On the Use and Acoustical Characteristics of Mechanically Augmented Musical Instruments and Early Recording Devices

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Abstract

At the time of invention of the mechanical recording machine, the phonograph, the string section was hardly heard on the playback, if the musicians during recording were not standing directly before the horn. A need for a violin with a stronger sound projection than the traditional violins appeared in the recording studios. The Stroh violin was invented and patented in Britain by J. M. A. Stroh in 1900. It had a comparable to the violin tone color, and a much stronger projection. Therefore it inhabited the recording spaces in England, Germany and USA until around 1925, when the microphone technology allowed a balanced reproduction of music. The Stroh violins do not have a vibrating surface, but a circular diaphragm which translates the string vibration to the horn (a bit similar to the horn loudspeaker). The diaphragm and the horn have their own resonances, which color the sound of a bowed string, and the sound off the horn axis is much “thinner”. The principle of the sound emission in the Stroh violins and in the recording machines is in the focus of this work. Particularly the construction, the mechanical sound amplification of the horn, and acoustical profile of the Stroh violin and the phonograph are discussed. Results of the recent investigation of the phonograph sound path in ETI support the topic. The sound transfer functions and radiation patterns of three Stroh violins are measured and compared to two reference violins. Listening examples are presented on the CD.
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1 Introduction

The Stroh violin is a horn fiddle aimed for sound reproduction closest to the traditional violin. Similarity of the violin’s step-brother has an impressive effect on the old recordings. Two factors make that possible. First, the Stroh violin provided a strong sound level in a narrow beam, which the conical horn of a phonograph required from a musical instrument for any good loudness. Second, - even though the Stroh violin almost does not radiate at the low frequencies, - the lack of a "body" sound, essential for the normal violin, can not be heard on the mechanical record due to its restricted range. Another concern is that the Stroh violin was invented a few decades after the phonograph, and though they are used for two totally different purposes, the sound reproduction mechanism has many similarities from a physical view.

The objective of this thesis is to explain the main features of the Stroh violin with regard to the sound of a conventional violin, and, from the other side, to the properties of acoustic recording devices.

Instrument makers and researchers in music acoustics rank the violins according to the main vibrational modes of the body and their effect on the radiated sound. Therefore, in the first place, the principles of violin function are outlined in Section 3. Section 4 summarizes the present investigations behind the Stroh violin, mainly focusing on two references: the scientific paper "A study of the acoustics of the Stroh violin" by R. N. Ghosh, 1926 [1], and a recent contribution "Acoustical measurements on experimental violins in the Hanneforth collection" by Robert Mores, 2013 [2]. The sound path of the Stroh violin and the phonograph is described step by step in Section 5. Comments on playability and application are given in Section 6. Harmonical spectrum of the open strings is analyzed in Section 7 and compared to the reference violins. Section 8 reveals in detail the measurement setup of Gunter Ziegenhalls, used for the transfer function and radiation pattern measurements. Results are shown in Section 9, complied with a discussion on the acoustical profile of the Stroh violin. In the final part, Section 10 gives an overview of the whole work, summarizing conclusions from the measurements and the theory.
2 The phonograph

A number of research works, musicological and historical publications, and patents have been published about the phonograph since the mechanical recording technology appeared in 1900. The following sections give an overview of the development of this device and my own investigations.

2.1 Development of the horn design in the phonograph

Percy Wilson and Geoffrey L. Wilson in their article "Horn Theory and the Phonograph" provide an overview of the development of horn design during a period between 1912 and 1972. Initially, the horns used for a phonograph were conical in shape and did not have any flare at the mouth, though the patents for a horn with a progressively increasing flare have been registered earlier. At that time, with some exceptions, the major gramophone manufacturers in Britain were producing models including the "internal amplifiers" with a poor response, which were popular due to their compactness.

The situation changed in the early 1920s with the theoretical analysis on horns performed by Webster, C. R. Hanna and J. Slepian, who extended the Rayleigh's analysis for pipes to cover the case of exponential horns. The wave equation is based on the following assumption. The wavefront is considered as a nearly plane at the throat of the horn and spherical at the mouth, expanding exponentially. This resulted in a row of patents claiming the optimal shape of the horn, which was 45° angle of slope to the axis at the open end, 42° in Wilson’s modified exponential horn, and Voigt’s tractrix curve. Comparison of the exponential horn with other types (conical, parabolic, hyperbolic) and a discussion on the tractrix shape is given by Dinsdale.

1E. M. Siemens, "Magneto-Electric Apparatus", U.S. Patent 149,797 (1874); "Telephones", British Patent 4685 (1877)
The fabulous response of an acoustic phonograph down to 30 Hz was obtained by loading with an external exponential horn. These experimental horns have square or trapezoidal mouths and are made by folding. For example, in 1930 in London, the 8.2 meters long terneplate horn with a square mouth had a cutoff frequency of 32 Hz and efficiency of over 25 percents. Another horn had an opening of 2.4 meters width and 1.8 meters height, like a corridor. Wilson points out that the volume and quality of reproduction were tremendous for that time, “although with a certain directionality in a lateral sense” due to the bend of the horn. The idea behind the trapezoidal shape of the mouth is to accelerate the wavefront around the bend. The low-frequency limit was acquired by the horn which was imposing more resistive than reactive loading onto the stylus. Smaller horns perform worse at the lower frequencies. Using bass reflex enclosures, one can improve the response. This is, however, not the case for the Stroh violin, dimensions of which are much smaller for the sake of playability.
2.2 The phonograph and the singing voice

An investigation of how the phonograph and gramophone influenced the vocal technique and what are the physical reasons of that phenomena, was initiated in 2014 by Karin Martensen, docent of musicology at the University of Paderborn. Her motivation was to learn if the phonograph makes a singing voice more pleasant by enhancing the singing formants. The investigated phonograph "Edison Home" belongs to the Ethnologischen Museum Berlin-Dahlem. The author of this thesis conducted the research work, which included the phonograph recordings and the acoustical analysis of the sound path, under the supervision of Dr. Malte Kob. The results were presented in a DAGA-2015 contribution "Phonograph und Gesangsstimme" [9].

We recorded sweep, chirp and pink noise on an appropriate wax cylinder in a laboratory of Erich-Thienhaus-Institut. For recordings, a conical horn of 23 cm mouth diameter was used; length of the conical part is 24 cm; cylindrical throat is 2 cm length and 1.5 cm diameter. For playback, an exponential horn of mouth diameter 23 cm and length 25 cm was used. The mouth diameter of the small recording horn is about 6 cm, and length is 24 cm. The recording setup in Fig. 2 shows the conical recording horn on the left and the exponential playback horn on the right side.

Figure 2: Measurement setup with KH120 loudspeaker and NTi microphone for the test signal recording with the phonograph wax cylinder, ETI Detmold [9]
Since phonograph mechanics is noisy itself, the measurement dynamic range suffers from noise. Noise of the mechanism is "colored" by resonances of the horn-membrane-needle system. It is present constantly when recording or playing, therefore during the playback the double amount of colored mechanical noise is delivered together with the recorded content. This "background" noise, though, is also limited by the phonograph frequency range.

Range limitations are demonstrated in time representation of a swept sinus tone from KH120 loudspeaker compared to the phonograph playback in Fig. 3. During first half of the sweep, the wax cylinder record is pure noise amplified through the horn. After 15 seconds, at about 500 Hz, the signal appears. Then at 800-1700 Hz, many harmonics are present, since this is the area of the phonograph frequency response where most of horn resonances concentrate. At 1800 Hz a short dip follows, where the fundamental tone level is not higher than of mechanical noise. After it, harmonics appear again, until the upper frequency limit of 4000 Hz.

![Figure 3: Sweep signal from KH120 loudspeaker recorded and played back from the phonograph wax cylinder, measured in ETI Detmold.](image)

Acquired with Praat software.
The range limitations can be observed even better in Fig. 4, where the frequency response curve is compared to the reference pink noise excitation, acquired with the same setup. The information below 250 Hz is not relevant due to acoustics of the lab. The response is above the noise floor between 500 Hz and 4 kHz. A characteristic dip at 1800 Hz and an especially strong amplification at about 1000-1300, 2000 Hz are well displayed.

Figure 4: Sweep signal from KH120 loudspeaker recorded and played back from the phonograph wax cylinder, measured in ETI Detmold

Factors influencing the recording quality, assuming the same horn and membrane, but changing cylinders:

· Cylinder material, shape, and condition have a direct influence on sound quality. Thickness of the cylinders of different manufacturers may vary. This leads to the need of “pre-settings” of the screw adjusting the driving arm height, and therefore the load on a rotating axis. These affect the velocity and the pitch.

· The character of mechanical noise may change from time to time since it is an old device.

· The angular velocity of a cylinder depends on the spring charge.

· Velocity can be modulated if the cylinder cross-section is not perfectly round, therefore
the pitch is periodically altered and the periodical scratching noise appears.

A conical recording horn amplifies the sound acoustically by directing the spherical sound waves into the membrane, and an exponential horn is used for playback to achieve a better radiation efficiency \[0\]. Sound pressure level in Fig. 5 shows the bandpass filter effect and harmonic resonances of the conical recording horn. This transfer function was obtained using three NTi microphones: one at the horn opening plane, and two at the horn throat plane. One of those is mounted air-tight inside the horn throat, imitating the membrane. It is worth to note, though, that in a real diaphragm there is an air enclosure which plays a role of a reactive muffler (acoustic filter). Confined air volume in the soundbox raises the frequency of the axisymmetric modes.

![Figure 5: Measurement setup and the transfer function of the conical recording horn, measured in ETI Detmold](image)

In the article ”Horn loudspeaker design” (1974), J. Dinsdale stated that in spite of the large size and difficulties in design implementation, the exponential horn has advantages in terms of presence, clear bass, and low distortion \[8\]. It allows the source output to remain balanced over its frequency range. A drawback is in a narrow radiation pattern of the exponential horn for the higher frequencies, which results in a dull sound off axis. Another drawback is that a throat of small diameter is needed for high efficiency at high frequencies, but a larger throat is best for low frequencies. Therefore the conical horn, although its range is less balanced, is used for recording, and the exponential horn for playback.
Sound of the mechanically amplified instruments and the phonograph is shaped by the vibrational modes in the membrane, the transfer function of the horn and the radiation impedance characteristic of the horn.

Diaphragm plays a role of a compression chamber which drives the horn. Its vibration is similar to that of a supported plate with an additional load (the needle) fixed in the center. The rubber ring, implemented in most of the acoustic gramophones and the Stroh violins, introduces imperfect boundary conditions which lead to asymmetrical movement of the membrane.

Contactless measurements on a recording diaphragm were conducted with laser vibrometer in ITA laboratory at RWTH Aachen. A fragment of the animated laser vibrometer frequency response in Fig. 6 shows an asymmetrical character of the diaphragm movement.

![Figure 6: Asymmetrical movement of the phonograph recording membrane, measured with a laser vibrometer in ITA laboratories [9].](image)

At the diaphragm resonance, the distortion develops due to the stiffness of a recording medium. The needle at the center point increases the effective inertia of diaphragm and prevent the excitation of the diametral modes. In Stroh violins, a beating develops, resulting in a larger bow pressure required to maintain the motion.
Another phenomena of the phonograph frequency response is the origin of a spectral dip at 1800 Hz. This was investigated with the accelerometer placed between the membrane needle and the metallic cylinder base. The phonograph membrane in a recording position was attached to the small accelerometer instead of a wax cylinder, as pictured in Fig. 7 left. Boundary conditions, in this case, are extremely hard and unnatural in comparison to the soft cylinder, but give a hint for a spectral composition of the membrane vibration. This setup is considered as a "fixed end", whereas the laser vibrometer frequency response represented a "free end". In both cases, the horn and the membrane are excited with the loudspeaker KH120, and the microphone in a membrane plane is taken as a reference signal. Fig. 7, right picture, shows frequency response curve. High levels in the range above 4 kHz are explained by the hard boundary. A dip at 1800 Hz is pronounced, same as in the phonograph transfer function. The frequency of the dip was shifted when the accelerometer position was changed. In laser vibrometer measurements with "free needle", which are not given here, there is no dip in the spectrum. Therefore, the most probable conclusion would be that the origin of the antiresonance lies in the needle position in relation to a recording medium, a wax cylinder.

Figure 7: Frequency response of the needle loaded with accelerometer imitating a recording medium, and the measurement setup (sweep excitation with KH120).
The horn matches the impedance of recording medium with the impedance of the air and plays a role of an amplifier, so the membrane movement is strong enough to drag the needle through the wax layer. The input impedance of both recording and playback horns measured with the calibrated impedance head BIAS 7 is shown in Fig. 8.

Figure 8: Input impedance plot for the conical and exponential horns of the phonograph, acquired with BIAS measurement head

The cutoff frequency for the exponential horn (red) is 676 Hz, which corresponds to the first peak in a phonograph frequency range shown in Fig. 4. It is widely used as a playback horn. The conical shape is beneficial for a recording situation. The horn aperture, which collects the sound energy, shall be wide enough to avoid too strong resonances, as in case of the narrow recording horn (green). The input impedance plot of the conical horn (blue) shows why the exponential horn is preferred for the playback: although a conical horn has no cut-off frequency, it has a poor transmission at low frequencies [10]. The low-frequency oscillation lacks the energy to move the recording stylus. The horn’s transfer function in Fig. 5 represents the bandpass-filtering which with the voice undergoes during the recording.
Vowels sung in different pitches were recorded to see how the formants of the human voice are reproduced by a phonograph. The formants are transformed in a way that some voice partials are missing, and some are added, depending on where the resonances and dips of the phonograph transfer function are located. An example of such transformation is given in Fig. 9.

Figure 9: Spectrogram image and LPC-formant analysis (using Praat software) of "A" vowel of male tenor voice. Left: microphone, right: phonograph.

Two educated singers, Boris and Doris, performed a bass aria from the opera ”Ariadne on Naxos” by Richard Strauss and a soprano aria ”Quando men’vo” from act 2 of Puccini’s opera La bohème. These are given in the attached CD (see Table 5 in Appendix I).
3 Acoustics of the violin

3.1 Strings

String vibration plays a determining role in shaping of the violin sound, therefore, a violin is recognized even if there is no vibrating corpus as in electro violin or the Stroh violin.

The strings are set to harmonic oscillation by either bowing or plucking. When a string is plucked, two displacement waves travel in opposite directions from the point of excitation and are reflected at the ends of the string (Fletcher and Rossing 1998, 38 [11]). Since waves are traveling in both directions on the string, they will quickly overlap and interfere, producing standing waves that vibrate in multiple harmonically related modes. Energy loss gradually dampens the string until it stops vibrating.

As with plucking, bowing causes two waves to travel in opposite directions, but one is quickly dampened by friction of the bow against the string (Fletcher and Rossing 1998, 50), so no standing waves are present. A moving bow continues to add energy to the string, keeping the sound relatively constant until the bow is removed or changes its direction.

A core feature of the bow excitation is a “stick and slip” motion between the bow hair and a bowed string, which brings the sting to vibration. The horse hair is used for the bow, refined with colophonium (or rosin\(^2\)) to make it harder. As the bow is pushed over the string, the string is deflected in bowing direction by means of static friction. The force of deflection grows continuously with the string tension until the static friction limit is exceeded, then the string loses contact with the hair and snaps back. This sliding friction movement is essentially short in comparison to the static friction. As the bow is moved with constant velocity, the deflection of the string is slow, and the movement back is relatively fast. Together, the sum velocity is equal to the bow velocity, and this stick-and-slip process is periodical: the string sticks and is brought further.

\(^2\)Rosin is a solid form of resin obtained from pines and some other plants, produced by heating fresh liquid resin to vaporize the volatile liquid terpene components (Wikipedia).
Velocity and frictional force are the main characteristics during the forward and backward motion of the bowed string. The sawtooth-like oscillation of a bowed string consists of many harmonic sinusoidal partials or overtones, as described in eq. (1), where \( k \) is the order number of the partial. Amplitude of each partial is expressed as \( A_k = A_0 \frac{1}{k} \). This form of oscillation, among other factors, is responsible for the characteristic sound of a bowed string instrument.

\[
A = \sum_{n=1}^{\infty} A_k
\]  

Open strings sound brighter than fingered. Sometimes this extra brightness is exploited, sometimes avoided to make the melody line more homogeneous. Because of the lack of partials, harmonics have a flute-like sound which is thinner than the normal note. Natural harmonics sound louder than artificial ones. The 3rd or 4th register, at about the middle of the string, is the most "effective", having a soft, penetrating warmth.

The musicologist Daniel Smutny describes in his lecture notes the sound character of the individual violin strings as follows:

- G string (G3–C5, G5): alt-timbre, earthy and intense, hard with appropriate bowing. Dark and sonorous in the low register with a tendency toward roughness. Highly expressive and soulful cantilenas can be expected in the high register.

- D string (D4–G5, D6): full sounding and mellow, with great sweetness. The sound of the D string resemble a human voice and is used for melodious cantilenas.

- A string (A4–D6, A6): gentle, more mellow than the D string.

- E string (E5–A7, D8): brilliant, open, cutting, rich in focus. Lustrous and metallic hues dominate in lower-pitched middle tones. Very bright in the upper register, though less full sounding. Its brightness makes the E string more audible.

The further one goes beyond B4, the thinner is the tone, but outstanding violinists can make it sound nice and with great care. Left-hand technique affects the tonal quality.
When the composer desires a beautiful sound of the 3rd and 4th registers, he specifies the string, otherwise the player chooses an other, easier and more ordinary register.

Due to the waveform of a string excited by the bow, quiet dynamics do not lead to fewer overtones, like in brasses, but bring higher frequency components. The bow offers a wide scope for forming the tone’s attack, which is stronger than the attack in wind instruments. However, sharp attack of the violin tone is still slightly slower than of the oboe. This is due to the complex energy transfer through the bridge, building up a maintained body oscillation. In wind instruments, on the opposite, the tone is built up almost immediately, in tenths of milliseconds, whereas for the violin string the attack time takes from 30 to 200 ms, depending how softly the bow is applied. The attack time is shorter at higher tones.

3.2 Bridge and the soundpost

The process of energy transfer begins at the contact point of the string with the bridge. The vibrating string moves the bridge in a complex rocking motion, mostly transversal, but also longitudinal, flexural, and torsional movement. The sound post performs two main tasks: it provides an asymmetrical impedance to the bridge feet movement and enhances the higher partials. According to R. Mores, the sound post is located in the nodal point of most of the plate modes, but in the same time a little variation in space drastically changes the high-frequency content above 1500 Hz. At some frequencies above 6 kHz, the bridge radiates itself, and its shape alters the frequency response as well.

Each violin string has its own timbre because of different tension and string mass, resulting in different load on the bridge. Greater tension of the higher strings increases significantly the static force on the soundpost. Fletcher, referring to Hacklinger (1979), reports that the E string vibration is almost parallel to the plate plane, as the G string reaches nearly a 50° angle [11].

A damper is used for darkening the violin tone. This effect is based on adding an additional mass to the vibrating bridge, which lowers its natural frequencies.
3.3 Violin modes

Violin acoustics has been investigated intensively over the last century, with numerous research works on string motion, acoustics of the body, radiation, and timbre. Though the timbre differs a lot from instrument to instrument, mostly there are common formants, which an experienced listener expects from the violin sound, associating them to the subjective descriptors such as warm, bright, soft, nasal, etc.

Typical formants of a violin tone are described by Smutny as follows. Low tones about 400 Hz, which have a formant color of a dark 'o' are responsible for sonority of the G-string. The second formant area from 800 to 1200 Hz ('a'-vowel) is responsible for the strength and substance and prevents a nasal sound. Exact register, which is crucial for the unique sound of the violin, varies between 700 Hz and 1250 Hz. Formants from about 1600 Hz can result in a damped, covered sound and nasality. Formant areas for more brilliance and brightness are located between 2000-2600 Hz and 3000-4000 Hz (i.e. 'e'- and 'i'-vowels).

So how these formants appear? Standing waves are formed at the natural frequencies of the vibrating body, and their combination results in a modal pattern of the plates and the cavity. Modes which are stronger in some frequency regions and weaker in others, determine the violins sound character.

In a wooden violin body, potential resonances are determined by the two direction-dependent sound velocities $c_l$ and $c_w$ (Fletcher, p. 89 [11]):

$$f_{mn} = 0.453h[c_l(\frac{m+i}{L})^2 + c_w(\frac{n+i}{W})^2]$$

Modes, or standing waves, of order $m$ are possible across the length of the plate and modes of order $n$ across its width. Their frequencies are interdependent, but not harmonically spaced, as in the one-dimensional case of the string. If the frequencies of the (2,0)- and (0,2)-modes are close, they superimpose in so-called ring mode and X-mode. For spruce, the material-determined length-width ratio is $L/W = 1.9$. This ratio can be considered as a determining factor for the evolution of string instruments.
Of course, the modal pattern of a free vibrating plate is not the same as of the instrument assembled together with the walls, the sound post, and the bass bar. Resonances of the entire body, cavity and plates construct the vibrational profile of the violin, which is related to radiation in a nonlinear way. The non-uniform material strain properties and the top plate thickness may also vary the modal frequencies from instrument to instrument in a range of ten percent. This makes it hard to predict the violin modes analytically.

Open violin strings are tuned to the following frequencies: G3=196 Hz, D4= 293.7 Hz, A4 = 440 Hz, E5 = 659.3 Hz. Signature modes in this region play an important role in shaping the violins sound impression.

For the purpose of this investigation, the air coupling between the top and the back plate, the two-dimensional body modes and the one-dimensional body modes are considered. Let’s locate these modes, looking at the violin transfer function plot shown in Fig. 10:

- One-dimensional first bending mode of the entire violin body coincides with the fundamental mode of the C string \( f_{C1} = 193..199 \) Hz.
- Helmholtz mode A0 or a cavity resonance, \( f_{A0} = 270 \) Hz is the lowest strongly radiating mode.
- The first corpus mode CBR around 400 Hz is of type (1,2) and depends on the material strain properties. It has a shear-like in-plane relative motion between top and back plates, out-of-phase f-hole volume flows and thus relatively weak corpus and f-hole radiation.
- A1 is the first longitudinal mode with frequency \( f_{A1} = 1.7 \cdot f_{A0} \). It is seen in Fig. 10 that its position is affected by the next strong corpus bending mode B1+.
- The corpus bending modes B1- and B1+ radiate strongly from the surface and the f-holes [12]. Bending modes are dependent on body stiffness, therefore the tuning of frequencies can be achieved by changing the rib strength.
- The top and back plate modes are in the range from 700 to 2000 Hz.
In Fig. 10, the first partials of the four open strings are shown with arrows, pointing to the corresponding frequency bands of the transfer function. Consequently, if in some instrument these bands have a high level, the open strings with their overtones will have a rich sound with a very slow decay.

In these two violins\textsuperscript{2}, the Helmholtz mode A0 and a CBR mode are similar in frequency and spectral shape, whereas the higher signature modes are spaced in more different patterns, with slightly varying levels. Modes of the higher order are always like fingerprints.

Figure 10: Main body modes of the two reference violins, with the frequency partials of the four open strings indicated by arrows. Transfer functions were measured at IfM Zwota.

\textsuperscript{2}These violins belong to the reference instruments collection of the IfM Zwota (Institute für Instrumentenbau) and are used in this work for comparison with the Stroh violins.
3.4 Principles in modal tuning

Formants of the violin tone are in close range to the female soprano singing voice. In his recent work, Joseph Nagyvary proposes that Stradivari, Guarneri and the Italian violin makers of other periods could have used the high sung vowels as a matter of quality control, and considers the possibility that the violin makers intentionally aimed for a vowel-like sound [13].

Most of the violin makers use a method called modal tuning, holding a violin top or back plate at the nodal lines and listening to the ring mode and X-mode while adjusting the plate thickness. For example, this is a common practice taught in the violin maker study program in Markneukirchen (Westsächsische Hochschule Zwickau, University of Applied Sciences). There, the luthiers also have access to acoustical measurement equipment, monitoring their works by means of vibrational analysis and visualization of the Chladni patterns. According to R. Mores, the following set of physic-related principles has been developed based on a long tradition of violin making:

1. A sufficiently strong Helmholtz mode $A_0$ is important. It is appreciated by violin makers and even used as a criteria of a good instrument by Bissinger [12]. $A_0$ shall be located in a certain frequency range to meet the expectations of the player in the context of repertoire.

2. The signature modes $CBR$, $B1-$ and $B1+$ are different from violin to violin (as we already have seen in the previous chapter) due to material strain. The target is to achieve a wide range of resonances, so more string partials are supported in a balanced manner.

3. The balanced sound level principle applies to the entire spectrum, as to contain both, the feeling of a spacious body, as well as a bright and brilliant sound. Meinel\textsuperscript{3} and

Dünnwald studied valued instruments and identified desirable proportions of energy in frequency bands. High levels from 190 to 650 Hz are suggested to be responsible for the fullness of sound. Brilliance and clarity imply high levels from 1300 to 4200 Hz.

4. Lower levels between 650-1300 Hz and above 4200 Hz also emphasize the brightness. Moreover, spectral dip in the area of 700-800 is desirable for a good quality tone.

The Stradivari violin’s bridge admittance and radiated sound level in Fig. 11, acquired by Mores, illustrates these principles. The old Italian violins, though, according to J. Meyer, have a broad formant maximum around 1900-2500 Hz, which is followed by a strong roll-off toward high frequencies. This roll-off is not present in the newer masterworks.

Figure 11: The radiated SPL (top) and the bridge admittance (bottom) of the 1712 Stradivari violin measured by R. Mores

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There are two reasons why the transfer function ”impact hammer - microphone”, averaged from a few positions, is chosen in this work as a basic measurement method.

First, as it is seen in Fig. 11 the structure vibrations represented by bridge mobility are not directly related to the resulting radiated sound (SPL). This is due to the complex combinations of the modes and the interaction with the surrounding air.

Second, the tone quality in a large extent depends on the violinist’s competence. Such factors as choice of the string, the bowing point, speed, and pressure determine the level of oscillation of certain partial vibrations, i.e. the timbre.

The transfer function method eliminates the influence of the strings quality on the measurement. It has a controlled repeatability in comparison to a player. It considers propagated sound, not the sound in structure.

A mechanical bow is mostly preferred by researchers of violin acoustics when it comes to investigations of bow excitation effects, but an accurate setup is not available for everyone. Jansson, though, measured the long-time average spectra of bowed violin music and provided additional information about the differences between groups of violins. Ghosh and Mores proceeded in their research work using a mechanical bow with a controlled bowing pressure.
4 The Stroh violin

In 1902, a year after the Stroh violin was patented, an article of D. Donovan appeared in The Strand Magazine, promoting the Stroh violin as having "the reserve power of three Josephs [Guarnerius], and as loud as 4 ordinary violins" [14]. Later in Galpin Society Journal in 1975, J. Pilling investigates the origin of the instrument, concluding that the first purpose of the Stroh violin was the phonograph recording [15]. Pilling proposes that the bumbass (or "bladder-and-string") is an ancestor of a horn fiddle.

Readers interested in historical and aesthetical aspects of the topic might appeal to the recent works of Alison Rabinovici. Rabinovici's first publication [17] provides a precise and full description of patented instruments with numerous illustrations. Five years later, in 2010, Rabinovici accomplished her master research thesis "A History of Horned Strings: Organology and Early Sound Recording 1899-1945", an investigation of the Stroh violin and the phonofiddle. She examines how the Stroh violin is related to the development of the phonograph and scientific methods in acoustics. It is pointed out that the phonofiddle, in contrast to the Stroh violin, has a background of the "blackface minstrelsy and popular music-hall entertainment". Also, Rabinovici experimented with wax cylinder recordings of a horn fiddle.

Olavi Linden, Linden instruments [19], and La Fausse Compagnie [20], though they do not have published reports, have a rich practical experience in manufacturing Stroh instruments and are open for contact. Linden's comments on the construction of different Stroh violins and horn designs are given in the next Section 4.1.

Acoustical research on Stroh violins counts not so many contributions. The most recent work is done in 2014 by the team of Francois Gautier. Researchers in ITEMM, France, did measurements and physical modeling on the Stroh violin and presented the poster at ISMA-2014 conference on musical acoustics, but did not publish their results yet. As described in the abstract of "Acoustic characteristics of the Stroh-violin", the spectral analysis of the instrument's sound showed "a filtering effect induced by strong resonances of the coupled bridge-diaphragm-horn system". The physical model of the Stroh violin includes the horn
acoustic input impedance and a lumped element model of the bridge admittance. As a conclusion, it is stated that the resonant behavior of the bridge has similar features with those encountered in some classical violins and known as Bridge Hill [21].

In the following chapters, attention is paid to the construction and main features of the Stroh violin, as well as the investigations of Ghosh (1926) and Mores (2013), who measured the acoustical characteristics of the Stroh violin and published their works. These contributions are analyzed with regard to the measurement results presented in this work.

4.1 Construction of the horn fiddle

In musical instruments design, the horns have a rich story of implementation. An oriental bowed instrument called Qeychak (Gheichak, Ghaychak) is still in use in Iran. As depicted in Fig. 12, it is made of a dual box with expanding openings and a membrane surface at the bridge part. It seems to be essentially a horn fiddle: it has a diaphragm, and a body that acts as a double horn.

![Figure 12: Photo of the Qeychak](image)

Four main parts contribute to the sound path of the Stroh violin and the like: the strings, the bridge, the diaphragm and the horn. Each of them shapes the sound path’s characteristic with their natural frequencies.
1) The diaphragm

In Burma, one of the very few places in the world where one still might see a horn fiddle, an adapted version of the Stroh violin is produced. It has a thick diaphragm and, therefore, lacks the level of the fundamental and the first overtone.

Olavi Linden commented on different designs of the Stroh violin in a personal correspondence. Unfortunately, he says, most of the modern Stroh violins from Burma seem to have this thick diaphragm, giving the original Stroh a bad reputation. One Burmese Stroh violin from Linden’s collection has a 0.5 mm thick aluminum diaphragm, while a Stroh violin from about 1920 has a better sound and the diaphragm thickness is 0.4 mm.

The Tiebel violin, created by Willy Tiebel in Markneukirchen in the thirties has the thinnest diaphragm of 0.3 mm. Linden states that it has the softest sound, but it does not carry the same power as the Stroh violin. In this work, the Tiebel violin appears as a measurement object in Sections 5-7. The difference in 1/10 mm thickness might seem small, but it influences the stiffness in third power, so the 0.5 mm diaphragm is about 4.6 times stiffer than one of 0.3 mm thickness.

2) Types of the bridge lever

The string vibration produces a transverse force on the bridge. The bridge performs angular oscillations about a pivot, setting the diaphragm center to vibration. The diaphragm center is beneficial in a sense that diametral modes are not excited. The rocking lever on the instrument base determines the rotation axis of the bridge. Elastic vibrations of the bridge are of little importance in the production of musical tones.

Partially, energy is transmitted also to the fingerboard and to the cylindrical body of the Stroh violin. This makes it easier to get vibrational feedback for the player.

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6Olavi Linden – a violinist, an instrument maker and the designer of Fiscars garden tools – developed multiple acoustically amplified instruments and multi-soundhole technology, experimented with various designs of horns and membranes (mostly of carbon fiber), and has founded the company Linden Instruments.
The lever joint of the bridge-membrane can be constructed in different ways, depending on the membrane type and where it is placed. The gramophone-type membrane has a leverage point at the rim of the diaphragm, while the classical Stroh membrane is always outside the instrument, connected to the bridge by a small foot.

In case of a gramophone membrane, the metal bridge base can be placed symmetrically right on the rim, when the membrane is mounted inside the instrument corpus under the strings, - or outside, as in a Stroh violin, with the rocking bridge foot connected to the membrane “needle”, which is also a lever. Then, there are two levers in a coupled system.

Figure 13: Photos of the violins of the The Markneukirchen Musical Instruments Museum taken in IfM Zwota. Left: the Stroh violin coupling via the one-side bridge foot; right: an alternative coupling in the Tiebel violin.

Variations of coupling system are shown in Fig. 13. The picture shows the most common membrane type, a rippled diaphragm made of aluminium, firmly fixed along the rim, and attached to the bridge foot in its central point, which is curved like a loudspeaker diaphragm.
3) The horn

In most cases, a string instrument with the horn is too nasal and unpleasant if there is no filtering of frequencies. Olavi Linden has found a number of ways to implement filtering. An inner horn, shown in Fig. 14, reduces nasality by attenuating some energy around 1500 Hz. The air enclosure just behind the diaphragm can also do some filtering, as mentioned in Section 2.2.

Figure 14: Pekka Kuusisto playing a double horn violin at Kuhmo Chamber Music Festival in Finland, 2013. Photo published with agreement of Olavi Linden

Linden instruments show that the horn vibrations themselves do not add much to the Stroh sound. Linden manufactures horns for his instruments out of carbon fiber, and it does not result in a perceivable difference except that of instrument weight.

To understand the behavior of the horn, as discussed in Section 2, two effects have to be considered: the wave propagation, and the radiation. To produce low frequencies huge horns are needed, the rule of thumb is that the circumference of the horn mouth should be equal with the wavelength of the lowest note played.
Linden notes that “well-designed horn systems can have a very high efficiency, more than ten times the efficiency of traditional instruments.” An example of Olavi Linden’s double bass with a large wooden horn is shown in Fig. 15.

Figure 15: Picture of the horn double bass from 2013 Kuhmo Chamber Music Festival in Finland performing a Vivaldi a- minor concerto [19].

Distortion in horns, such as harmonics and interference or intermodulation products, is caused by the inherent nonlinearity of the air. The horn equation is derived assuming that the pressure variations are infinitesimal, and this does not hold for the intensities at the throat of horns. Poisson showed in 1808 that sound waves, generally, cannot be propagated in air without change in form, resulting in the generation of distortion.

The acoustical characteristics of a simple horn can be predicted. Input impedance curve for simple geometries can be modeled by deriving the input impedance $Z_{in}$ from radiation impedance $Z_{rad}$, counting the loss coefficient and end correction of the tube length.

By measuring the length and the outer diameter, the geometry of the air column is determined and processed in Matlab or BIAS optimization software, assuming the wave propagation to be one-dimensional and plane. In practice, many additional factors influence the acoustical behavior of the horn, such as viscous and thermal damping, wall losses, and length correction.
4.2 Calculations and measurements on the phonofiddle

R. N. Ghosh was the first investigator of the acoustics of horn fiddles. It had been taken for the verification of the theory of bowed instruments due to its simpler mechanical system compared to an ordinary violin.

The photo in Fig. [16] and the described construction in the paper allow to say that this instrument is a phonofiddle (a single string and the membrane mounted into the body). It follows a similar mechanical principle as the original model of the Stroh violin, but the resonances of the membrane and the horn are, of course, not exactly the same due to the different geometry. The radius of the steel diaphragm is 2.6 cm, with 0.25 cm thickness of the plate. The horn is of 33 cm length. The cylindrical part of the horn’s throat is about 5 cm length and 9 cm internal diameter. At the horn’s mouth, a short flange is attached, the diameter of the open end is 12 cm.

![Figure 16: A photo of the phonofiddle with and without the horn (R. N. Ghosh [1]).](image)

Ghosh reports about the increase of radiation at high frequencies, at the resonance frequency of a diaphragm and of the horn. His calculations report that adding a flange or a horn significantly increases the output level. The damping coefficient of the string and the
minimum bowing pressure also rise considerably at the resonance pitch of the diaphragm. The theoretical estimations agree with the observed values.

In 1926, using a standardized sonometer, a mirror on the bridge and a spot of light reflected to the screen (a very common technique at that time), he empirically estimated the membrane and horn resonance frequencies. Attaching and removing the horn and visually observing the amplitude, he established that the Stroh violin has three characteristic resonances: the first and the third (380 and 760 Hz) belong to the diaphragm while the second (at 497 Hz) is the horn resonance. Calculated natural frequencies are 370 Hz for the diaphragm and 510 Hz for the horn.

A deviation between observed and calculated resonances is due to the boundary conditions of the membrane, which are imperfect due to the rubber ring clamping the rim of the diaphragm. The resonance frequency of the clamped membrane varies depending on tension. Therefore, to "retune" the diaphragm in order to avoid the wolf note at a particular frequency, one shall adjust the tension of the rubber rings.

Ghosh established that the membrane resonance is responsible for the weak point at the Stroh violin’s fret: a disturbing beating frequency, or "wolf note".

![Figure 17: A time representation of the beating tone (R. N. Ghosh)](image)

The wolf note phenomena has quite a simple explanation based on the cyclic energy exchange, resembling a breathing process. Fletcher proves in [11], that the characteristic impedance of the violin string is ten times smaller than the impedance of the bridge. This way, the strong reflection allows the string to oscillate at its fundamental frequency. But as soon as the vibrating body builds up the energy near one of its natural frequencies, the
bridge impedance drops by approximately the quality factor of the resonance. In this case, the reflection is too weak and the string oscillation dies out, depriving the body from its energy source. The amplitude of the body resonance drops down, allowing the string to reestablish its vibration level, and a new cycle begins. The string and the body vibrations alternately increase and decrease in amplitude, typically, about 5 Hz, which is heard as a beating tone. Its time representation is shown in Fig. [17].

In case of the Stroh violin, at its wolf tone, the string vibrations excite the mode of the diaphragm, which is near to the frequency of the played note. It starts to vibrate with a larger amplitude, but it needs also a larger force input from the bow to maintain the fundamental vibration of the string. Otherwise, energy will dissipate and the string will vibrate at its octave. The diaphragm alters the mode of vibration, with the octave partial having priority. The diaphragm is not excited anymore, and vibrations decrease in amplitude. The string fundamental mode returns to the first partial and the energy cycle repeats. A steady tone at the diaphragm resonance frequency appears with larger bow pressure.

With mechanical bow, Ghosh estimated the bowing pressure at different frequencies, and observed that bowing pressure rises at the diaphragm and horn resonances. Required bowing pressure rises also when bowed by the bridge and with the increase of the bowing speed.

During experiments, it was found, that at both resonances of the diaphragm, the rise of bowing pressure required to maintain the oscillation regime is accompanied by a strong frequency beating. To prevent the beating tone effect, the bowing point shall be further away from the bridge, where the conditions for bowing speed are different.

The important fact is that at the horn resonance there is no beating tone produced. At the same time, bowing pressure rises due to increased dissipation of energy. The bow at that particular pressure is capable of maintaining the string fundamental, although it is difficult because of the resonance.
### 4.3 Comparison of the Stroh violin to a reference violin

Robert Mores, professor at HAW Hamburg, investigated experimental violins from Hanneforth collection in 2013. Among them, Mores compared the Stroh violin to the reference Stradivari masterwork. For that he uses measurements of the bridge admittance, comparing modes of the instruments range by range. Violins are excited at the bridge with an impulse hammer at the plane of the bridge, following the direction of rocking motion. An accelerometer sensor records the impulse response, which represents the input admittance of the bridge. Peaks correspond to a high mobility of the structure, which does not always directly relate to sound radiation, as explained in the previous section.

Mores introduces the following assumptions for the Stroh violin physics. The horn function differs from the wood resonator, quasi-replacing the plate resonances by a compression wave developing in the horn. To quantify it, the pole-zero plot at the end of a horn may be used to define the amplification frequencies.

![Bridge admittance comparison](image)

**Figure 18:** Left: Bridge admittance of the Stroh violin (black) compared to a Stradivari violin by R. Mores, HAW Hamburg.

As the Stroh violin horn is conical, a periodical spacing of the frequencies can be expected. Its regime of the periodical pattern lies between the regimes of the closed and open organ pipes and depends on the ratio at their ends [11].

The horn of the Stroh violin from the Hanneforth collection is about 35 cm long, with the relation of diameters 4.29 R. The bridge admittances of the Stradivari violin and of the
Stroh violin are shown in Figure \[30\]. The air mode A0 and the first signature mode both coincide with the fine reference. Among ten experimental violins investigated, the Stroh violin is one of the few instruments where the A0 level and frequency position are similar to the reference. The horn seems to be adjusted in a way to fit the Helmholtz mode and the signature modes of the reference violin. This is not the case for all instruments, how it will be shown in the next sections.

Mores suggests that the first four peaks (272, 448, 676, and 964 Hz) directly relate to the conical horn. The row of frequencies does not strictly follow an arithmetic progression, which agrees with the findings of Ayers et al. (1985), quoted by Fletcher and Rossing, for singly closed conical horns. The first peak has a higher frequency in relation to the other peaks for the case when the horn’s mouth is wider than its throat. The diaphragm resonance found by Ghosh is not mentioned.

Mores analyzed the modes according to the principles of modal tuning (see Section 3.4). In the whole, the peaks are balanced in the spectrum. A0 mode matches in frequency, as stated earlier, with the level only 2.5 dB below the reference. In the range of signature modes, there is only one mode between 400 and 500 Hz with a level of 4 dB higher than the strongest mode in the reference. The ”brilliance” band is about 8 dB lower, but this is compensated by the band of 650-1300 Hz which is rather moderate than strong. As noted in Section 3.3, it emphasizes the tone brilliance. This quality is welcome in violins, and Mores suggests that this may explain the popularity of the Stroh violin.

It is notable that, when the Stroh violin is played, a violin is clearly heard. This originates in the bowing mechanism and the slip-stick motion of the string, as it is mentioned before in Section 3.1. A metal horn is heard as well, the most at the lower notes. When played in a low register, the Stroh violin sounds like a gramophone reproduction of a conventional violin. High registers sound the most similar to the violin tone. Listening examples comparing two violins with two Stroh violins are given in the CD.
5 Playability and usage

It is well known that playing depends very much on comfort with an instrument and some sort of auditory feedback. The Stroh violin is an absolutely special case since the weight and geometry have nothing in common with a conventional violin. The one Stroh violin with the horn made of brass, investigated in this work, weights 2 kilos, and this makes it hard to play long.

Instrument holding position significantly differs. Photo in Fig. 19 shows the ordinary holding of the violin and the Stroh violin: neck of the Stroh violin points to an absolutely different direction than violinists are used to.

Figure 19: Holding position for the Stroh violin and for the reference violin.

Auditory feedback is limited due to the horn pointing forwards. Most of the Stroh violins have an additional small horn built in the rear membrane surface, aimed to deliver some part of the sound to the musicians’ ear. Unfortunately, in some models it is designed
wrong (with an abrupt change of the diameter, for example) and does not work efficiently. This only lowers the output power of the violin because of pressure leakage.

Another point is the instrument quality itself: when the bridge position is adjusted wrong or the diaphragm is not rigidly connected to the bridge feet, a number of problems arise. Violin maker Yoshiaki Akamatsu commented on the craftsmanship quality of the two instruments from The Markneukirchen Musical Instruments Museum. He noted that the bridge does not have an identical geometry and position compared to an ordinary violin, which is a reason why it is harder to play "clean". For example, the bridge is placed lower, and the nut is higher than normal.

The distance between the strings and the top of the fingerboard measured at the end of each string, called the string heights, is crucial for playability and projection. Strings that are too low can buzz while strings that are too high can be difficult to play. Correct standard string heights for a violin (4/4 size, gut/standard) are 3.2 - 3.5mm for E string, and 5.0 - 5.5mm for G string, while at the Stroh violin, the G string has a 4.5 mm height.

5.1 Repair

A buzzing noise at some notes can be fixed by tightening the screw connecting the diaphragm with the bridge feet. If this does not help, the problem is inside the diaphragm. The Stroh violins usually have rubber gaskets around the rim of the membrane. The cause of unpleasant sounds could originate from the rim, it might have gone loose, or the bottom end of the connection screw is badly coupled. In this case, it is necessary to open the diaphragm housing. Then, there are two solutions: to dampen the rim by inserting a line of elastic material along the rim, or to enlarge the screw head area by attaching a small sheet of aluminum foil and tighten the connection. The latter works well, but dampening the rim can cause dull and thin sound afterwards. Moreover, not each diaphragm housing is easy to open. For instance, in the Tiebel violin, the diaphragm is assembled like a sardine jar, while a Stroh housing can easily be opened and closed. This gets even more complicated, taking into account a vulnerable 0.3 mm thick membrane, which easily deforms.
5.2 Playing techniques and listening examples

To answer the question how the Stroh violin sound differs from the conventional violin, two Stroh violins from The Markneukirchen Musical Instruments Museum and two reference violins of IfM Zwota were taken for a recording session. This section describes the recording process and the playing techniques used for the listening examples.

Binaural recordings took place in a slightly reverberant conference room in IfM Zwota, using a dummy head. The room has ca. 1.2 s reverberation time and a volume of ca. 90 m³. All instruments were played by a violin player Yoshiaki Akamatsu, a student of violin maker studing program of FH Zwickau in Markneukirchen. The same bow was used for all recordings. A photo of the recording situation is shown in Fig. 20.

Thanks to the variety of playing techniques, a violin can sound very different. There
are left- and right-hand techniques: the left hand stops the strings on the fingerboard, determining the pitch of the fingered note, the right hand plucks or bows the strings.

An important rule in the bowing technique is that the bow moves slower at the bridge area, and faster at the middle point of the string, otherwise it will lose the tension needed to produce the string oscillation. If one plays slower far from the bridge, and the hand is “hanging” holding the bow with almost no pressure on it, the sound will be flutando with strong noise components. Bowing technique, in principle, is comparable with breathing and needs an adequate training.

When a violinist takes a violin he or she never played before, at first it feels like driving a different type of car. One knows where the pedals are and how it works, but it takes time to check how long the effective way of pedals is. Quite the same psycho-mechanical trick happens when switching to the Stroh violin. Therefore, 40 minutes of warming up were given for Yoshiaki Akamatsu, who played for the listening test. The results are given in the CD.

Short musical phrases are performed for a subjective evaluation in following playing techniques: vibrato, glissando, flageolet, legato, staccato, spiccato, pizzicato, double stops, and a musical piece, a melody line of Bach’s Cello Suite No. 1.

The idea behind using a wide scope of playing techniques is to emphasize the different behavior of the instruments. The following instruments were recorded:

1. Tiebel violin, aluminum conical horn, 811.2 g (The Markneukirchen Musical Instruments Museum)
2. Stroh violin, brass conical horn, 1826.1 g (The Markneukirchen Musical Instruments Museum)
3. Two reference violins (IfM Zwota collection)

The tracklist for the CD with the samples of playing techniques is provided in Appendix I.
6 Spectral analysis of the violin sound

This section opens the acoustical analysis part of the thesis. Spectral components of the bowed open strings are in focus.

For the objective comparison of the instrument sound, it is necessary to eliminate the acoustical characteristics of the recording space. For this reason, the recordings of open strings were made in a large anechoic room of IfM Zwota. This room corresponds to the norms for free field measurements in a frequency range of violins. Fig. 21 shows the recording setup in the anechoic room. The dummy head is used for binaural recording.

![Recording setup in anechoic room for the spectral analysis](image)

Since the Stroh violins belong to the museum, it was not allowed to change the strings, so the sets of strings are different. Also because of large differences in construction and weight between the Stroh violins and reference violins, it is not easy to produce reproducible and comparable tones. Therefore, the best parts of the stable tones were chosen for spectral analysis.
A string oscillates with its whole length at the fundamental frequency simultaneously with its parts, dividing the length by a whole number. Higher order vibrations are called harmonics, and their frequencies are evenly spaced. Open strings are used for the tonal analysis since the partials decay the longest and allow to see the distribution of the partials in the string spectrum.

To see the differences between the spectral components of the instruments, the recorded samples are chosen and analyzed with the computer program Stx / CEP Spectral Magnitude. An algorithm searching for the fundamental and the first 12 partials of the string is used. Then data for all four instruments is normalized to the averaged level for each string. This approach was used in S. Judith’s diploma thesis in IWK, Vienna [18].

The following formulae is used for logarithmic averaging:

\[
L_{\text{average}} = 10 \times \log\left(\frac{10^{L_1} + 10^{L_2} + \ldots + 10^{L_{12}}}{10^{12}}\right)
\]

The results are presented in Fig. 22, with the four colors denoting the instruments. For each harmonic, the level shows a relation of the single level to the average of all partials of all instruments for a given string. For the D string, the most of the energy in concentrated within the first seven partials of the spectrum. For the A string, the five first partials have maximum energy. When the fundamental has a high frequency, its overtones are spaced in a bigger distance, and at very high frequencies the overtones are not effective.

For the A string, the seventh partial in the Tiebel violin is weaker than the average by 40 dB. As shown at transfer function in Fig. 35 in Appendix II, Tiebel violin has a large dip around 4500 Hz.
Figure 22: Tone analysis of the open strings
7 Measurement setup and data

From the impulse and its response, the transfer function can be derived in frequency domain. Transfer function is a good choice to evaluate and compare stringed instruments, because it is not dependent on the quality of the strings (strings are damped with a soft stripe and the operator’s hand) and the repeatability of the measurement can be controlled.

Mobility of the investigated structure does not always directly translate to sound radiation. Therefore, for deriving the transfer function, the three-dimensional measurement is done according to the setup developed by Gunter Ziegenhals [25] for measuring the transfer functions and radiation characteristics of the stringed instruments. It is used in IfM Zwota since many years for certifying tested instruments by comparing them to the reference instruments data. Measured objects are mostly violins and guitars, but also other bowed and plucked instruments, and experimental masterworks such as a new Turkish instrument called Divane.

This section provides a description of the microphone setup with a half-hemispherical microphone array in a big anechoic room in IfM Zwota. The setup is used for two-dimensional measurements of the acoustical characteristics of two Stroh violins from The Markneukirchen Musical Instruments Museum and two reference violins of IfM Zwota. With assistance of a colleague, Christoph Gilbert, transfer functions are measured with this setup to evaluate the differences in the spectral composition of their modes.

The polar radiation pattern is measured to show the directional efficiency of the main resonances. The horn impedance and the transfer function of another Stroh violin (with and without a horn) were measured in ETI, Detmold. This allows to make assumptions about the natural frequencies of the elements of the sound path.

The anechoic room of the institute has the distance $h = 3,1\,\text{m}$ between the acoustic foam spikes, and lengths $l = 4,5\,\text{m}$ and $b = 4,88$ at the door axis, which makes it possible to measure at the 1-meter radius hemisphere without interference of wall effects. The low-frequency end of the room is at 125 Hz.
Measurement microphones hang on their cables at 12 fixed positions in a half-hemisphere with one meter radius at the middle point of the room, according to the measurement standard DIN 45635/1, as shown in Fig. 23.

Figure 23: Microphone positioning for measuring the radiation pattern

The equipment of the laboratory allows to use 12 channels with phantom power. An additional channel is used as a reference signal corresponding to the excitation - the force sensor of an impulse hammer. By rotating the measured object 180° in the horizontal plane, two measurement cycles are sufficient for extending the setup to 23 microphones (12 real and 11 virtual channels) positioned in a hemisphere. The result is a direction-dependant sound level for the hemisphere, from which one can extract the plane needed. Transfer functions are averaged from 23 positions in the microphone sphere to locate the strongest resonances.

The force spectrum of the hammer strikes shall be the same each time. The frequency-dependent coherence coefficient of the current measurement compared to the others allows to discard bad strikes. The measurements are normalized to the calibration values.

Frequency data is recorded with 8192 Hz sample rate in a range between 0 Hz and 5 kHz, averaged over 10 impulse hammer strikes. The striking point is the middle of the bridge normal to the bridge plane.
From 2 x 12 channels in a hemisphere, it is possible to plot the polar radiation pattern in different planes (around the vertical axis and in the horizontal plane) by choosing the channels, as shown in Table. 1.

**Table 1: Microphone positions in the measurement half-hemisphere setup in 45°-positioning, h - the height of the microphones over the suspended floor level.**

<table>
<thead>
<tr>
<th>Position Nr.</th>
<th>Azimut</th>
<th>Zenit</th>
<th>h/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos. 1</td>
<td>90°</td>
<td>-30°</td>
<td>25</td>
</tr>
<tr>
<td>Pos. 2</td>
<td>45°</td>
<td>0°</td>
<td>75</td>
</tr>
<tr>
<td>Pos. 3</td>
<td>0°</td>
<td>0°</td>
<td>75</td>
</tr>
<tr>
<td>Pos. 4</td>
<td>-45°</td>
<td>-30°</td>
<td>25</td>
</tr>
<tr>
<td>Pos. 5</td>
<td>-90°</td>
<td>0°</td>
<td>75</td>
</tr>
<tr>
<td>Pos. 6</td>
<td>90°</td>
<td>60°</td>
<td>162</td>
</tr>
<tr>
<td>Pos. 7</td>
<td>45°</td>
<td>45°</td>
<td>146</td>
</tr>
<tr>
<td>Pos. 8</td>
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<td>125</td>
</tr>
<tr>
<td>Pos. 9</td>
<td>-45°</td>
<td>60°</td>
<td>162</td>
</tr>
<tr>
<td>Pos. 10</td>
<td>-90°</td>
<td>45°</td>
<td>146</td>
</tr>
<tr>
<td>Pos. 11</td>
<td>0°</td>
<td>90°</td>
<td>175</td>
</tr>
<tr>
<td>Pos. 12</td>
<td>-45°</td>
<td>0°</td>
<td>75</td>
</tr>
</tbody>
</table>

For transfer function measurements of stringed instruments of violin’s dimensions, it is practical to average three microphones in the following positions relative to the front side of the instrument [25]:

- **Channel 3**: perpendicular to the front plane about the bridge level;
- **Channel 2**: at 45° to the microphone 1 in a horizontal plane about the bridge level; microphone 2 represents the audience direction. This position was used by H. Meinel in his measurements in the 1930s.
- **Channel 7**: at 45° to the microphone 2 in a vertical plane, shifted in the direction of the neck.

**Table 2: Microphone positioning for the polar radiation pattern in the horizontal plane.**

<table>
<thead>
<tr>
<th>MIC</th>
<th>3</th>
<th>2</th>
<th>17</th>
<th>23</th>
<th>15</th>
<th>12</th>
<th>5</th>
<th>14</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANGLE</td>
<td>0</td>
<td>45</td>
<td>90</td>
<td>135</td>
<td>180</td>
<td>225</td>
<td>270</td>
<td>315</td>
<td>360</td>
</tr>
</tbody>
</table>
Table 3: Microphone positioning for the polar radiation pattern in two vertical planes.

<table>
<thead>
<tr>
<th>ANGLE</th>
<th>0</th>
<th>45</th>
<th>90</th>
<th>135</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIC, 0 level</td>
<td>3</td>
<td>8</td>
<td>11</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>MIC, 45 level</td>
<td>2</td>
<td>7</td>
<td>11</td>
<td>18</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 24: Measurement setup in the anechoic room of IfM Zwota. Left: Tiebel violin, right: Stroh violin
8 Results and discussion

In this section, the measurement results and interpretation are presented. These are the key results of the Stroh violin’s sound path analysis, specifying the resonances of the horn. Three horn violins are measured in the scope of this work. The first violin, owned by Vinorosso ensemble in Detmold, has an aluminum horn and a one-sided bridge connection, typical for the Stroh violin, described in paragraph 4.1.2 and shown in Fig. 25. Its sound transfer function and the input impedance of the horn were measured in ETI Detmold.

Two other violins come from The Markneukirchen Musical Instruments Museum: the Tiebel violin built in the 1930’s, and the Stroh violin found at a marketplace in Ibiza. The latter has a brass horn and a one-sided bridge connection. The Tiebel violin has an aluminum horn and a two-sided bridge connection. Photos of both violins is given in Fig. 24, listening examples are on the CD. Their transfer functions and radiation patterns were measured in IfM Zwota.

Figure 25: The Stroh violin of Vinorosso ensemble in Detmold.
As the reader already knows from Section 4.3, the Stroh violin from Hanneforth collection, measured by Mores, has its first resonance below 300 Hz and a 4 dB lower level than the Helmholz mode of the reference violin. The Stroh violin from Hanneforth collection is claimed to be an original instrument. In this work, first resonances listed in Table 4 show that this is not the case for all Stroh violins, and moreover, none of the investigated instruments are original Strohs.

Table 4: Table of resonance frequencies of each investigated violin.

<table>
<thead>
<tr>
<th>Violin</th>
<th>f1, Hz</th>
<th>f2, Hz</th>
<th>f3, Hz</th>
<th>f4, Hz</th>
<th>f5, Hz</th>
<th>f6, Hz</th>
<th>f7, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. 17</td>
<td>268.8</td>
<td>343.8</td>
<td>492.2</td>
<td>778.1</td>
<td>956.3</td>
<td>1453</td>
<td>2410</td>
</tr>
<tr>
<td>Ref. 20</td>
<td>270.3</td>
<td>340.6</td>
<td>521.9</td>
<td>800</td>
<td>978.1</td>
<td>1361</td>
<td>2466</td>
</tr>
<tr>
<td>Tiebel violin</td>
<td>323.4</td>
<td>410.9</td>
<td>478.1</td>
<td>793.8</td>
<td>1055</td>
<td>1214</td>
<td>2606</td>
</tr>
<tr>
<td>Stroh violin, brass horn</td>
<td>334.4</td>
<td>389.1</td>
<td>556.3</td>
<td>753.1</td>
<td>1105</td>
<td>1564</td>
<td>2453</td>
</tr>
<tr>
<td>Stroh violin, alum horn</td>
<td>355</td>
<td>391</td>
<td>632</td>
<td>854</td>
<td>1096</td>
<td>1582</td>
<td>1854</td>
</tr>
</tbody>
</table>

8.1 Transfer functions

Looking at the transfer functions given in Fig. 26 and Fig. 27, the following points can be observed:

1. Both the Strohs and the Tiebel violin have their first resonance 50-70 Hz higher than the reference violins - a cavity resonance at 270 Hz in a frequency region responsible for "spacious" body sound. Especially for the lowest tuned C string. Nevertheless, for the higher notes played, this difference is not so obvious. Basically, the first resonance of the Strohs lies between the A0 and CBR modes of the conventional violin.

The Tiebel violin outperforms both Strohs in the lower range of string fundamentals (196..659 Hz), probably because of the double-side connection of the bridge. For the Tiebel, the level of the first peak is 5 dB lower than the reference. For the brass Stroh violin, it is about 12 dB lower. The aluminum Stroh violin shows the lowest values up to 550 Hz. This range is crucial for the fullness of sound.
2. The peak at about 500 Hz, marked as $f_3$, is 5 dB lower for the Stroh and 10 dB lower for the Tiebel compared to the reference. Its frequency corresponds to the longitudinal mode A1, with an ordinary "from-violin-to-violin" deviation of 30-80 Hz. Although, as it is seen in Fig. 27, for the aluminum Stroh violin this peak is less pronounced and overtaken by the next broad peak at 632 Hz.

3. At $f_4$ (780-850 Hz, top plate modes region), all five violins have quite similar peaks. For the back plate modes region (up to 1000 Hz), the Strohs’ modes are more modest in level, though spaced in a balanced manner.

4. The brass Stroh violin has a broad spectral maximum at about 1800-2300 Hz, followed by a spectral roll-off. It shares the same characteristics with the old Italian violins. A balanced sound level is desired for the entire spectrum. Therefore, this instrument comes closest to the reference, although it lacks the low-frequency part.

5. Assuming that lower levels between 650-1300 Hz and above 4200 Hz emphasize the
brightness, this applies to the horn violins very well. According to this criteria given by Mores, the brass Stroh violin is definitely brighter than the reference violins.

6. Notable are the large dips in the transfer function of the aluminum Stroh violin at 1384, 2300 and 3000 Hz, breaking the balance in the spectrum. Nevertheless, the spectral dip desirable for a good quality tone, described in Section 3.3, lies exactly between 700-800 Hz and has a benefit over the reference. The brass Stroh, in opposite, has a resonance in this area, with lower and broader dips at about 500-600 Hz.

Figure 27: Transfer functions of three Stroh violins: the one with a brass horn, one with an aluminium horn, and the Tiebel violin with an aluminum horn.

The Tiebel violin proved a better response in lower frequency areas, but a less bright sound impression than the Strohs. The Strohs can vary considerably, depending on the horn material, on diameter and shape of the rippled diaphragm, the condition and the quality of the instrument. The brass horn Stroh outperforms all of the present violins in level of mid-high range from 1500 Hz. The aluminium Stroh violin from Detmold is weaker in the low ranges. Its resonances are shifted to higher frequencies, and are not so balanced, suffering from numerous dips and peaks above 1300 Hz.
8.2 Horn measurement results

It is difficult to predict the vibration modes for a rippled curved membrane. Thinking of what are the possible resonances, one can go a subtractive way and look at the transfer function (TF) of the Stroh violin without a horn. The aluminum Stroh violin’s TF was measured in ETI Detmold using an average signal from three mics positioned as in IfM Zwota at page 46. The first measurement cycle was done with the horn, and for the second cycle the horn was unscrewed from the diaphragm box. The TF without the horn is shown at the upper plot in Fig. 28.

Figure 28: Top: TF of the Stroh violin without the horn. Bottom: Horn input impedance magnitude (BIAS).
The TH with the horn is shown at the previous page in Fig. 27 (green). Three resonances in the TF without the horn at the top picture in Fig. 28 at 766, 1736 and 2225 Hz, are the strongest. To emphasize the difference between two transfer functions, the real input impedance of the horn is measured using the BIAS measurement head. It is represented at the bottom picture in Fig. 28.

The first and the second resonances at 380 Hz and 770 Hz are the horn resonances. The strongest diaphragm mode is found at 766 Hz. This mode overlaps with the second resonance of the horn, which is lowered when the instrument is assembled together. Therefore at the TF in Fig. 27 the first resonance at 360 Hz is 20 dB lower than the combi-mode at about 640 Hz. This corresponds roughly to the TF image of the reference violin, where the A1 mode is stronger than the A0 mode.
8.3 Sound projection

There are more factors influencing the sound impression, namely the directional characteristics and the sound effect in a room. Sound radiation for stringed instruments depends on the way vibrating plates are divided into zones of different amplitudes and phases \[11\]. For the Stroh violin, the horn plays a determining role.

The following polar plots present radiation characteristics of the Stroh violin, the Tiebel violin and the ordinary violins, in the horizontal and vertical planes. The 0° position corresponds to the instruments front plane. It is seen that the reference violins radiate forwards, whereas in the Stroh violin the most energy is concentrated at the horn’s mouth.

Figure 29: Radiation in a horizontal plane. Left: Stroh violin. Right: Tiebel violin

Figure 30: Radiation in a horizontal plane. Left: Ref. violin 17. Right: Ref. violin 20
Figure 31: Radiation in a vertical plane at 0°. Left: Stroh violin. Right: Tiebel violin

Figure 32: Radiation in a vertical plane at 0°. Left: Ref. violin 17. Right: Ref. violin 20
Figure 33: Radiation in a vertical plane at 45°. Radiation in a vertical plane at 45°. Left: Stroh violin. Right: Tiebel violin.

Figure 34: Radiation in a vertical plane at 45°. Left: Reference violin 17. Right: Reference violin 20.
9 Conclusions

The Stroh violins differ significantly in timbre and construction. Some of them show better performance, with resonances closer to the reference violins, and some do not. Though there is a considerable frequency dispersion, their modes are surprisingly close to the violins we are used to.

It is found that the horn is responsible for the lowest resonance of the Stroh violin, which is between 200 and 360 Hz, depending on the instrument quality. Generally, sound impression of the Strohs is brighter than of the conventional violins. The feeling of the absence of a wooden body is not so strong when played in the high registers.

Level and width of the resonances in the signature range depend on how close the modes of the diaphragm and horn are located. To reach a lower A0-like mode in the Stroh violin, one shall try to employ a bigger and more effective horn, for example of exponential shape, like it is implemented in the phonograph. To design such a horn, one could use the software BIAS 7 Optimizer. Another wise step is to design the membrane choosing the thickness and the diameter (as an option, with the help of shaker-accelerometer measurement experiments) in such a way that it resonates at the same frequency as the horn, or lower. Then, the level of a "Helmholz" mode would be higher.

Considering the "Edison Home" phonograph, the measurements show that the frequency range of the device is limited from 500 to 4000 Hz. The frequency response of the phonograph is not flat, which is the reason why the voice timbre is changed. The resonances lie in the region of vocal formants. This results in two effects. First, since the device itself is incredibly loud, the mechanical noise is amplified almost to the same level as the recorded voice. Therefore, the formants which are initially not there, appear in the recording and "color" the voice. Second, multiple harmonic partials develop at the horn resonance. Their overall level is decaying slower than the non-resonant tones, and a reverberation effect appears. These resonances are dependent on the dimensions of the recording horn.
9.1 Summary

The Stroh violin and the phonograph follow a similar physical principle and work in the same frequency range. Both the singing voice and the string have harmonic partials in their spectrum, and are reproduced by the horn in a similar way.

The introduction in this work is followed by a description of the phonograph, its features and the history of its development. Measurements and recording experiments have shown an influence of the device on the singing voice. The frequency response of the whole device is obtained by recording test signals on the wax cylinder. Its single parts are analysed by means of contactless measurements of the membrane using a laser vibrometer, the horn transfer function and impedance. Phonograph recordings of the singing voice are presented on the CD.

The outcome is that the non-linearity of the horn strongly influences the voice, adding and removing formants during the recording, which is explained by the characteristical mechanical noise and the horn harmonics. As it is described in the literature overview in 2.1, the requirement for a better reproduction in a wide frequency range is the horn’s size and shape. The diaphragm condition must be good, and its tension shall be adjusted by the rim.

Another objective of this work is to determine the characteristics of the Stroh violin sound, which are different or similar to the sound of an ordinary violin. First, an overview of the violin acoustics is given in Section 3. The Stroh violin’s construction and function is described in Section 4, considering the previous findings. As Mores stated, their first resonance can reach a surprisingly low region of 200 Hz, seeming to be ”tuned” to the Helmholtz mode. This work, however, shows that this quality is present not in all instruments, and that mostly the first horn resonance is above 300 Hz. This is true for the copies of the original Stroh instruments. The Tiebel violin, which has a little different design of the bridge connection, achieves a better result than the copies, but still the frequency of the first resonance is higher than in the ordinary violins. The difference in playability is emphasized in Section 5.
Acoustical measurements of different Stroh violins are supported with listening examples. The sound samples of the open strings are analysed by the first 12 partials in Section 6. This allows to characterize the timbra of the Strohs, compared to conventional violins. For scientists interested in two-dimensional acoustical measurements, it might be helpful to take a look at the setup with 12 microphones in a hemisphere, given in Section 7. In Section 8, modes of the horn and the diaphragm were located by measurements of the transfer function with and without the horn, and the horn input impedance. This shows that the diaphragm and the horn resonances coincide and give a larger level of the mode, which resembles the longitudinal mode A1 in violins.

The gained knowledge gives a hint for the instrument builder interested in Stroh violins, what to take into account when designing the diaphragm, the bridge and the horn, so that the horn fiddle sounds close to the ordinary violin.
References


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[23] Zakharchuk, P.: *History of Strings with Horns: A Study Overview*, In-proceedings DAGA 2015, Nuernberg


10 Appendix I: CD Tracklist

<table>
<thead>
<tr>
<th>Track</th>
<th>Instrument</th>
<th>Musical Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reference violin 17</td>
<td>Musical piece fragment (Bach’s Cello Suite No. 1)</td>
</tr>
<tr>
<td>2</td>
<td>Reference violin 20</td>
<td>Musical piece fragment (Bach’s Cello Suite No. 1)</td>
</tr>
<tr>
<td>3</td>
<td>Stroh violin (brass)</td>
<td>Musical piece fragment (Bach’s Cello Suite No. 1)</td>
</tr>
<tr>
<td>4</td>
<td>Tiebel violin (alum)</td>
<td>Musical piece fragment (Bach’s Cello Suite No. 1)</td>
</tr>
<tr>
<td>5</td>
<td>Reference violin 17</td>
<td>Vibrato</td>
</tr>
<tr>
<td>6</td>
<td>Reference violin 20</td>
<td>Vibrato</td>
</tr>
<tr>
<td>7</td>
<td>Stroh violin</td>
<td>Vibrato</td>
</tr>
<tr>
<td>8</td>
<td>Tiebel violin</td>
<td>Vibrato</td>
</tr>
<tr>
<td>9</td>
<td>Reference violin 17</td>
<td>Glissando</td>
</tr>
<tr>
<td>10</td>
<td>Reference violin 20</td>
<td>Glissando</td>
</tr>
<tr>
<td>11</td>
<td>Stroh violin</td>
<td>Glissando</td>
</tr>
<tr>
<td>12</td>
<td>Tiebel violin</td>
<td>Glissando</td>
</tr>
<tr>
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<td>Reference violin 17</td>
<td>Flageolet</td>
</tr>
<tr>
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<td>Reference violin 20</td>
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</tr>
<tr>
<td>15</td>
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<td>Flageolet</td>
</tr>
<tr>
<td>16</td>
<td>Tiebel violin</td>
<td>Flageolet</td>
</tr>
<tr>
<td>17</td>
<td>Reference violin 17</td>
<td>Legato</td>
</tr>
<tr>
<td>18</td>
<td>Reference violin 20</td>
<td>Legato</td>
</tr>
<tr>
<td>19</td>
<td>Stroh violin</td>
<td>Legato</td>
</tr>
<tr>
<td>20</td>
<td>Tiebel violin</td>
<td>Legato</td>
</tr>
<tr>
<td>21</td>
<td>Reference violin 17</td>
<td>Staccato</td>
</tr>
<tr>
<td>22</td>
<td>Reference violin 20</td>
<td>Staccato</td>
</tr>
<tr>
<td>23</td>
<td>Stroh violin</td>
<td>Staccato</td>
</tr>
<tr>
<td>24</td>
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</tr>
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<td>Spiccato</td>
</tr>
<tr>
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<td>Track 27</td>
<td>Stroh violin</td>
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</tr>
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<td>Track 28</td>
<td>Tiebel violin</td>
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</tr>
<tr>
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<td>Reference violin 17</td>
<td>Pizzicato chords</td>
</tr>
<tr>
<td>Track 30</td>
<td>Reference violin 20</td>
<td>Pizzicato chords</td>
</tr>
<tr>
<td>Track 31</td>
<td>Stroh violin</td>
<td>Pizzicato chords</td>
</tr>
<tr>
<td>Track 32</td>
<td>Tiebel violin</td>
<td>Pizzicato chords</td>
</tr>
<tr>
<td>Track 33</td>
<td>Reference violin 17</td>
<td>Double stops</td>
</tr>
<tr>
<td>Track 34</td>
<td>Reference violin 20</td>
<td>Double stops</td>
</tr>
<tr>
<td>Track 35</td>
<td>Stroh violin</td>
<td>Double stops</td>
</tr>
<tr>
<td>Track 36</td>
<td>Tiebel violin</td>
<td>Double stops</td>
</tr>
<tr>
<td>Track 37</td>
<td>Reference violin 17</td>
<td>Bowed scale (anechoic room)</td>
</tr>
<tr>
<td>Track 38</td>
<td>Reference violin 20</td>
<td>Bowed scale (anechoic room)</td>
</tr>
<tr>
<td>Track 39</td>
<td>Stroh violin</td>
<td>Bowed scale (anechoic room)</td>
</tr>
<tr>
<td>Track 40</td>
<td>Tiebel violin</td>
<td>Bowed scale (anechoic room)</td>
</tr>
<tr>
<td>Track 41</td>
<td>Boris, bass</td>
<td>Fragment of the aria ”Ariadna auf Naxos”, phonograph</td>
</tr>
<tr>
<td>Track 42</td>
<td>Doris, soprano</td>
<td>Fragment of the aria ”Quando men’vo”, phonograph</td>
</tr>
</tbody>
</table>

Table 5: The CD tracklist with the listening examples.
Appendix II: Transfer functions (not averaged)

Figure 35: Seven main resonances of the Stroh (top) and Tiebel violin (bottom). Transfer functions are obtained from four positions.
Figure 36: Seven geometry-defined resonances of the reference violins 17 (top) and 20 (bottom). Transfer functions are obtained from four positions.
12 Declaration

I, Polina Pirch, confirm that the thesis is my own intellectual work, and that no other aids or sources were used than those listed in the references. Quotations are marked as such and the thesis has not been submitted elsewhere for the purpose of examination.

I want to thank sincerely all the people who helped and supported me with this work:

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