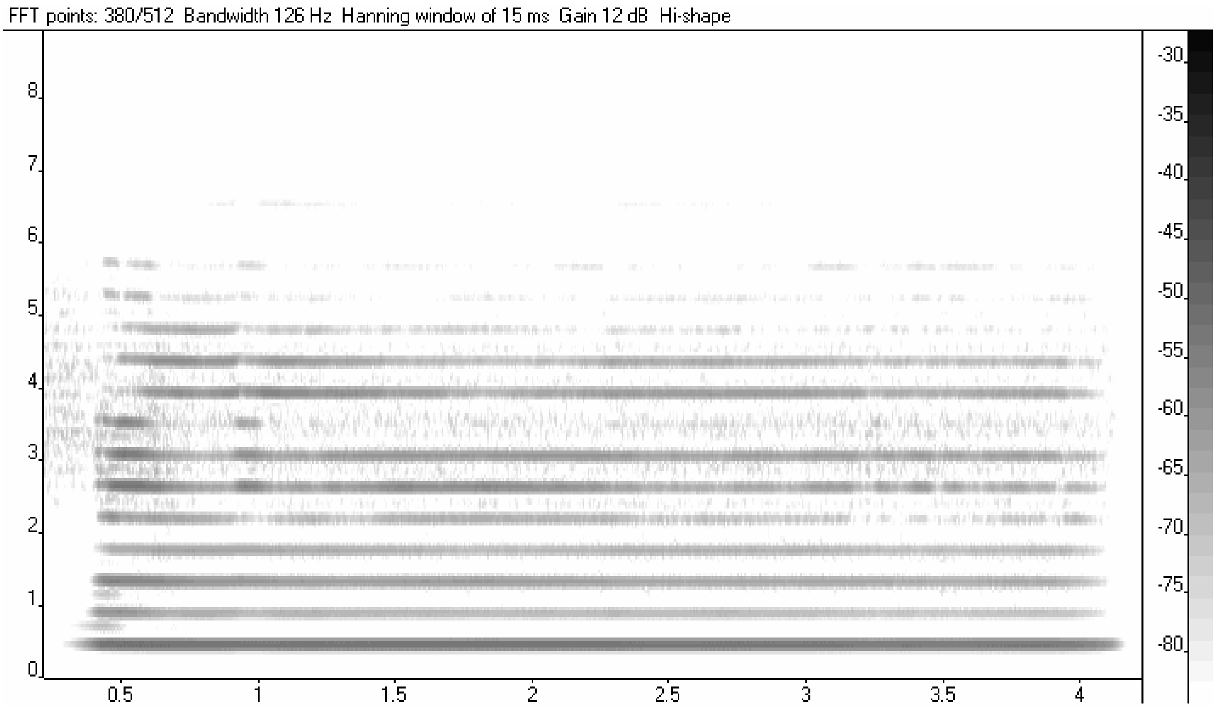


Figure 49: Spectrogram for B^{Mid} hollow tone produced with less lip pressure

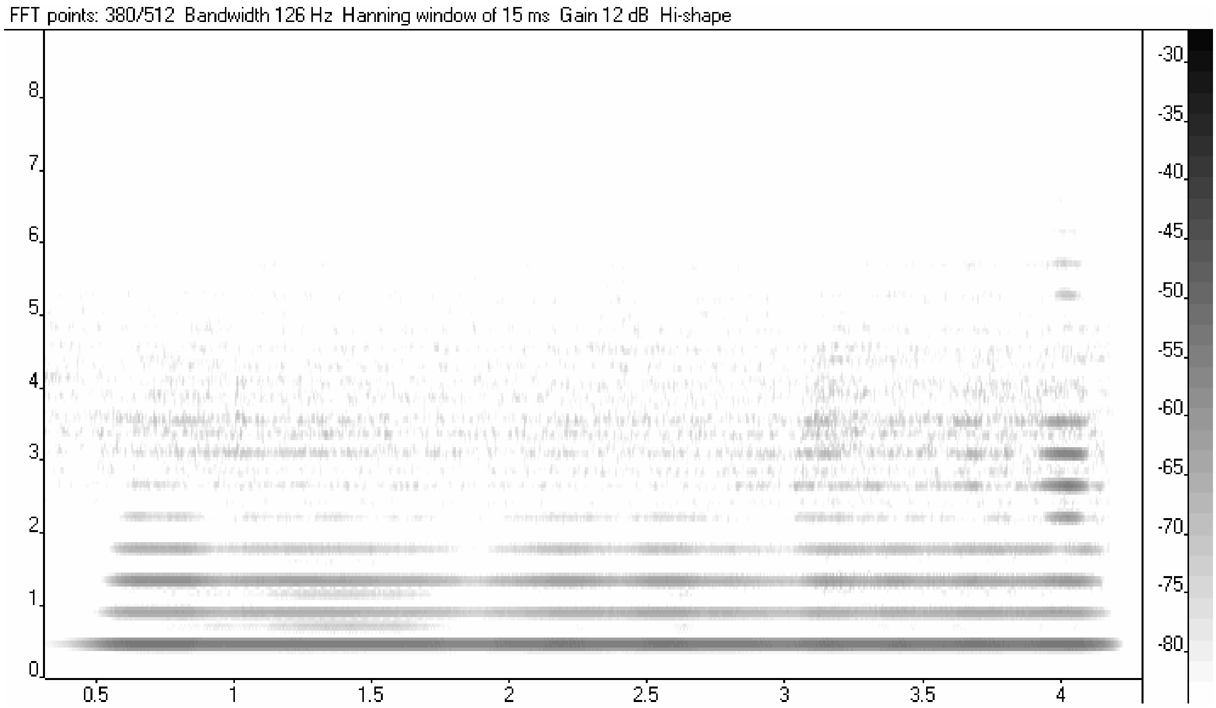


Figure 50: Spectrogram for B^{Mid} hollow tone produced with loose embouchure

Bad reed

Looking at the spectrogram for $\mathbf{A^{Up}}$ produced with bad reed (see *Figure 52*), the extra overtones just before 1 s should be ignored being a squeak. f_2 and f_3 are not particularly clear and strong compared to the normal *mf* tone but still there (see *Figure 51*). The cut-outs in the harmonics that can be seen in the spectrogram are a characteristic for the unstable tones. This implies that the tone is not only hollow but unstable too. Moreover, f_4 disappears completely, although f_5 exists but is unclear. Between the higher harmonics, the spectrum is filled with energy.

Less lip pressure

For the $\mathbf{A^{Up}}$ tone produced with less lip pressure (see Figure 53), the frequencies of both the fundamental and the overtones were down-shifted in frequency, lowering the pitch compared to the other $\mathbf{A^{Up}}$ tones. Moreover, the spectrum is filled with energy between the partials and the same cut-outs as seen in the spectrogram for the tone produced with bad reed can be observed.

Loose embouchure

For the $\mathbf{A^{Up}}$ tone produced with loose embouchure it is possible to see a trace of f_2 and f_3, although they are not clear at all (see Figure 54). At higher frequencies there is just noise. At about 3.8 s all overtones get stronger, and this could possibly be explained with the fact that there is temporarily more airflow.

Summary

All $\mathbf{A^{Up}}$ hollow tones were quite unstable. A student that has problem with hollow and empty tones will probably not be able to sound an $\mathbf{A^{Up}}$ tone at all. It has to be underlined that the tones produced with less lip pressure and with loose embouchure had quite large frequency shifts. This could not clearly be seen in the spectrograms but is more obvious in the following line spectra analyses. The energy observed in the spectrograms just before the tone is started is blowing sound. In line with the observations for the other hollow tones, the $\mathbf{A^{Up}}$ tone produced with loose embouchure shows the poorest frequency content. The overtone content for the normal *mf* tone extends up to above 6 kHz (see *Figure 51*).

General discussion on the spectrogram analysis of all four tones

- The hollow tones produced with bad reed had actually the best quality of all three types of hollow tones. Moreover, they showed higher overtone content.
- The hollow tones produced with less lip pressure had higher content of stronger and clearer lower harmonics than those produced with loose embouchure. It could also be observed that they had even higher amount of lower overtones.
- The hollow tones produced with loose embouchure were filled with energy in the higher frequencies and cut-outs could be present in the lower harmonics. In all four analyzed tones in this category, except for $\mathbf{A^{Up}}$, the fundamental was the only clear harmonic. These tones were also the poorest in sound richness and quality. Perceptually they endured more blowing sound than the two other types of hollow tones.

A^{Up}

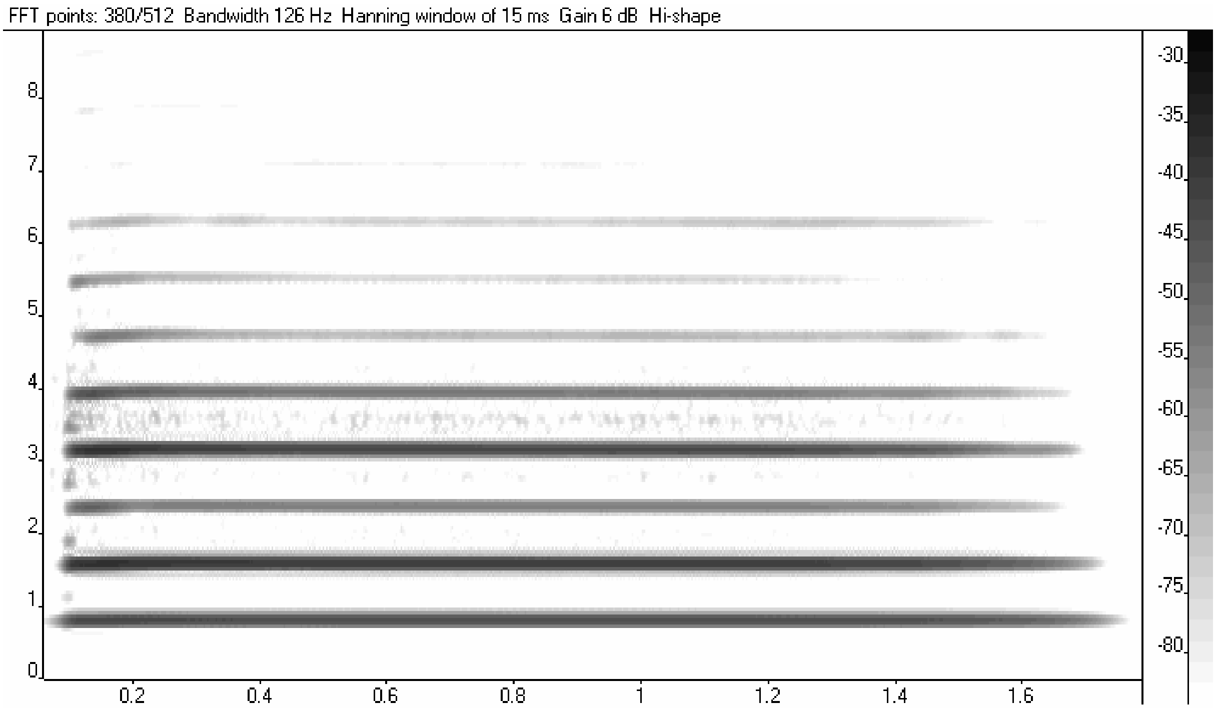


Figure 51: Spectrogram for A^{Up} normal mf tone

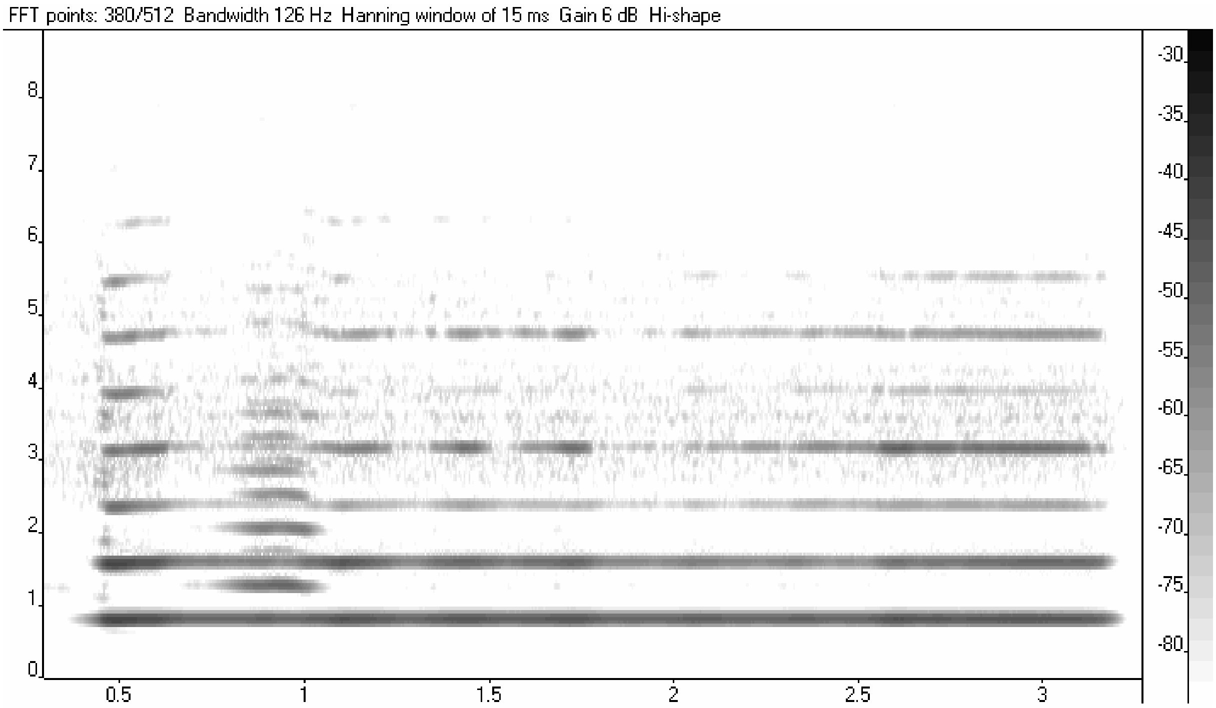


Figure 52: Spectrogram for A^{Up} hollow tone produced with bad reed

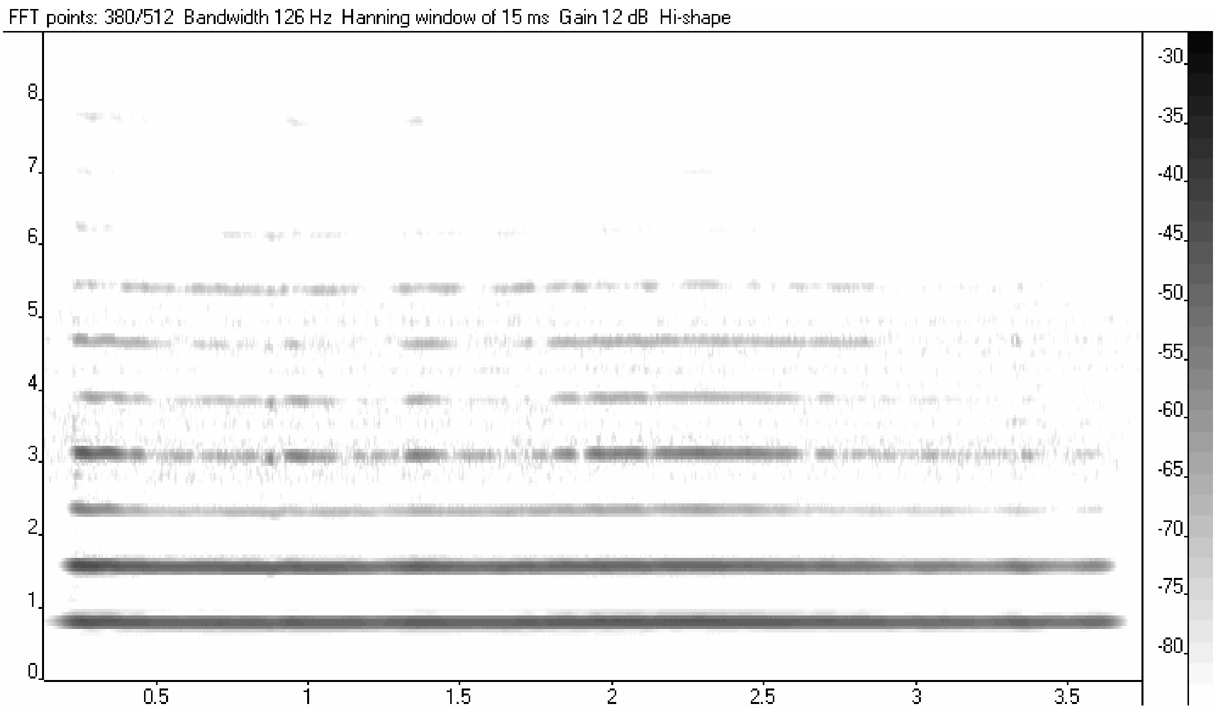


Figure 53: Spectrogram for A^{Up} hollow tone produced with less lip pressure

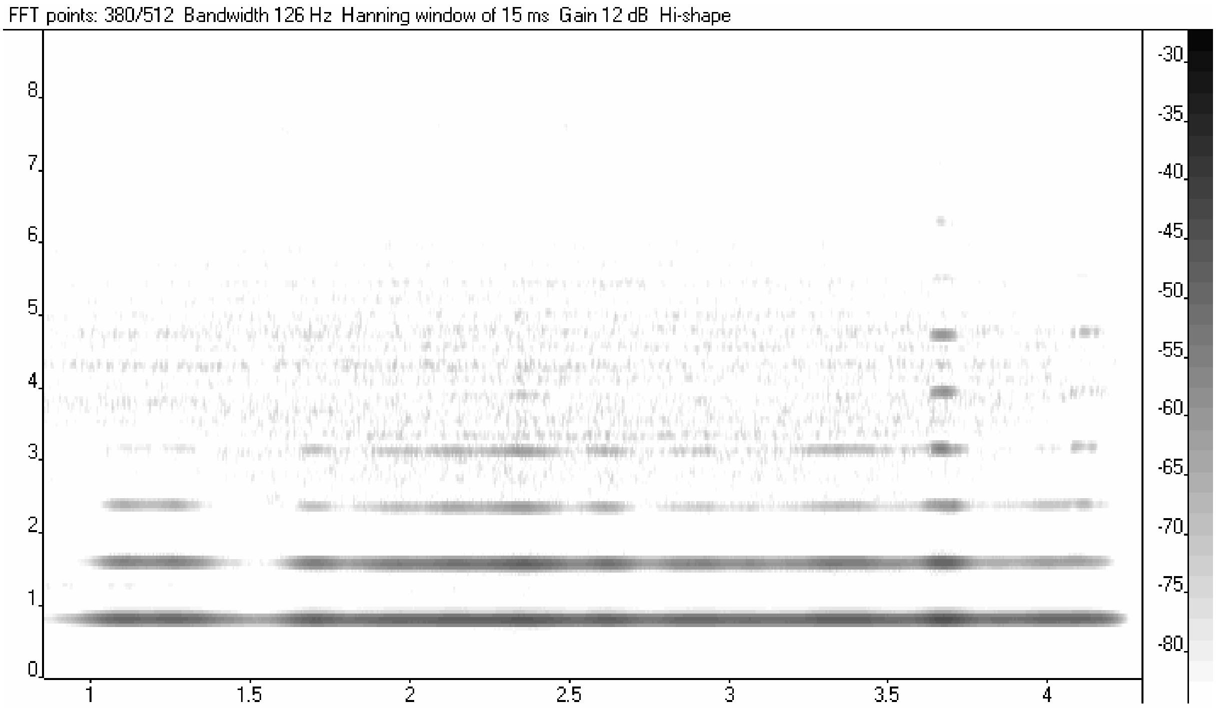


Figure 54: Spectrogram for A^{Up} hollow tone produced with loose embouchure

Line spectra analysis

F^{Low} Hollow Average

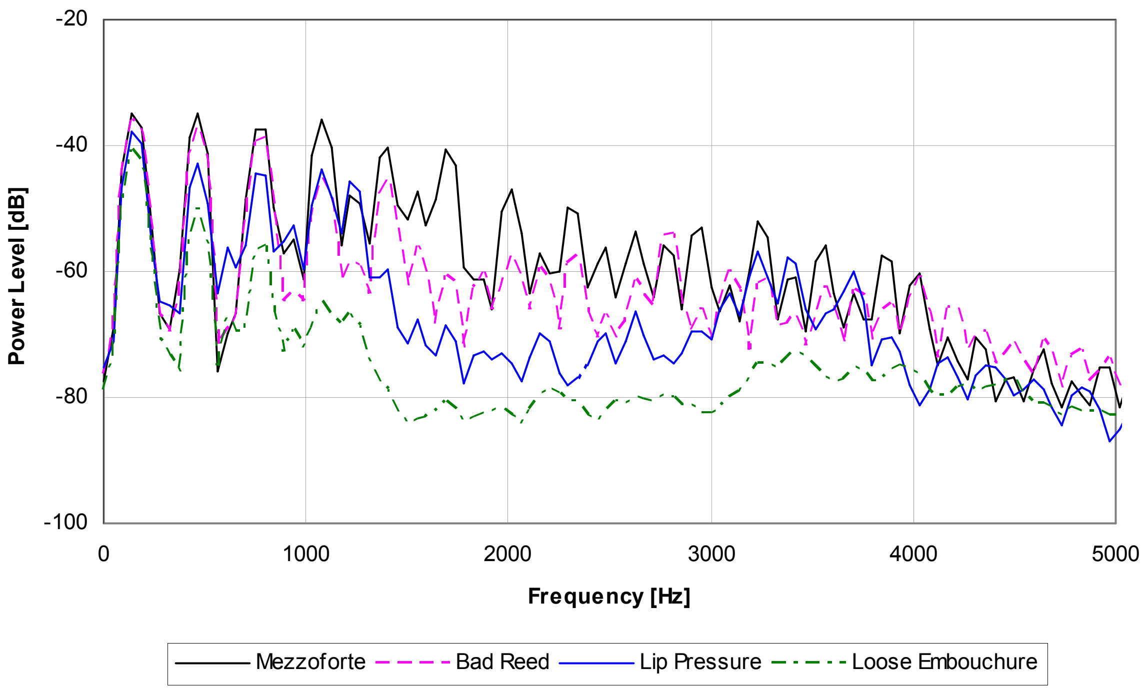


Figure 55: Averaged line spectra for F^{Low} tone in all four conditions; F^{Low} normal mf, F^{Low} hollow tone produced with bad reed, less lip pressure and loose embouchure.

Comparing the four $\mathbf{F}^{\mathbf{Low}}$ tones of different quality (normal *mf*, and hollow tones caused by bad reed, less lip pressure and loose embouchure (see *Figure 55*), a major decrease in level above f_6 at about 1.1 kHz can be observed for the hollow tones. The level increases again at about 3 kHz.

Especially for the $\mathbf{F}^{\mathbf{Low}}$ hollow tone produced with bad reed can be seen that f_0, f_2 and f_4 has almost the same power level as the normal *mf* tone, f_6 and f_8 fall in level with about 10 dB and above follows the above mentioned decrease which is characteristic for all three hollow tones.

The fundamentalof the $\mathbf{F}^{\mathbf{Low}}$ tone produced with less lip pressure has almost the same power level as f_0 for the normal *mf*, although f_2, f_4 and f_6 fall with about 10 dB. The following decrease in level, observed for all three tones, is even more striking for this tone.

For the $\mathbf{F}^{\mathbf{Low}}$ tone produced with loose embouchure only the three first harmonics are visible. f_0, f_2 and f_4 decrease in level with 15, 20 and 30 dB, respectively. No overtone content can be seen above 1 kHz.

G^{Mid} *Hollow Average*

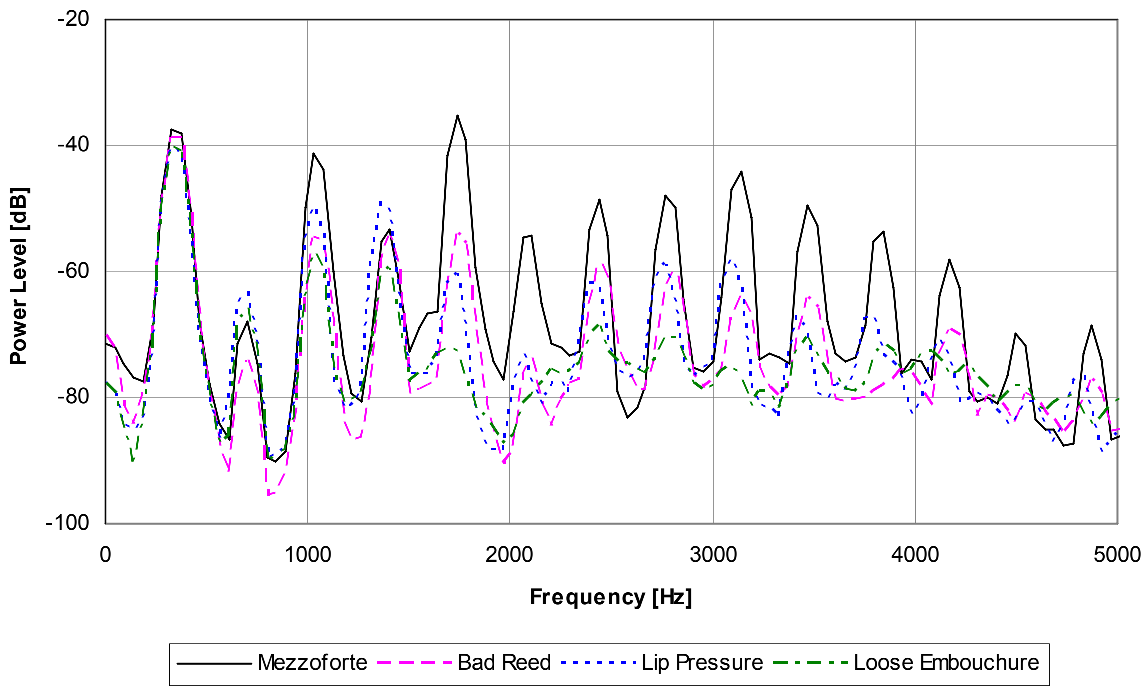


Figure 56: Averaged line spectra for G^{Mid} tone in all four conditions G^{Mid} normal mf, G^{Mid} hollow tone produced with bad reed, less lip pressure and loose embouchure.

For $\mathbf{G}^{\mathbf{Mid}}$ all harmonics above the fundamental f_0 decrease in level, except from two individual cases (f_1 and f_3 for the tone produced with less lip pressure) (see *Figure 56*). Just below 2000 Hz, f_4 shows an important difference among the three different produced tones. The level in this case, decreases more for the tone produced with loose embouchure than for the other two, whereas f_5 disappears in all three tones. The fall in level is greater for the tone produced with loose embouchure than for the other two, and the spectrum shows almost no overtone content above f_3 at about 1500 Hz. A shift in frequencies for the higher harmonics of the **G^{Mid}** tone produced with less lip pressure is also observed.

B^{Mid} Hollow Average

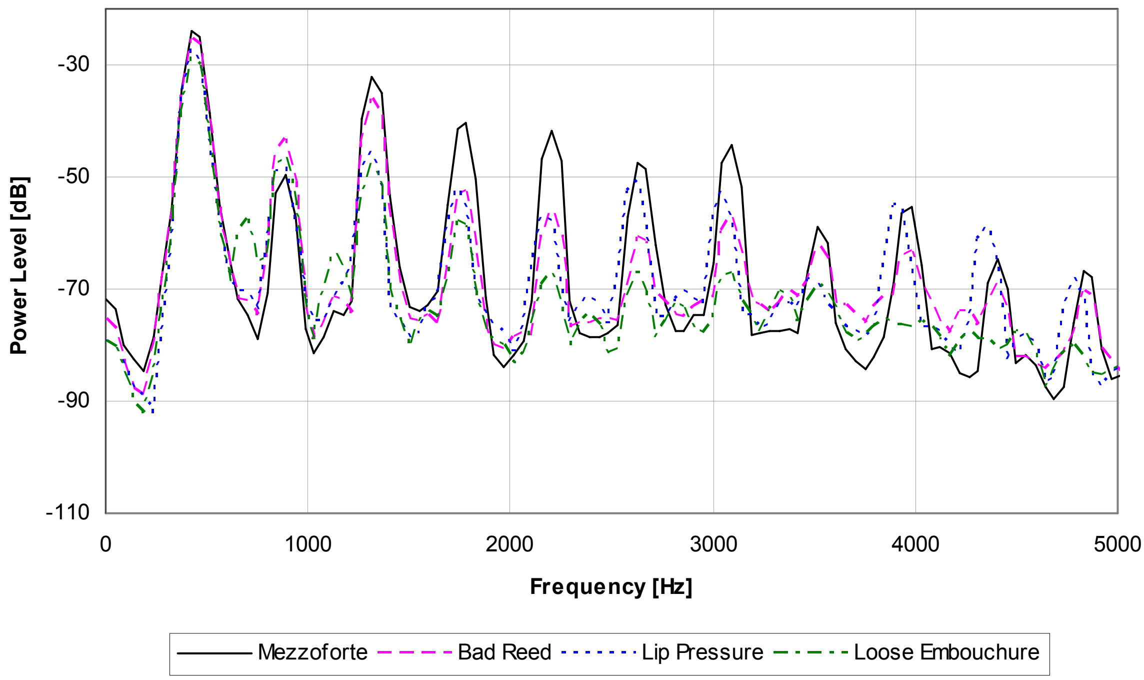


Figure 57: Averaged line spectra for B^{Mid} tone in all four conditions; B^{Mid} normal mf, B^{Mid} hollow tone produced with bad reed, less lip pressure and loose embouchure.

For the **B^{Mid}** tone produced with bad reed the overtones decrease in level after f_2, where the average level fall is about 12 dB up to f_6 (see *Figure 57*).

For the **B^{Mid}** tone produced with less lip pressure the level fall is about 11 dB for f_2, f_3 and f_4 while the level increases again for the higher frequencies. A slight shift in frequencies for all higher overtones can be observed as well.

For the tone produced with loose embouchure, f_2 decreases in level with 13 dB, f_3 with 18 dB and a striking level decrease can be seen for f_4 with 25 dB. At higher frequencies almost no overtones can be seen.

For all three types of hollow tones, f_4 disappears (see *Figure 58*). For the **A^{Up}** hollow tone produced with bad reed and less lip pressure, a decrease in level with about 13 dB (for f_1, f_2 and f_3) can be observed. For the hollow tone produced with loose embouchure the decrease for f_3 is almost 30 dB. f_5 and f_6 for the tones produced with bad reed and less lip pressure, increases in level almost as much as the normal *mf* tone, while the tone produced with loose embouchure has no overtone content after f_4. Moreover, a shift in frequencies above f_4 can be seen for the **A^{Up}** tone produced with less lip pressure. The consequence of this is that the tone is not just regarded as hollow but as slightly deviating in pitch as well.

A^Up Hollow Average

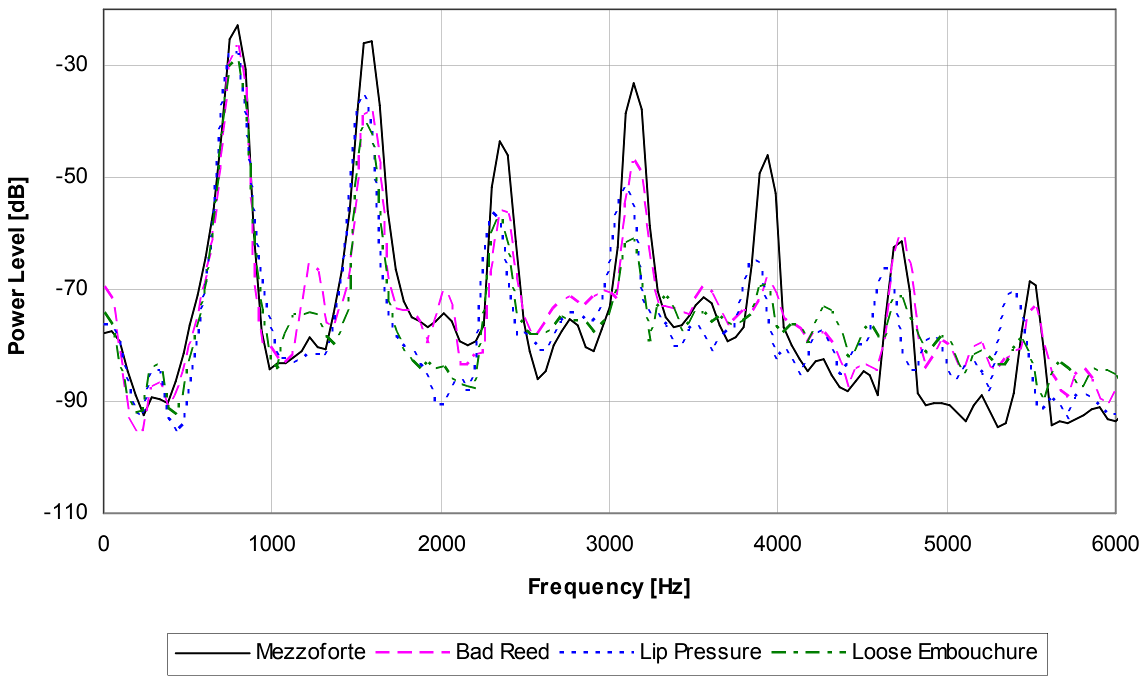


Figure 58: Averaged line spectra for A^Up tone in all four conditions; A^Up normal mf, A^Up hollow tone produced with bad reed, less lip pressure and loose embouchure.

Time instance spectra

The most striking observation that can be made for all hollow tones of the three categories (bad reed, less lip pressure, loose embouchure) is a fluctuation in the of the level of the overtones, although not as pronounced as for the unstable tones. For some of the tones, individual overtones completely disappeared but only for short periods of time. Generally, it was not necessary to look into details of the spectra at specific time instances, since the average spectra gave enough information to find the characteristics for hollow tones.

Conclusions

The analysis of the hollow tones showed that the fundamental frequency for all four cases is always the same, the first harmonics tend to decrease in level with about 10-15 dB, and the higher frequencies tend to disappear completely. There are more similarities between the tones produced with bad reed and the tones produced with less lip pressure than those produced with loose embouchure. The hollow tones produced with loose embouchure tend to decrease in level much more than the other two types compared to the normal *mf* tone.

Moreover, the spectra for the three hollow tone categories show a variation in sound level over the duration of the tone. Such a variation has to be accepted since a normal tone played by a student will not be held constant at all times.

Algorithmic description

In order to be able to recognize hollow tones, the existence of all the harmonics compared to a good-quality tone should be checked for. When individual harmonics disappear, or if there are harmonics up to a certain frequency but not above, the tone will not have a good quality. It will miss depth, brilliance, edge, shape, intensity and glow, in other words sound hollow.

Specifically for the case of hollow tones produced with bad reed there is still a high activity at higher frequencies but there are not as strong as in a good-quality tone. Noise can be found at higher frequencies.

The tones produced with less lip power can have a clear overtone activity up to f_3 or f_4 but higher up, less clear overtones will be found mixed with noise.

For the tones produced with loose embouchure a clear overtone activity can be seen up to f_1 or f_2. In the tones used for this study, there was no overtone activity higher up than f_2, only noise caused by blow sound.

The detection of temporary cut-outs in the harmonics points towards unsteadiness in the tone, while shifts in the overtone frequencies point towards an out-of-tune tone.

Comparison of hollow and unstable tones

There is a resemblance between the hollow and the unstable tones. Both prove to have unstable spectra, but for the unstable tones the individual line spectra at different moments in time show larger variations in power level than for the hollow tones. Moreover, the individual spectrum for the unstable tones can have a power level which is as high as for the *mf* good-quality tones, which is not really the case for the hollow tones. The fluctuations in partial amplitudes for the hollow tones apply basically to the lower harmonics, whereas for the unstable tones these variations apply to the whole spectrum. Moreover, the unstable tones are not characterized by the noise or blowing sound which exists in the hollow tones.

6.2.5 Double tones

Spectrogram analysis

The analyzed double tones were played by students. As explained before in the description of the recordings for this experiment, it was not possible for the teacher to produce the intended type of double tones. The double tones played by the teacher had more the form of a squeak, both perceptually and as seen in the acoustical analysis. For this reason it was considered more appropriate to analyze only double tones played by students.

Two pitches were chosen in order to find their characteristics, a $\mathbf{G^{Mid}}$ tone and an $\mathbf{E^{Mid}}$ tone. The difference between the two tones was that the side-tone which appears at the beginning of the actual tone is lower in the case of $\mathbf{G^{Mid}}$ and higher in the case of $\mathbf{E^{Mid}}$. As seen in the

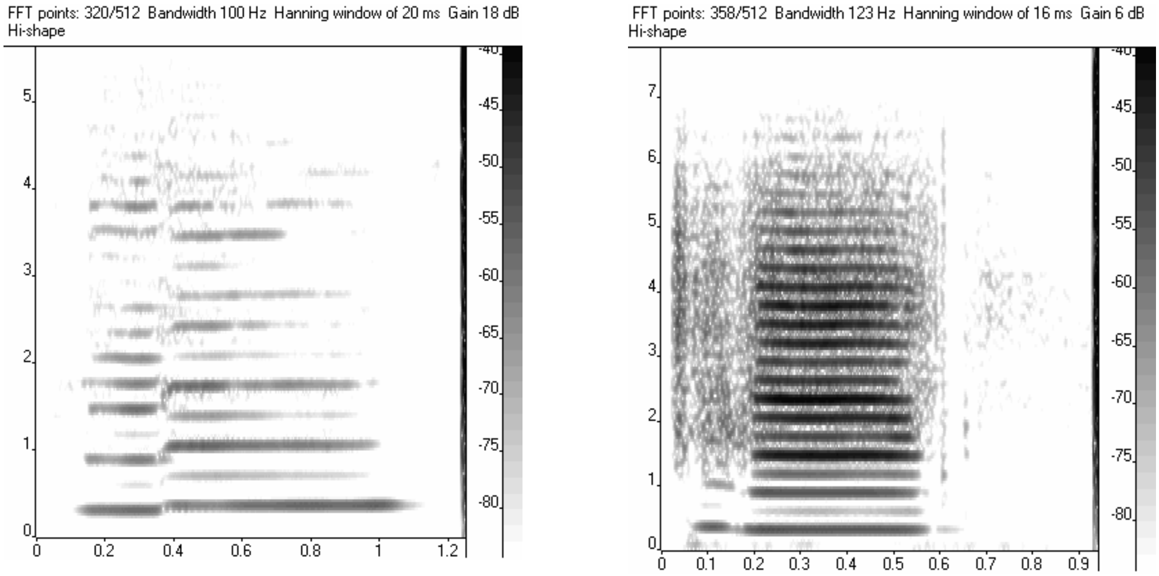


Figure 59: Spectrograms for a) G^{Mid} and b) E^{Mid} double played by a student

spectrogram for $\mathbf{G^{Mid}}$ (see *Figure 59* a) it is clear that this side-tone is actually another tone. In the case of $\mathbf{E^{Mid}}$ (see *Figure 59* b) the spectrogram is blurry and it is difficult to decide if it is another tone or just noise with traces of a fundamental frequency which could fit to a real tone. In addition, it can be seen that the side-tones can have different duration, longer for $\mathbf{G^{Mid}}$ and shorter for $\mathbf{E^{Mid}}$. The spectrogram for $\mathbf{G^{Mid}}$ proves to be clearer without much noise, but some of the higher overtones are not particularly strong. For $\mathbf{E^{Mid}}$ it is obvious that more noise exists, both in the beginning and during the intended tone. For the first milliseconds of the side-tone just noise in the higher frequencies can be seen, although at about 0.09 seconds a fundamental frequency is visible that is higher than the fundamental for the intended tone.

Further analyses of double tones played by students showed the same tendencies and results and this made it possible to conclude with some certainty that double tones are a consequence of bad finger coordination.

Line spectra analysis

It is clear that the first part of the tone, the so called side-tone is shifted in frequency, see *Figure 60*. The fundamental frequency is 281 Hz which is the f_0 for $\mathbf{D^{\#Mid,}}$. In comparison the intended frequency of $\mathbf{G^{Mid}}$ is 343 Hz. The side-tone is perceived as having a completely different pitch compared to the following good part. The good part is far from the normal $\mathbf{G^{Mid}}$ *mf* tone of good-quality but it is still recognizable as this tone.

The initial side-tone for $\mathbf{E^{Mid}}$ cannot really be separated from following main part of the tone. The only thing that clearly can be seen at two instant time spectra, taken at 0.09 and 0.12 s, is that the peak for the fundamental frequency f_0 occurs at 344 Hz which is near the fundamental for a $\mathbf{G^{Mid}}$, which is 349.2 Hz (see Figure 61). Moreover, the spectrum taken at 0.12 s resembles the spectrum for a $\mathbf{G^{Mid}}$, since the frequencies correspond to the frequencies of a

G^{Mid} Double tone

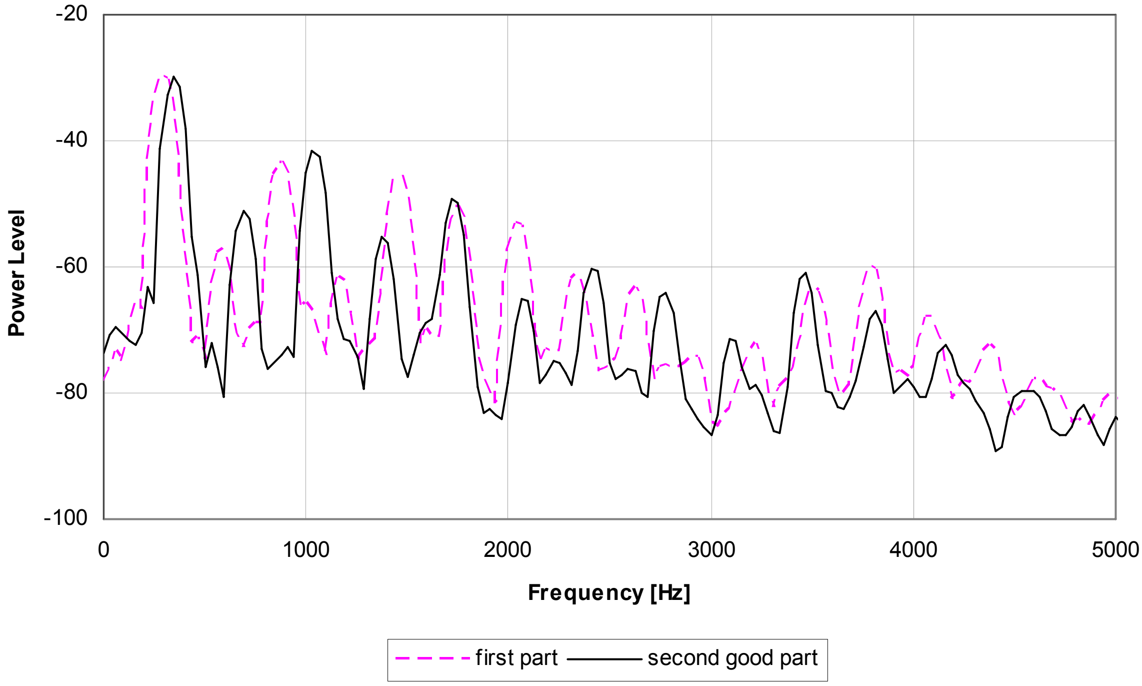


Figure 60: Averaged line spectra for G^{Mid} double tone, including the initial side-tone and the intended G^{Mid} good part tone. E^{Mid} Double tone

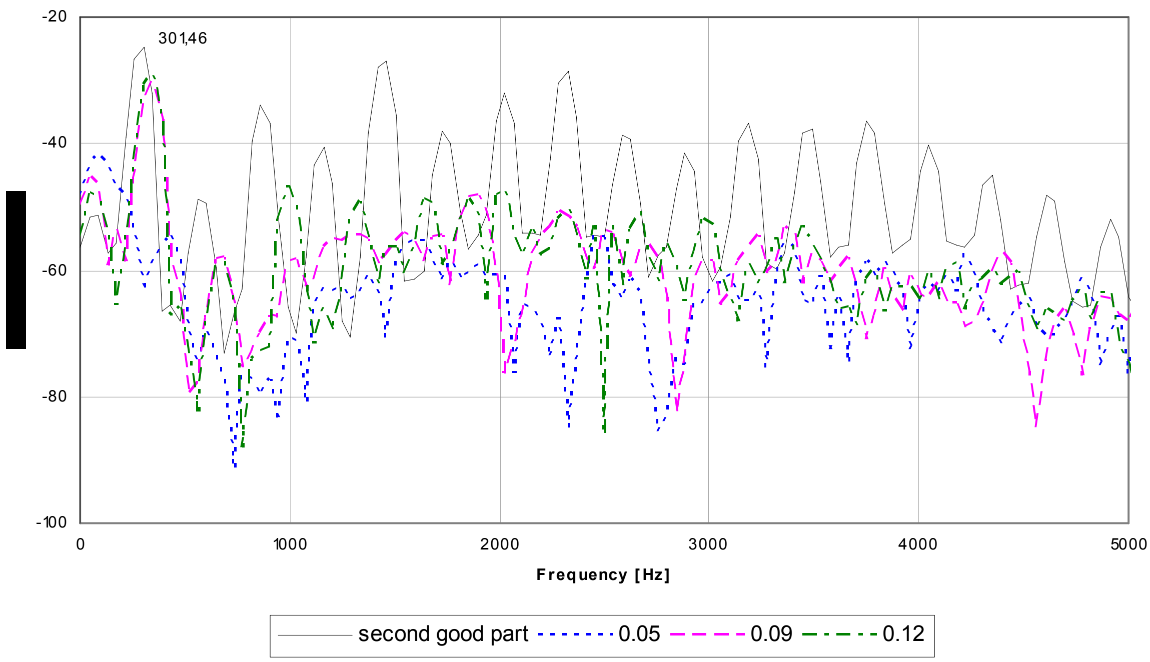


Figure 61: The good part of E^{Mid} and three different states of the side-tone occuring before the actual tone.

G^{Mid} up to f_6. In contrast, the spectrum taken at 0.05 s has nothing in common with the other spectra, being more like noise than a real tone.

The second good part of this tone corresponds to an **E^{Mid}** even though it may be of less good quality than an **E^{Mid}** played by an experienced player.

Conclusion

Double tones are perceived as two subsequent tones with different pitches, the first (accidental) side-tone being weaker than the second (intended) one. The side-tone can be either higher or lower in pitch than the intended tone. From analysis of several double tones it became quite clear that they are caused by bad finger coordination. The double tones show up clearly in the spectra, the first part with a short duration of some milliseconds and with a different fundamental frequency than the intended tone. This side-tone can either fit in another tone's spectral content or it may consist of a fundamental frequency and noise at higher frequencies. Analysis of the intended part of the tone showed that the students actually succeed in playing the right pitch, although the tone cannot be considered as having sufficiently good tone quality.

Algorithmic description

The main feature to be checked in order to recognize double tones is the presence of a weaker side-tone in the beginning of the intended tone. This side-tone is short in duration and it can either have the spectrum of a bad-quality tone, or just contain a fundamental frequency and noise instead of higher harmonics.

7 Discussion and conclusion

Concerning the first part of this study about the identification of the bad-quality clarinet tones, how they can be described perceptually, and a suggested discrimination of causes for each one of them, the results show that professional clarinetists and teachers can identify possible causes for bad tones quite reliably. The most experienced showed to be more confident about the exact cause. It seems that the main causes for almost all bad tones for students in the target user group can be attributed to the embouchure and the airflow. Most of the teachers emphasized that a firm embouchure and a good breathing technique can secure a good tone quality even if the student plays a malfunctioning instrument or covers the holes improperly. In other words, by prioritizing and focusing on embouchure and breathing most of the problems can be avoided.

Specifically for the squeaks, other probable causes were hard or broken reeds, or leaking instruments. A leakage in the instrument could also help explain unstable tones. It seems that the main reason for the double tones was bad finger coordination, indirectly as a result of a difficult note or register change.

The second part of this study, the acoustical analysis of bad tones and the identification of their spectrum characteristics, showed that it would be possible to find certain characteristics that can help in automatic identification of such tones. Admittedly, there are other ways of analyzing the spectrum which could possibly present more details for automatic recognition.

Spectral changes at the beginning or the end of a tone are signs of a squeak. If the spectra show a compressed spectral variation compared to the good part of the tone, or if there are peaks in-between the actual harmonics, a squeak in the beginning of the tone could be present. Characteristic for the squeaks at the end of the tone is the absence of the expected fundamental frequency.

Both the unstable and the hollow tones are characterized by a striking variation in their spectra; an increase and decrease of the power level of the harmonics. For the unstable tones those variations are larger and influence the whole spectrum, whereas for the hollow tones they basically apply to the lower harmonics. Moreover, the hollow tones are characterized by noise and blowing sounds. The main characteristic of the double tones is a side-tone of short duration before the intended tone. This side-tone can either be an actual tone or just give the impression of a tone, because of the presence of a fundamental frequency.

The acoustical analysis included only four pitches, one for the low register, two for the mid register and one for the upper register. A main characteristic of the clarinet, the existence of almost only odd-numbered low harmonics in the *chalumeau* register, was seen in the analyzed $\mathbf{F}^{\mathbf{Low}}$. For the rest of the pitches low-numbered even harmonics were present, with increasing amplitude the higher the pitch. Unfortunately it was not possible to find common characteristics between the tones in the same register. In order to get more accurate results and to see if there are certain distinguishing features for tones in the same register, more tones should be analyzed.

The analyzed tones were produced by a professional clarinet player, mimicking typical bad tones in student performances. It would be interesting to make a systematic comparison with similar errors found in actual student performances. A clear correspondence between bad tones produced by teachers and students, respectively, would strengthen the results of this study. Using a professional player was a strategic decision in order to be able to reproduce the errors with different causes and combinations of causes.

The proposed algorithmic descriptions are not implemented in software, but should be considered as strategies in developing the methods. While other factors, for instance the musical context, always must be regarded in the search for bad tones, the algorithms will detect the most common bad-quality tones and their probable causes.

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