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Mechanics and acoustics of violin bowing

Freedom, constraints and control in performance

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Abstract

This thesis addresses sound production in bowed-string instruments from two perspectives: the physics of the bowed string, and bow control in performance. Violin performance is characterized by an intimate connection between the player and the instrument, allowing for a continuous control of the sound via the main bowing parameters (bow velocity, bow force and bow-bridge distance), but imposing constraints as well. In the four included studies the focus is gradually shifted from the physics of bow-string interaction to the control exerted by the player.

In the first two studies the available bowing parameter space was explored using a bowing machine, by systematically probing combinations of bow velocity, bow force and bow-bridge distance. This allowed for an empirical evaluation of the maximum and minimum bow force required for the production of a regular string tone, characterized by Helmholtz motion. Comparison of the found bow-force limits with theoretical predictions by Schelleng revealed a number of striking discrepancies, in particular regarding minimum bow force. The observations, in combination with bowed-string simulations, provided new insights in the mechanism of breakdown of Helmholtz motion at low bow forces.

In the second study the influence of the main bowing parameters on aspects of sound quality was analyzed in detail. It was found that bow force was totally dominating the control of the spectral centroid, which is related to the perceived brightness of the tone. Pitch flattening could be clearly observed when approaching the upper bow-force limit, confirming its role as a practical limit in performance.

The last two studies were focused on the measurement of bowing gestures in violin and viola performance. A method was developed for accurate and complete measurement of the main bowing parameters, as well as the bow angles skewness, inclination and tilt. The setup was used in a large performance study. The analyses revealed clear strategies in the use of the main bowing parameters, which could be related to the constraints imposed by the upper and lower bow-force limits and pitch flattening. Further, it was shown that two bow angles (skewness and tilt) were systematically used for controlling dynamic level; skewness played an important role in changing bow-bridge distance in crescendo and diminuendo notes, and tilt was used to control the gradation of bow force.

Visualizations and animations of the collected bowing gestures revealed significant features of sophisticated bow control in complex bowing patterns.

Keywords: bow-string interaction, bowed string, violin playing, motion capture, bowing parameters, performance control

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Studying the bowed string with a bowing machine turned out to be a relatively lonely business after that. My "Short Term Scientific Mission" (financed by Cost287-ConGas) at IRCAM and the cooperation with Nicolas and Frédéric Bevilacqua formed an important turning point in bringing the human aspect back in my work.

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Contents

Declaration

The contents of this thesis is my own original work except for commonly understood and accepted ideas or where explicit reference is made. The dissertation consists of four papers and an introduction.

Paper I E. Schoonderwaldt, K. Guettler, and A. Askenfelt. *An empirical investigation of bow-force limits in the Schelleng diagram*, Acta Acustica united with Acustica, Vol. 94 (2008), pp. 604–622.
The main part of the work was performed by the candidate, including data acquisition, data analysis and the authoring of the text. The simulations and the corresponding text in the discussion, as well as the derivation presented in the appendix represent the work of Guettler. Askenfelt and Guettler contributed to the planning of the experiment and the interpretation of the results.

Paper II E. Schoonderwaldt. *The violinist's sound palette: Spectral centroid, pitch flattening and anomalous low frequencies*, Accepted with minor revisions for publication in Acta Acustica united with Acustica.
The content of this paper represents entirely the candidate's work.

Paper III E. Schoonderwaldt, and M. Demoucron. *Extraction of bowing parameters from violin performance combining motion capture and sensors*, Submitted to the Journal of the Acoustical Society of America June 2008, reviewed, status pending awaiting companion manuscript (Paper IV).
The parts related to motion capture and calculation of bowing parameters and the authoring of most of the text represent the work of the candidate. Demoucron developed the method for measuring bow force and wrote the corresponding parts of the manuscript.

Paper IV E. Schoonderwaldt. *The player and the bowed string: Coordination and control of bowing in violin and viola performance*, Submitted to the Journal of the Acoustical Society of America. Status: Returned because the length exceeded JASA standards. The manuscript will reorganized and resubmitted in two parts.
This paper represents entirely the candidate's work.

Related publications

K. Guettler, E. Schoonderwaldt, and A. Askenfelt. Bow speed or position – which one influences spectrum the most? In *Proceedings of the Stockholm Music Acoustics Conference (SMAC03)*, pp. 67–70, Stockholm, Sweden, 2003.

E. Schoonderwaldt, K. Guettler, and A. Askenfelt. Effect of the width of the bow hair on the violin string spectrum. In *Proceedings of the Stockholm Music Acoustics Conference (SMAC03)*, pp. 91–94, Stockholm, Sweden, 2003.

E. Schoonderwaldt, A. Askenfelt, and K. F. Hansen. Design and implementation of automatic evaluation of recorder performance in IMUTUS. In *Proceedings of the International Computer Music Conference*, pp. 431–434, Barcelona, Spain, 2005.

P. N. Juslin, J. Karlsson, E. Lindström, A. Friberg, and E. Schoonderwaldt. Play it again with feeling: Computer feedback in musical communication of emotions. *Journal of Experimental Psychology: Applied*, 12 (2), pp. 79–95, 2006.

E. Schoonderwaldt, N. Rasamimanana, and F. Bevilacqua. Combining accelerometer and video camera: Reconstruction of bow velocity profiles. In *Proceedings of the 6th International Conference on New Interfaces for Musical Expression (NIME06)*, pp. 200–203 Paris, France, 2006.

E. Schoonderwaldt, K. Guettler, and A. Askenfelt. Schelleng in retrospect – a systematic study of bow-force limits for bowed violin strings. In *International Symposium on Musical Acoustics (ISMA 07)*, Barcelona, Spain, 2007.

E. Schoonderwaldt, S. Sinclair, and M. M. Wanderley. Why do we need 5-DOF force feedback? The case of violin bowing. In *Proceedings of the 4th International Conference on Enactive Interfaces*, pp. 397–400, Grenoble, France, 2007.

E. Schoonderwaldt, and M. M. Wanderley. Visualization of bowing gestures for feedback: The Hodgson plot. In *Proceedings of the 3rd International Conference on Automated Production of Cross Media Content for Multi-channel Distribution (AXMEDIS)*, pp. 65–70, Barcelona, Spain, 2007.

Preludium

Live violin performance is catching to the eye. The motion of the bow, necessary for the sound production, also reflects the performance, from the shaping of phrases down to the attacks of individual notes. The player's bowing gestures enhance the aural perception of the performance by visualizing the mechanical input to the violin in a striking manner.

A bowing gesture can be simple, like playing a single note, or complex, including a series of rapidly attacked notes with a bouncing bow. Independently of the level of complexity, a useful working definition of the term "bowing gesture" could be "A coordinated variation of several bowing parameters aiming at producing a sound (note, series of notes, phrase) with certain predetermined acoustical qualities and with a specific musical purpose."

It goes without saying that the bowing gestures cannot be executed ad hoc just for the sake of an artistically appealing visualization of the acoustical or musical characteristics of the performance to the audience. On the contrary, the bowing gestures are to a large extent heavily constrained by the sound produced at the moment and of the notes which will follow. The constraints arise from three areas: physical (bow-string interaction), biomechanical (the player's build and level of performance technique), and musical (the score).

The violin and the other bowed instruments are often claimed to possess a high musical expressivity, comparable only to the human voice. It may well be questioned how the numerous constraints on the bowing allow for such an expressiveness. The answer lies probably in the fact that the spaces for the control parameters, although strictly constrained in general, include sufficient freedom for the player to continuously modulate the tone in the attacks and during the "steady-state" part at a level of detail that allows the musical intentions of the player to shine through the performance. For comparison, singers are also heavily constrained due to the physiology and acoustical conditions of the voice organ, but nevertheless the expressiveness in performance is high for the same reasons as for the bowed strings. Further, for both strings and voice an important observation is that it is not only the notes themselves, but how the performer navigates from one note to another in the control parameter space, which carries a large part of the expressiveness in performance.

Bowing gestures need to be carefully planned and controlled even for seemingly simple tasks, in order to reach the intended acoustical characteristic of notes and phrases. This notion leads to the question of strategies for bowing gestures. The string player needs to coordinate a rather large set of bowing parameters continuously, and several of them may be in conflict with each other due to the three types of constraints mentioned. It can be hypothesized that players learn and adapt early to common strategies for basic, frequent playing tasks, but as experience is gained they explore their personal qualifications and develop a personal playing style.

The work included in this thesis bridges the borderland between the physics of the bowed string and the players' control of the bow-string interaction through bowing gestures. The main theme can more concisely be formulated as

> "the control and coordination of bowing parameters in violin playing and their relation to the produced sound."

A string player's perspective on the questions addressed is kept throughout the studies.

In order to treat different aspects of the main theme thoroughly, the focus of the four included studies is successively shifted from basic limitations on the bow-string interaction to the player's bow control in well-defined tasks. Together, the studies illustrate the influence of all three types of constraints on the players' choice of bowing parameters for specific conditions, as well as general strategies in bowing.

The studies address in turn:

- Empirical evaluation of the bow force limits necessary for verifying bowed-string theory and simulations.
- Mapping of the bowing parameter space accessible by the player to basic properties of the sound.
- Studies at a detail level of the control strategies employed by string players in basic tasks.

Bowing parameters

The bow interfaces the player with the violin. Interestingly, the simple idea of mounting a bundle of hair from a good horse tail on a wooden stick has shown to yield a interfacing device with unusual opportunities, due to the many degrees of freedom associated with the control of bow motion. The dynamics of the bow enters in many of these control aspects, in particular facilitating complex bowing patterns, like when the bow is allowed to bounce off the string between notes.

The control parameters for the sound available to the player – the main bowing parameters – are basically three:[1] (Typical values in violin playing are shown in parenthesis.)

[1] The connections between the bowing parameters and the bow-string interaction is discussed in Chapter 1.

1. *Bow velocity* (5–100 cm/s): The velocity of the bow as imposed by the player's hand at the frog. The local velocity at the contact point with the string is not exactly the same due to small modulations in the bow hair and bending vibrations of the stick. Bow velocity sets the string amplitude together with the bow-bridge distance.

2. *Bow-bridge distance* (5–60 mm): The distance along the string between the contact point with the bow and the bridge. The bow-bridge distance sets the string amplitude in combination with the bow velocity.

3. *Bow force* (0.1–2 N): The force with which the bow hair is pressed against the string at the contact point. The bow force determines the timbre ("brightness") of the tone by controlling the high-frequency content in the string spectrum. In tones of normal quality (Helmholtz motion) the bow force needs to stay within a certain allowed range. The upper and lower limits for this range in bow force range increase with increasing bow velocity and decreasing bow-bridge distance.

In addition, four "secondary" bowing parameters come into play for facilitating the control of the three main parameters above, and implementing strategies for changing the bowing parameters to the target values for the following note(s).

4. *Bow position* (0–65 cm): The distance from the contact point with the string to the frog. The bow position as qualitatively often said to alternate between "at the tip," and "at the frog." The bow position does not influence the string vibrations per se, but has a profound influence on how the player organizes the bowing. The finite length of the bow hair is one of the most important constraints in playing.

5. *Tilt* (0–45°): The rotation of the bow around the length axis. The bow is often tilted in playing in order to reduce the number of bow hairs in contact with the string. In classical violin playing the bow is tilted with the stick towards the fingerboard.

6. *Skewness* (±10°): The angle between the length axis of the bow and a line parallel to the bridge. Skewness indicates the deviation from "straight bowing."

7. *Inclination* (range about 65° between G and E string): Pivoting angle of the bow relative to the strings. The inclination is mainly used to select the string played.

Studies of bow control in performance

The study of the string players' bowing gestures is a rather limited field of research. It all started from a pedagogical interest. Still, important applications of the measurement systems developed in this thesis are in the field of string teaching.

In the 1930s Hodgson published the first results on visualizations of trajectories of the bow and bowing arm using cyclegraphs [27]. Using this technique, which had been developed by the manufacturing industries for time studies of workers, he could record brief bowing patterns by attaching small electrical bulbs to the bow and arm and exposing the motions on a still-film plate. The controversial results that the bow trajectories were always curved ("crooked bowing"), and that the bow was seldom drawn parallel to the bridge, caused an animated pedagogical debate.

Some years before Hodgson published his results, Trendelenburg had been examining string players' bow motion from a physiological point of view [64]. Without access to measurement equipment for recording the motions of the players' arms and hands, he drew sensible conclusions on different aspects of suitable bowing techniques based on his expertise as a physician.

Fifty years later Askenfelt studied basic aspects of bow motion using a bow equipped with custom-made sensors for calibrated measurements of all bowing parameters except the bow angles [1, 2]. Besides establishing typical ranges of the bowing parameters, basic bowing tasks as détaché, crescendo-diminuendo, sforzando and spiccato were investigated. A general conclusion was that it is the coordination of the bowing parameters which is the most interesting aspect. The result was not surprising in view of the many constraints which determine the player's decisions on when and how to change the bowing parameters. However, it was a reminder of that the control of bowed-string synthesis needs interfaces which easily can control several parameters simultaneously, like a regular bow.

During the last 20 years there has been a strong trend in developing sensor-based systems ("controllers") for capturing bowing gestures for the use in interactive electronic music performances [37, 65, 43, 45, 72, 5] (see also the K-bow[2]). The requirements on such systems are different from, and sometimes in conflict with, the requirements on measurement systems aiming at close analyses of the bow motion, or for feeding physical models of the bowed-string with accurate, calibrated control data [12]. In basic analyses of the bow motion one important aim is to collect sufficient amount of data to be able to draw reasonably safe conclusions on common strategies in bowing and individual differences therefrom.

The MIT Hyperbow, which initially was designed for a controller application, has more recently been developed for real measurement tasks [72]. The technique used is advanced, including electrical field sensing of bow position and bow-bridge distance, and tri-axial accelerometers and gyroscopes on the violin and bow for determining their relative positions. It has been shown that the data generated by this system could be used to distinguish between different bowing patterns (détaché, martelé, spiccato) and players. However, the output using this system has not proven to give reliable or analyzable results which increase the understanding of violinists' bow control and strategies in playing [72].

More recently, the interest for accurate measurements of bowing gestures has been revived in connection with control of physical models of the bowed string

[2] http://www.keithmcmillen.com/kbow/

("virtual violins") [57, 47, 12]. The interesting issue here is that a good physical model is bound to the same constraints as a real violin and requires a "violinist-like" control to play satisfactorily. A side effect is that the models are not easier to "play" than an acoustical violin. In order to achieve a realistic violin synthesis the control parameters need to be varied much in the same way as in a real performance. This requires a good understanding and modeling of common classes of bowing styles, based on accurate measurements of real string performances [12].

Coda

It is only by combination of continued basic research on the physics of the bow-string interaction and studies of the player's control of the string (via the bow and the left hand, respectively) that a thorough understanding of the sound generation in the violin from a musical point of view can be achieved. The studies included in this thesis give a contribution to this understanding by addressing fundamental issues in the string players' bow control and the relations to the resulting sound.

Part I

Introduction

Chapter 1

The bowed string

In this chapter, the theoretical concepts of the bowed string and previous research on bow-string interaction relevant to the studies in this thesis will be shortly introduced. The kinematics of the bowed string was first observed and described by Helmholtz in the second half of the 19th century [26]. Since then, the understanding of this phenomenon has gradually increased, and today the motion of the bowed string is the only example of vibration excited by friction which can claim to be well understood [70]. Raman, in the beginning of the 20th century, was the first to provide a mathematical description of the dynamics of the bowed string, based on several simplifications [49]. In the second half of the 20th century, computer simulations allowed for more realistic models of bowed-string dynamics, taking the basic properties of real strings, damping, stiffness, and torsional compliance, into account, as well as the boundary conditions at the string terminations. Later refinements on a more detailed level, but still of relevance from the string player's point of view, included influence of the finite width of the bow [48] and more sophisticated friction models [69]. An excellent and concise overview of the topic up to 2003 has been given by Woodhouse et al. [70]. A more complete reading is found in Cremer's standard work "Physik der Geige/The Physics of the Violin" [10].

1.1 The idealized string: Helmholtz motion

The regular vibration of the bowed string was first observed by Helmholtz using a vibration microscope [26]. His observations allowed him to derive a kinematic description of the motion of the whole string. Helmholtz discovered that the motion of the string could be described by a sharp corner, traveling back and forth on the string along a parabola-shaped path. The fundamental period of vibration T is determined by the time it takes for the corner to make a single round trip.

The principle is shown in Figure 1.1, assuming a perfectly sharp corner (idealized, perfectly flexible string). At any position along the string, the displacement as a function of time is characterized by a triangular wave, the slopes depending on the point of observation. Correspondingly, the string velocity is characterized by two alternating velocities v_+ and v_-. Under the bow, v_+ corresponds to the velocity of the bow v_B.

The interaction between the bow and the string is characterized by a sticking phase (the string moves along with the bow at the same velocity), and a slipping phase (the string slips back in opposite direction). The traveling corner is responsible for the time-keeping of the transitions between the two phases, triggering slipping (release) and sticking (capture).

As the string follows the motion of the bow during sticking, the amplitude of the string vibrations is determined by the combination of bow velocity and the relative bow-bridge distance: the amplitude is proportional to the bow velocity v_B, and inversely proportional to the relative bow-bridge distance β (where β is defined as the bow-bridge distance divided by the length of the string: $\beta = x_B/L$).

1.2 The real string: Theory of the rounded corner

The transversal force exerted by the string on the bridge, which excites the violin body and produces the sound, is proportional to the angle of the string at the bridge. For idealized Helmholtz motion characterized by a perfectly sharp corner, the angle changes linearly as the corner travels from the bridge and back again along the parabolic envelope during one period. At the arrival of the corner at the bridge the angle flips momentarily from one side to the other. The waveform of the bridge force becomes a perfect sawtooth which is independent of the point of excitation (the bowing point x_B), and consequently the string spectrum cannot be influenced by the bowing. The description above of the bowed string without losses corresponds strictly to a free oscillation, which could as well take place in absence of the bow. The excitation by the bow, as well as the role of bow force (the force by which the bow is pressed against the string), has not come into play yet, and the player´s control of the sound is limited to the amplitude only.

For a real string, energy losses and stiffness matter. In that case an excitation by the bow is required to keep the string vibrating. The energy losses, including internal losses in the string and at the string terminations, combined with dispersion due to stiffness (higher frequencies traveling slightly faster than lower frequencies) introduce a smoothing of the traveling corner. The net rounding of the corner is determined by a balance between this smoothing and a resharpening effect at the bow during release and capture.

The effect of corner rounding and resharpening has been described by Cremer [10]. Sharpening takes place mainly during release, when changing from sticking to slipping. If the perfectly sharp corner is replaced by a rounded corner of finite length, the string velocity no longer drops suddenly when the corner arrives at the bow (see Fig. 1.2a and b). Instead a gradual change in velocity takes place. Taking the frictional force between bow and string into account, the string is now prevented from slipping at first instance when the rounded corner arrives at the

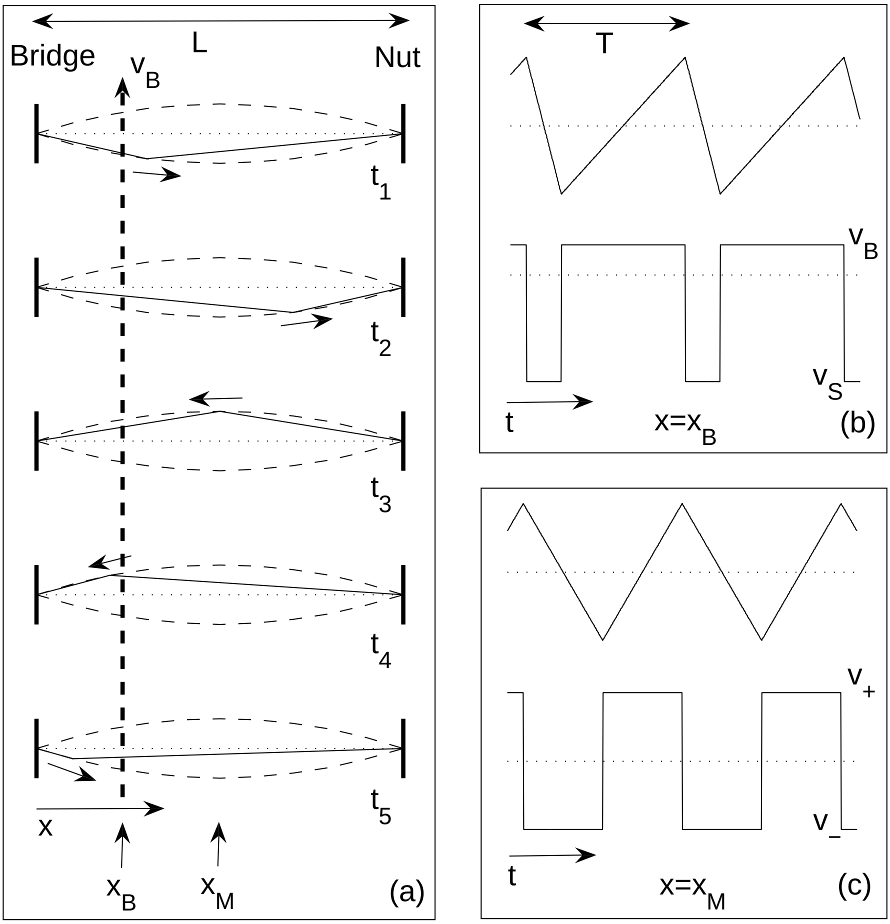

Figure 1.1: Principle of Helmholtz motion. (a) Snapshots of the traveling corner at different moments within a single period. At the moments t_1–t_3 the string is sticking to the bow, and at t_4 and t_5 the string is slipping (just after release and before capture). Right column: String displacement and velocity as a function of time at (b) the bowing point x_B, and (c) at the middle of the string x_M. At the bowing point the velocities v_+ and v_- correspond to the bow velocity v_B and slipping velocity v_S, respectively.

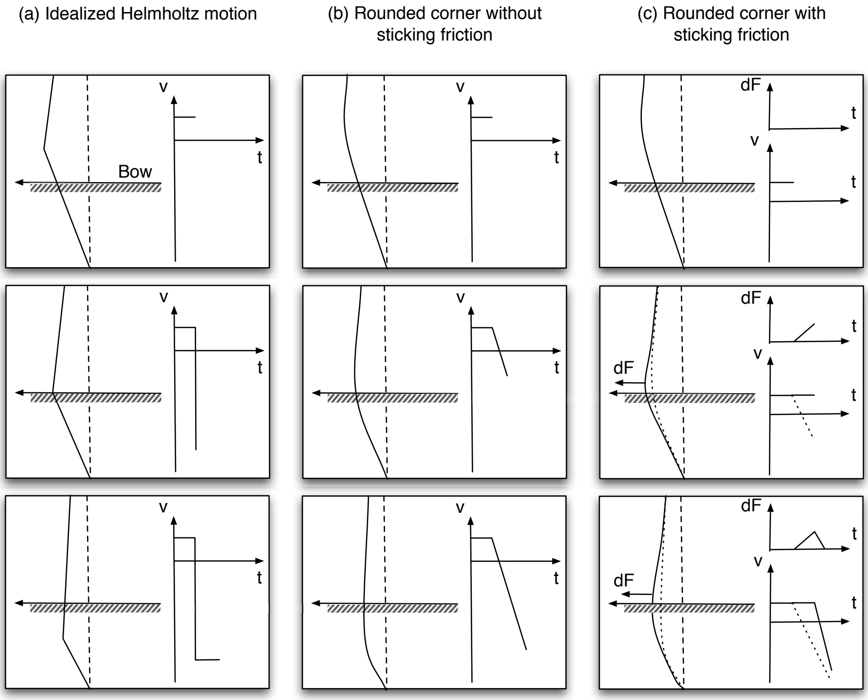

Figure 1.2: Effect of corner rounding during release. (a) Idealized Helmholtz motion. When the corner passes under the bow, triggering release, the string velocity is changed abruptly. (b) A rounded corner produces a gradual change of velocity. The influence of friction is ignored here. (c) When a friction force dF is taken into account, the string is prevented from slipping until the maximum static friction is reached. Consequently, release is delayed and the corner is sharpened. (After Cremer [10])

bow (see Fig. 1.2c). The frictional force increases until the maximum static friction force is reached, and the bow eventually loses the grip of the string. The slipping phase is initiated, slightly delayed compared to the idealized Helmholtz motion. As a result of the build-up in frictional force, the rounded corner is sharpened as it passes under the bow.

The balance between rounding and resharpening of the traveling corner explains the influence of bow force in playing. A higher bow force yields a higher maximum static friction, which in turn leads to a more pronounced sharpening during release. As a result, the energy of the higher partials will be boosted, leading to an increase in brilliance of the sound.

The theory of the rounded corner has several consequences. The first, already mentioned, is that the brilliance of the tone can be controlled via the bow force, providing an important expressive means to the player. Another consequence is the creation of "ripple" or secondary waves [52, 10].[1] The ripple is generated because the rounded corner does not immediately trigger release or capture when it arrives at the bowing point. As a result part of the incoming wave is reflected back from the bow. These disturbances are repeatedly reflected between the bow and the nut, and between the bow and the bridge, giving rise to a regular pattern with period βT.

A third consequence of the rounded corner is the "flattening effect" [40, 8]. Due to the delay of the triggering of release, the total duration of the round trip is prolonged, leading to a drop in pitch. The flattening effect is particularly noticeable at high bow forces, and for cases when corner rounding is pronounced, for example when playing in high positions on the violin G string.

In a complete description of the bowed string torsion (twisting of the string) needs to be taken into account. Torsional waves travel with much higher velocity than the transversal waves, but an interaction and exchange of energy takes place as the string "rolls" on and off the bow hair at capture and release. The torsional impedance of the string, which can be varied considerable by the design of wrapped strings, influences the details of capture and release [40, 55]. Moreover, torsional waves are relatively highly damped and provide an additional source of energy dissipation, contributing to the stability of the bowed string [68, 71].

1.3 Limits of bow force

The maintenance of regular Helmholtz motion, characterized by a single slip and stick phase per fundamental period, involves two requirements on bow force: (1) during the sticking phase the bow force must be high enough to avoid premature slipping under influence of variations in friction force, and (2) the bow force must be low enough that the traveling corner can trigger release of the string when it arrives at the bow. The limits of the playable region have been formalized by Schelleng [52], who gave expressions for maximum and minimum bow force as a function of relative bow-bridge distance β and bow velocity v_B:

$$F_{max} = \frac{2Z_0 v_B}{(\mu_s - \mu_d)\beta}\,, \tag{1.1}$$

and

$$F_{min} = \frac{Z_0^2 v_B}{2R(\mu_s - \mu_d)\beta^2}\,. \tag{1.2}$$

In these expressions Z_0 is the characteristic transverse impedance of the string, μ_s the static friction coefficient, and μ_d the dynamic friction coefficient. R is the

[1] This phenomenon was explained by both Schelleng [52] and Cremer [10], who referred to it as ripple and secondary waves, respectively.

mechanical resistance of the bridge termination in the Raman string model on which Schelleng based his derivations, and represents the combined losses due to internal friction in the string, the reflections at the string terminations (bridge and nut/finger), and the bow-string interaction.

Schelleng introduced a graphical representation of the bowing parameter space, showing bow force versus bow-bridge distance (both on logarithmic scales) at a fixed bow velocity. In this so-called Schelleng diagram (see Fig. 1.3), the maximum and minimum bow-force limits are represented as straight lines with slopes of -1 and -2, respectively, provided that the friction coefficient delta $(\mu_s - \mu_d)$, representing the difference between static and dynamic friction, is constant.

The exact value of the friction coefficient delta $(\mu_s - \mu_d)$ is dependent on the frictional characteristics between the bow and the string. Especially at low bow velocities and high values of β the value can vary, leading to a curvature in the bow-force limits in the Schelleng diagram, and finite limiting bow forces when approaching zero bow velocity. Observations of the existence of a finite minimum bow force by Raman [50], led Schelleng to derive a modified equation of minimum bow force, indicated by the dotted line in Figure 1.3. Schumacher applied a similar modification to the equation for maximum bow force, and proposed a more generalized form suitable for different types of frictional behavior [56].

As indicated in Figure 1.3 the string motion beyond the upper bow-force limit is characterized by raucous, aperiodic motion, corresponding to a scratchy sound. Below the lower bow-force limit string motion is mainly characterized by multiple slipping, with two or more slipping phases per fundamental period, corresponding to a "whistling" sound. Typical examples of string velocity patterns are shown in Figure 1.4.

In later studies it was found that also other types of string motion could be found beyond the upper bow-force limit. Lawergren found string oscillations composed of a sinusoidal component with nodes at the bowing point, and regular Helmholtz motion, so-called S-motion [35, 36]. Another interesting class of string motion is formed by the so-called "anomalous low frequencies" (ALF). The simplest type of ALF arises when the traveling corner is reflected back from the bowing point without triggering release. The friction force is then high enough to maintain the sticking phase until the corner returns a second time to the bowing point, and release takes place. This case leads to roughly a doubling of the period (i.e., a pitch lowering of one octave). Also more complex forms of ALF exist involving torsional string modes, as found by Guettler in bowed-string simulations [21]. ALF was also experimentally observed by Hanson et al. [25]. From a musical point of view, ALF (often wrongly referred to as subharmonics) can be interesting as an extended performance technique, the possibilities of which have been thoroughly explored in violin performance by Kimura [32].

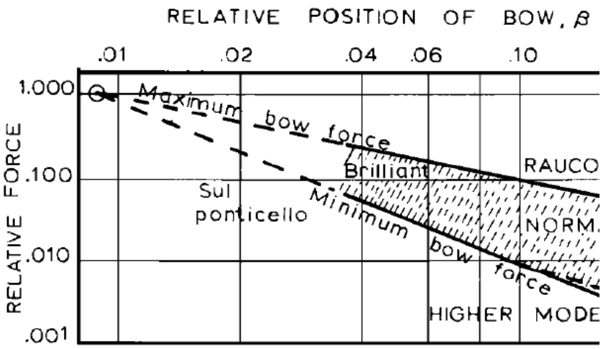

Figure 1.3: Schelleng diagram of relative bow force versus relative bow-bridge distance (logarithmic scales), indicating maximum and minimum bow force limits at fixed bow velocity. The curved dashed line indicates the modified equation for minimum bow force. (Adapted from Schelleng [52])

1.4 The attack: Creation of Helmholtz motion

In the descriptions of the bowed string above only steady-state vibrations are taken into account. A proper start of the tone, characterized by a quick development of Helmholtz motion, is at least as important in performance as the "steady-state." The conditions for the start of the tone (the "attack") have been formalized by Guettler [22] in terms of bow force, bow acceleration and bow-bridge distance. These conditions can be graphically represented in so-called Guettler diagrams of bow force versus bow acceleration at fixed value of β. Typical examples of Guettler diagrams for different values of β, obtained by simulations and predictions, respectively, are shown in Figure 1.5. The diagrams reveal triangle-shaped playable areas, characterized by a quick development of Helmholtz motion. The white areas indi-

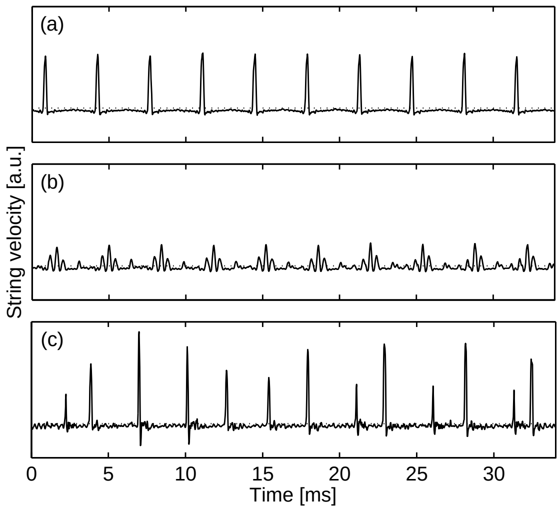

Figure 1.4: Common types of string motion. The panels show measured string velocity signals at the bowing point: (a) Helmholtz motion, (b) multiple slipping, and (c) raucous motion.

cate "perfect" attacks, with Helmholtz motion from the first period. With too high bow force (or too low acceleration) the attack is characterized by prolonged periods ("choked/creaky" sound), and with too low bow force (or to high acceleration) multiple slipping ("loose/slipping" sound) occurs. For small values of β the triangle for perfect attacks becomes very narrow, putting high demands on the player.

A perceptual study by Guettler and Askenfelt [23] showed that attacks were considered acceptable when the duration of the pre-Helmholtz transient was shorter than a certain threshold, which was determined to about 50 ms for prolonged periods and 90 ms for multiple slipping. These thresholds provide certain margins for the performer. Even in a professional performance much less than 50% of the attacks could be expected to be perfect,[2] but up to 80–90 % will fall within the acceptance limits.

1.5 Conclusions

The short introduction to the bowed string given above has presented the basic principles and most important phenomena necessary for the following presentation of the work included in this thesis. The study of the physics of the bowed string remains a challenging area of research. However, it is only by a combination of

[2]Between 20 and 50% of the attacks in the performances of two professional violinists were classified as "perfect" in [23], when allowing an initial 5 ms aperiodic transient.

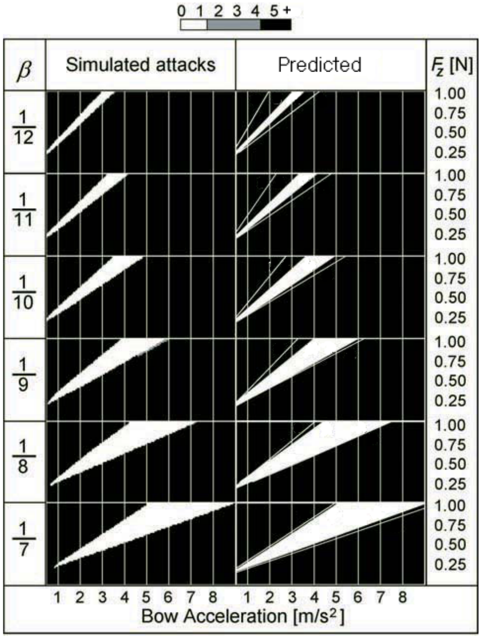

Figure 1.5: Simulated Guettler diagrams (left), and predicted conditions for a perfect attack (right) for several values of β. The white areas indicate combinations of bow acceleration and bow force leading to a "perfect" attack (Helmholtz motion from the very start). (Adapted from Guettler [22])

such basic research and studies of the player´s control of the bow and the string (by the right and left hand, respectively), that a thorough understanding of the sound generation in the violin from a musical point of view can be achieved. The studies included in this thesis give some contributions to this understanding by addressing basic issues in the string player's bow control and the relations to the resulting sound.

Chapter 2

Contributions of the present work

2.1 Objectives

The main topic addressed in this thesis is the control and coordination of bowing parameters in violin playing and their relation to sound production. In four studies the chain from bow-string interaction to generated sound is investigated. An important underlying goal was to provide a link between the scientific approach to the bowed string and the praxis of violin playing.[1] For this reason, the player's perspective is maintained throughout the studies, guiding the formulation of the research questions. From Paper I to IV the focus is gradually shifted from the physics of the bowed string to the bow control exerted by the player. All studies are experimentally oriented, with particular attention devoted to realistic performance conditions.

In more specific terms, the aim of the thesis was to contribute to the understanding of the following three aspects on the bowed string and violin playing:

- Empirical evaluation of fundamental results from bowed-string theory and simulations (Paper I).
- Mapping of the bowing parameter space at the violinist's disposal to basic aspects of the generated sound (Paper II)
- Detailed studies of the control strategies used by players in violin performance, illuminating freedom and constraints - physical, biomechanical, and musical (Paper III and IV).

In the first study (Paper I) the conditions for the maintenance of Helmholtz motion were determined experimentally by the use of a bowing machine. The measurements were performed with a normal bow and standard strings in order to stay close to the reality experienced by the player. The major goal of this study was to provide an

[1]The term violin is here and in the following often used as a generic term for all bowed string instruments.

empirical evaluation of the upper and lower bow-force limits predicted by Schelleng [52]. A systematic verification of these limits, covering a wide range in bowing parameters, has not been conducted previously. The upper and lower bow force limits are important constraints in the player's bow control and it is essential that the classical model proposed by Schelleng is verified. Also, the lack of reliable data on the force limits has made detailed evaluations of bow-string simulations and friction models difficult.

In the second study (Paper II) the measurements in the first study were analyzed from the perspective of sound production, focusing on two basic aspects of sound quality, timbre and pitch. Timbre was analyzed in terms of spectral centroid, related to the brightness of the sound. Exotic types of string motion, less commonly observed in normal violin performance, like anomalous low frequencies (ALF), were studied as well. The major goal of this study was to determine the influence of the individual bowing parameters on sound quality, describing a basic sound palette for the violinist. Furthermore, the pitch flattening effect was studied in detail, allowing for comparison with bowed-string simulations.

The third and fourth studies focused on the player. In Paper III a method was developed for complete and accurate measurement of the main bowing parameters in violin performance. This was achieved by a combination of motion capture and sensors. Motion capture was used to measure position and orientation (pose) of the violin and bow, allowing to calculate the motion of the bow relative to the violin. The sensors provided complementary data of bow force and acceleration. The method provided not only the main bowing parameters, but also the bow angles relative to the violin, which play an important role in bow control. Measurements of the bow angles are here reported for the first time.

In the last study (Paper IV) an experiment was conducted with violin and viola players, using the method developed in Paper III. The major goal was to shed more light on the control strategies used by players in the production of "steady" tones, closing the loop with the acoustical studies presented in Paper I and II. Two main questions were: (1) "How do players utilize the possibilities offered by the instrument?" and (2) "How do players adapt to the constraints involved in tone production?" All three types of constraints which the violinist has to tackle in performance were considered; (a) The constraints imposed by the bow-string interaction, dependent on the particular combination of bowing parameters and the properties of the string, (b) The biomechanical constraints, related to the movements of the bowing arm; and (c) The constraints imposed by the musical context, in "steady tone" production primarily set by the dynamic level, sound quality, and the use of the available length of bow.

2.2 Experimental conditions

The studies in this thesis are based on two types of experiment. In the first two studies (Paper I and II) measurements on the bowed string were performed in

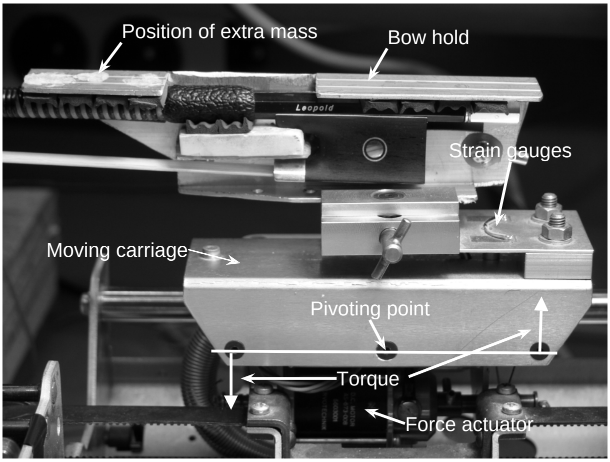

Figure 2.1: Moving carriage of the bowing machine. The most important parts, including the actuators and strain gauges for the control of bow force, are indicated.

order to provide insight into the details of the string motion as a function of systematically varied bowing parameters. The experiments were conducted with a computer-controlled bowing machine, which allowed a close control of the bowing parameters. In the third and fourth studies (Paper III and IV) a setup was developed and used for complete and accurate measurement of bowing gestures in real violin performance.

Bowing machine experiment

A computer-controlled bowing machine was used for detailed measurements of the string motion, allowing a systematic and accurate control of the main bowing parameters [11]. Most of the measurements were performed on a rigid monochord with the same dimensions as a standard violin. The monochord was chosen in order to obtain well-defined conditions at the string terminations, avoiding the influence of the vibrational modes of the violin. The strings and bow were common commercial products at medium to high quality level.

The bow strokes were tailored to the specific tasks in the experiments. A common condition was to establish Helmholtz motion quickly and then change bow force and velocity smoothly to target values, which were maintained during a "steady state" part of the note. The bowing machine, which is based on a reliable design using surplus parts, performed more than 6000 bow strokes during the experiments reported in Paper I and II.

Measurement of bowing gestures

For the measurement of bowing gestures in violin performance, a method was developed combining motion capture and sensors on the bow. An optical motion capture system (Vicon 460) with six cameras placed around the player was used to track the pose of the violin and the bow. "Landmarks," defining the geometries of the violin and bow, were indicated by reflective markers. On the frog, a bow force sensor developed by Demoucron [12] and a three-axis accelerometer were mounted. The third study (Paper III) is devoted entirely to the development, calibration and assessment of the measurement setup, and to methods for calculating the bowing parameters, bow angles and other performance features. The measurements of bowing gestures were conducted at the Input Devices and Music Interaction Laboratory (IDMIL) at McGill University, Montreal.

2.3 Paper I

Paper I reports an empirical study of the bow-force limits in the Schelleng diagram. The computer-controlled bowing machine was used for systematic measurements of the string motion for more than 1000 combinations of the main bowing parameters bow velocity, bow force and bow-bridge distance. A normal bow was used for bowing a violin string mounted on a monochord. The string velocity at the bowing point was recorded and the string motion was semi-automatically analyzed for classification of the type of motion (Helmholtz, multiple slipping, and raucous motion).

Empirical Schelleng diagrams

Figure 2.2 shows the empirical Schelleng diagrams obtained for a violin D string at four bow velocities (5, 10, 15 and 20 cm/s). The observed types of string motion are indicated with different colors and symbols. At all bow velocities a coherent playable region of Helmholtz motion (light green areas) was found with clear upper and lower bow-force limits. Above the upper bow-force limit mostly raucous motion was observed, as well as some cases of anomalous low frequencies (ALF) and S-motion. Below the lower bow-force limit mostly multiple slipping was observed.

The upper and lower bow-force limits showed a good qualitative agreement with the predictions by Schelleng. The upper bow-force limit was found to be proportional to bow velocity, as expected from Schelleng's equation (1.1). However, a closer look revealed some notable discrepancies. Especially at the lowest bow velocities (panels a and b), the slope of the observed bow-force limit (border between the green and red areas) was not as steep as predicted by Schelleng (black solid lines). A better fit (dashed lines) was obtained using a modified version of Schelleng's equation for the upper bow-force limit, taking variations in dynamic (sliding) friction between the bow and string into account.

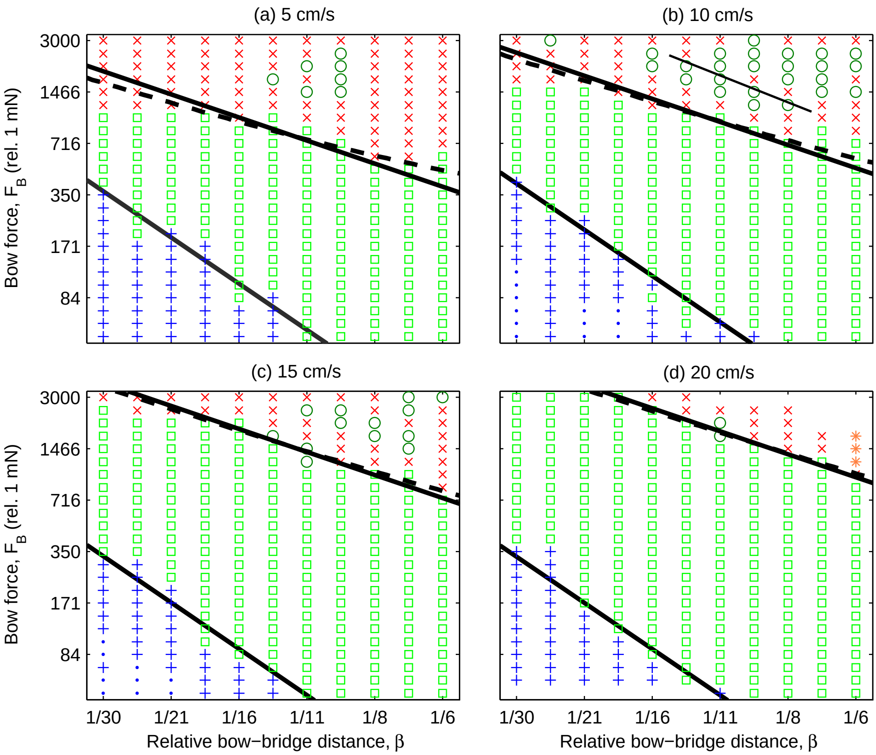

Figure 2.2: Empirical Schelleng diagrams for a violin D string at four bow velocities. Helmholtz motion is indicated by light green squares, constant slipping by blue dots, multiple slipping by blue +-marks, and raucous motion by red x-marks. Other types of motion observed were ALF (dark green circles), and S-motion (orange asterisks). The solid lines indicate the fitted upper and lower Schelleng limits; the dashed lines indicate the fitted upper limits according to the modified Schelleng equation for maximum bow force. (Paper II: The line in the upper part of panel (b) shows the separation between ALF with doubled and tripled period lengths. ALF with longer periods was found at combinations of large β and high F_B.)

Contrary to expectations, the lower bow-force limits did not show any dependence on bow velocity in the measured range (5-20 cm/s). This is in conflict with Schelleng's equation (1.2), which predicts that the lower bow-force limit is proportional to bow velocity.

The upper and lower bow-force limits were also determined for the E string. As expected, both the upper and lower limits were lower than those on the D string, however, not in proportion to the lowering of the characteristic string impedance Z_0. For the upper bow-force limit, the difference was smaller than expected. The discrepancy could be explained by taking the torsional impedance of the strings into account. A lower torsional impedance lowers the upper bow-force limit. As the torsional impedance of E strings is generally higher than that of D strings, the maximum bow force for the D string is lowered more than for the E string, leveling out the difference between the two strings.

The lower bow-force limit of the E string was much lower than that of the D string. This could be explained by the lower internal damping of the E string, yielding a larger value of R in equation (1.2), and thus a lower minimum bow force. Furthermore, the measurements on the E string confirmed the earlier observation that the lower bow-force limit did not depend on bow velocity.

The influence of damping

In deriving the expressions for the bow-force limits, Schelleng used the Raman string model, in which the string termination at the nut is fixed (perfect reflection) and the termination at the bridge represented by a purely mechanical resistance R. All energy losses, including the internal damping of the string and the damping caused by the finger when stopping the string, are represented by R.

According to equation (1.2), minimum bow force is directly dependent on R, and thus on the total damping. To determine the influence of R, the lower bow-force limit was measured for different string-instrument combinations (violin, monochord) and open and stopped strings. The mechanical resistance R for the different combinations was estimated from the decay times of plucked string signals, allowing for direct comparison of the measured lower bow-force limits with equation (1.2).

It was found that the measured minimum bow forces were almost an order of magnitude higher than predicted by Schelleng. Furthermore, the dependence of the minimum bow force on damping was much stronger than expected from equation (1.2). These puzzling results, which are in clear conflict with Schelleng's predictions, were further investigated in a separate experiment in which the breakdown of Helmholtz motion at minimum bow force was studied more closely.

Breakdown of Helmholtz motion at minimum bow force

More insight in the breakdown of Helmholtz motion at minimum bow force was gained by using bow strokes with gradually decreasing bow force. A typical transition from Helmholtz to multiple-slipping motion is shown in Figure 2.3. Just before the transition (panel c) the formation of extra partial slips, indicated by the arrows, could be observed. After the transition the waveform became unstable, and consisted of two distinct slip phases per fundamental period.

Interestingly, the additional slip phase appeared quite early after the main slip, and not in the middle of the stick phase as predicted by the Raman/Schelleng model. This is a strong indication of that ripple in the frictional force forms an important source of perturbation for the breakdown of Helmholtz motion, as suggested by Woodhouse [67].

Discussion and conclusions

The experiments with the bowing machine showed that there was a good general agreement between the measured upper bow-force limits and Schelleng's predicted maximum bow force, given by equation (1.1). The agreement was further improved by using a modified version of Schelleng's equation, based on a more realistic friction characteristic between the bow and the string. Furthermore, the measurements suggested that torsional impedance influenced the upper bow-force limit, leveling out the difference in maximum bow force between the D string and the E string.

Regarding the minimum bow force, the experiments showed marked deviations from Schelleng's predictions. Firstly, no significant dependence of the lower bow-force limit on bow velocity was found within the measured range of bow velocities (5–20 cm/s). Secondly, the measured lower bow-force limits were almost an order of magnitude higher than predicted by equation (1.2). Finally, the dependence on damping was much stronger than predicted. The explanation to these discrepancies between theory and experiments lies in the reflection properties at the string boundaries. Schelleng's derivation of the lower bow-force limit is based on the assumption that the impedance of the bridge termination is purely resistive (Raman model), which means that corner rounding and ripple are neglected. However, a detailed analysis of the breakdown of Helmholtz motion showed that ripple introduced perturbations in the velocity waveform at low forces, leading to the formation of additional slips.

Simulations of the bow-string interaction, using a model based on more realistic reflection functions, demonstrated further the important role of ripples in the frictional force for the breakdown of Helmholtz motion, and confirmed that the minimum bow force was to a much lesser degree dependent on bow velocity than predicted by Schelleng. It can be concluded that Schelleng's minimum bow force is based on incorrect assumptions, and therefore fails to provide an adequate description of the actual lower bow-force limits observed in experiments.

2.4 Paper II

In Paper II extended analyses of the string velocity signals recorded in the first study are presented. In this study the focus was shifted towards aspects of sound quality, mainly within the playable region, in relation to the main bowing parameters bow

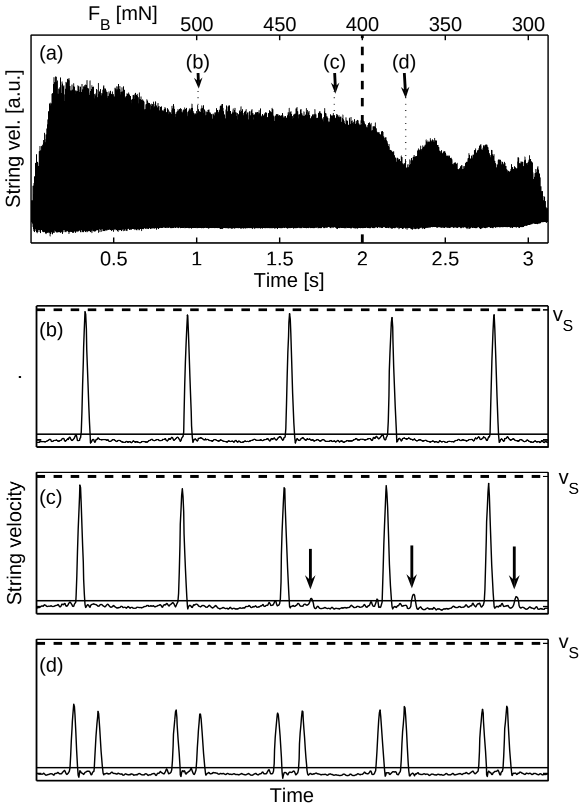

Figure 2.3: Breakdown of Helmholtz motion at the lower bow force limit. (a) A long bow stroke with continuously decreasing bow force is played at constant velocity by the bowing machine. The dashed vertical line indicates the transition from Helmholtz motion to multiple slipping. The lower panels show the string velocity in detail at the time points indicated in (a). (b) Regular Helmholtz motion, (c) traces of partial slips (arrows) begin to appear between the nominal slips, (d) multiple slipping has developed.

velocity, bow force and bow-bridge distance. Maps of spectral centroid (related to perceived brightness of the tone) and pitch are presented in a Schelleng-like representation, providing an overview of how violinists can vary the tone color within the playable region, and shedding more light on the practical upper limit of bow force imposed by the flattening effect. Furthermore, the conditions for anomalous low frequencies (ALF), and other more or less regular types of string motion beyond the upper bow force limit, were analyzed.

Spectral centroid

The spectral centroid is a basic measure of the spectral content of sound, representing the center of gravity of the spectrum. Several perceptual studies have shown that spectral centroid is a good predictor of the perceived brightness of the tone [20, 39, 9]. Further, the validity of the spectral centroid as a predictor of timbre has been affirmed by studies of the perception of violin sound [59]. The spectral centroid was therefore a natural choice as a global indicator of tone quality when investigating the influence of the bowing parameters on violin timbre.

Color maps of spectral centroid superimposed on Schelleng diagrams at four bow velocities are shown in Figure 2.4. The fitted bow-force limits are indicated with solid lines. Within the playable region the spectral centroid ranged between 0.8 kHz (large β, low bow force) and 3 kHz (small β, high bow force). It can be seen that spectral centroid was mainly dependent on bow force, and that the influence of relative bow-bridge distance β was very weak. With increasing bow velocity, the available range in bow force increases, yielding a larger effective range in spectral centroid.

Beyond the upper bow-force limit, there was a tendency of decrease in the spectral centroid. This is due to the presence of prolonged periods, the lower frequencies pulling the spectral centroid downwards. Below the lower limit, on the other hand, the spectral centroid showed a tendency to increase due to boosting of higher harmonics in the spectrum of multiple-slip tones.

The dependence of spectral centroid on bow force and bow-bridge distance is shown more explicitly in Figure 2.5. The curves confirm that the spectral centroid clearly increased with increasing bow force, and that there was no systematic relation between spectral centroid and bow-bridge distance. The spectral centroid was even observed to decrease at small values of β, indicating that the tone became duller rather than brighter.

Further analysis of the dependence of spectral centroid on the main bowing parameters bow velocity, bow force and relative bow-bridge distance was done by multiple regression, taking only cases of Helmholtz motion into account. The results confirmed that bow force was totally dominating in controlling the spectral centroid. The contributions from bow velocity and bow-bridge distance were much smaller. Spectral centroid was shown to decrease with increasing bow velocity, i.e. the tone becomes duller at higher bow velocities. It was further shown that spectral centroid decreased slightly with decreasing bow-bridge distance. The results indicate that

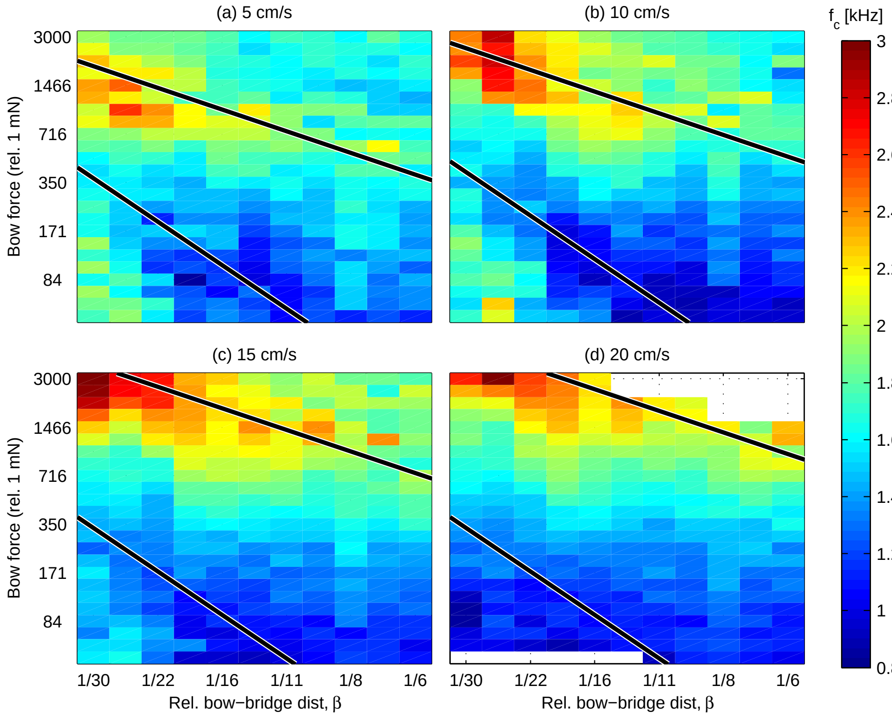

Figure 2.4: Color maps of spectral centroid superimposed on Schelleng diagrams at four bow velocities. The solid lines indicate the fitted Schelleng bow-force limits obtained in Paper I. The β axis represents a wide range of bow-bridge distances from very close to the bridge ($1/30 = 11$ mm) to the fingerboard ($1/6 = 55$ mm).

bow-bridge distance plays only a minor role in controlling spectral centroid, and that the timbre even tends to get duller by bringing the bow closer to the bridge, keeping the other bowing parameters constant. This result, which is in contrast to the intuition of most players, will be further discussed below.

The flattening effect

The pitch of a bowed string is dependent on the bowing parameters via several mechanisms acting in opposite directions. First, the length of the string is increased due to the vibration amplitude, leading to an increase in effective tension, which in turn leads to an increase of the natural frequencies [15]. The pitch rise is governed by the v_B/β ratio, which sets the vibration amplitude. A second effect causing pitch sharpening is string inharmonicity [8]. The amount of pitch sharpening is dependent on the energy distribution in the spectrum, which is mainly determined

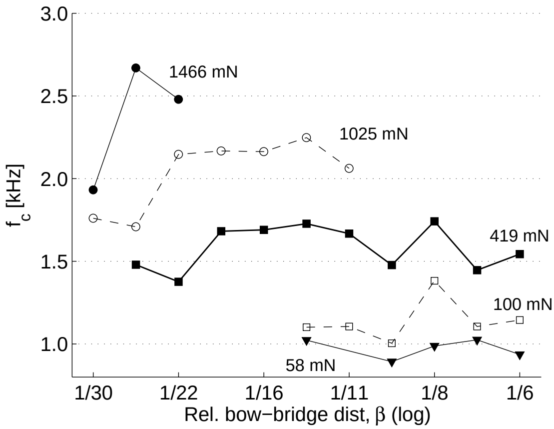

Figure 2.5: Spectral centroid as a function of relative bow-bridge distance at different values of bow force. Only cases of Helmholtz motion are shown.

by bow force F_B. Both effects are dependent on the physical properties of the string; the amplitude effect on Young's modulus, and the inharmonicity effect on the bending stiffness.

A third pitch effect, specific for the bowed string is the "flattening effect," which is caused by a delay in the round-trip time of the Helmholtz corner. The delay is due to a hysteresis effect in the resharpening of the corner at release and recapture as discussed in Section 1.2. The flattening effect is most prominent for combinations of high values of bow force, large bow-bridge distances and thick strings [40, 55, 8]. The effect may be large and it has been suggested that the flattening effect forms a practical upper bow-force limit in violin playing [55, 41].

The recorded signals from the first study were used for a detailed analysis of pitch and its dependence on the main bowing parameters. A color map of pitch level (in cent) superimposed on Schelleng diagrams at four bow velocities is shown in Figure 2.6 (Helmholtz motion only). It can be readily observed that the pitch went flat when approaching the upper bow-force limit, in accordance with expectations. Pitch flattening was more prominent at higher bow velocities. At $v_B = 5$ cm/s pitch flattening was limited to 26 cent, whereas at $v_B = 20$ cm/s flattening up to 77 cent (13 Hz) was observed.

Pitch sharpening was much less prominent. A pitch rise up to 10 cent was observed at $v_B = 15$ and 20 cm/s (panels c and d) at the smallest values of β. Another indication of pitch sharpening was that the pitch of the bowed string (tuning reference in panel d) was about 6 cent (1 Hz) higher compared to the pitch during the late decay (small amplitude) in pizzicato tones.

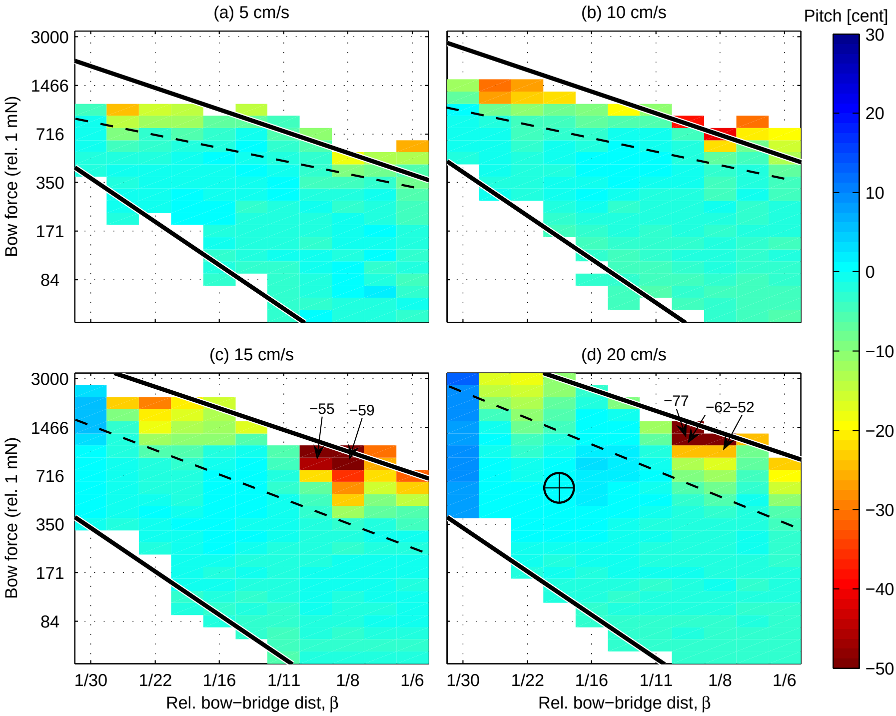

Figure 2.6: Color maps of pitch level superimposed on Schelleng diagrams at four bow velocities (Helmholtz motion only). The fitted bow-force limits are indicated by solid lines. The regions where pitch flattening exceeds 5-10 cent are demarcated by dashed lines, giving a rough indication of the practical upper bow-force limit due to pitch flattening. The bow stroke used for determination of the tuning (reference pitch) is indicated by a viewfinder (panel d).

Anomalous low frequencies

In the Schelleng diagrams shown in Figure 2.4 coherent regions of anomalous low frequencies (ALF) were found beyond the upper bow-force limit, especially at bow velocities of 10 and 15 cm/s (panels b and c). Different types of ALF were found with periods of about twice and three times the fundamental period in clearly separated areas (see subdivision of ALF region in Fig. 2.2 b). Typical examples of ALF string velocity signals are shown in Figure 2.7, where it can be seen that both the frequency and the amplitude are increased. Less stable ALF with longer periods was also observed at combinations of large β and high bow force. ALFs are not used in classical violin playing, but represent one interesting extension of the violin sound in performances of contemporary music.

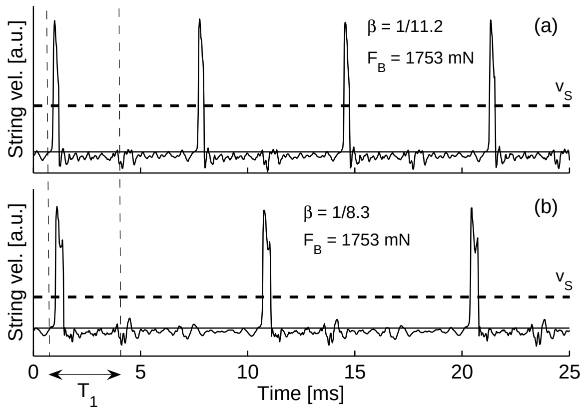

Figure 2.7: String velocity signals of anomalous low frequencies (ALF) with periods of about (a) twice and (b) three times the fundamental period T_1 (indicated by the vertical dashed lines). The nominal slip velocity (v_S) for Helmholtz motion is indicated by the horizontal dashed lines.

Discussion and conclusions

In Paper II it was shown that spectral centroid depended mainly on bow force and much less on bow-bridge distance and bow velocity, confirming the important role of bow force in obtaining a sharp Helmholtz corner (see Section 1.2).

The analyses also showed that spectral centroid decreased with increasing bow velocity, confirming earlier findings by Guettler et al., based on measurements and bowed-string simulations [24]. The finding that bow-bridge distance only had a minor influence on spectral centroid (and that spectral centroid even decreased with decreasing bow-bridge distance), is opposite to a common belief among string players that bringing the bow closer to the bridge would in itself cause an increase in brightness. The actual explanation for this increase lies in a coordinated change of bow force and bow-bridge distance. The bow force normally needs to be increased as bow-bridge distance is decreased, in order to stay within the playable region in the Schelleng diagram with some safety margins to the bow-force limits.

The pitch level maps clearly showed the presence of pitch flattening when approaching the upper bow-force limit. Estimated practical limits of 5–10 cent flattening were found to be parallel to the upper bow-force limits, but shifted down by a factor 2–3 in force. The flattening effect thus introduces a more serious constraint in playing than the actual breakdown of Helmholtz motion, confirming its role as a practical limit of bow force.

Beyond the upper bow force limit coherent regions of ALF were found. These represent alternative playable regions, interesting for extended performance techniques [32]. The regions are quite small, indicating that the maintenance of ALF is critically dependent on the steadiness of the used combination of bowing parameters, and therefore difficult to exploit in performance.

2.5 Paper III

In Paper III the development of a method for measurement of bowing gestures in violin performance is described. The method was specially designed for detailed studies of the relationship between physical aspects of bow-string interaction and the actions of the player. An additional goal was to shed light on other, more indirect aspects of control exerted by the player, including the bow angles skewness, inclination and tilt.

A primary requirement was therefore an accurate and complete acquisition of the main bowing parameters bow velocity, bow force and bow-bridge distance, as well as bow acceleration, which is an important parameter in attacks. Furthermore, an exact determination of the orientations of the bow and the violin was required for calculation of the angles of the bow relative to the violin. Further requirements were that the measurements should be able to perform using any regular bow and instrument, and that the measurements should not interfere with normal playing conditions.

The work was performed at the Input Devices and Music Interaction Laboratory (IDMIL), McGill University, Montreal in collaboration with Matthias Demoucron.

Experimental setup

For a reliable and complete measurement of all control parameters it was decided to use a combination of optical motion capture to determine the position and orientation (pose) of the bow and the violin, and sensors mounted on the bow for measuring bow force and acceleration. A schematic of the complete measurement setup is shown in Fig. 2.8. Motion capture and sensor data, as well as sound and video, were synchronously recorded on two computers. Six motion capture cameras were placed in a circular configuration around the subject, capturing the position of reflective markers attached to the violin and bow.

Bow acceleration in two directions was measured using a an accelerometer. Bow force was measured using a custom-made sensor developed by Demoucron [12] (see Fig. 2.9). Both sensors were mounted on the frog, adding a mass of 15 g to the bow. The addition of the accelerometer allowed for accurate measurement with a high time resolution, supplementing motion capture data.[2]

Motion capture of bowing gestures

The marker configurations for the motion capture measurements were designed to allow for determination of the positions and full orientations of the bow and the vi-

[2]The camera configuration used was not optimized with regard to spatial resolution, leading to a rather noisy second derivative (acceleration).

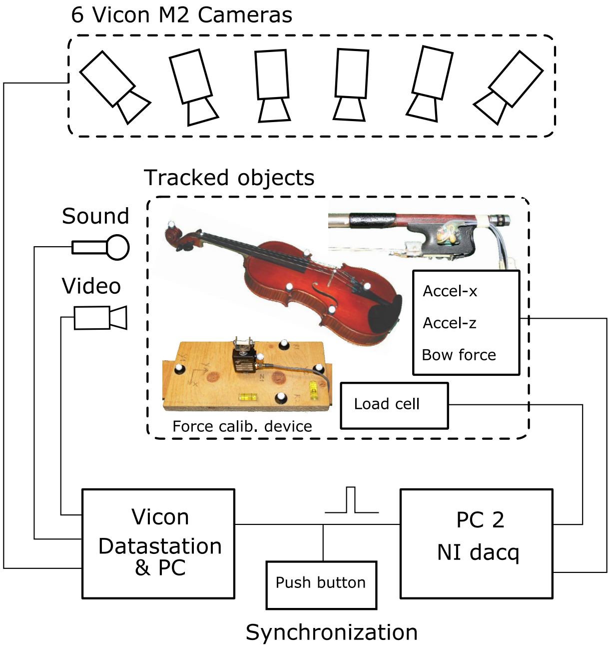

Figure 2.8: Schematic of the setup used for measuring bowing gestures, combining motion capture (Vicon system) and sensors.

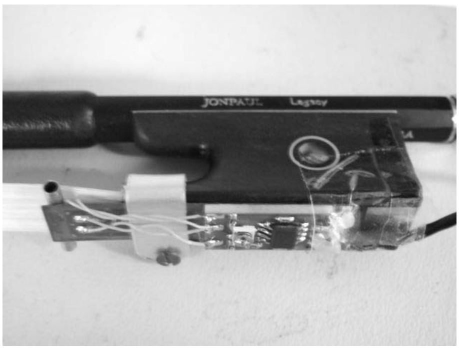

Figure 2.9: Bow force sensor mounted on the frog. A metal leaf spring with strain gauges on both sides measures the deflection of the bow hair at the frog. The electronic board under the frog integrates a Wheatstone bridge and a conditioning amplifier.

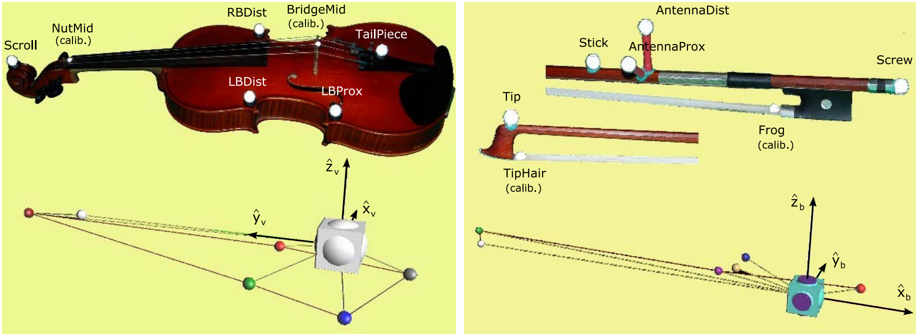

Figure 2.10: Left: Marker configuration and kinematic model of the violin. The origin of the model corresponds to the middle of the bridge, and the y-axis is in the direction of the strings. The x-axis coincides roughly with the bowing direction. Right: Marker configuration and kinematic model of the bow. The two "antenna" markers were added for a reliable measurement of bow tilt. The origin of the model corresponds to the termination of the bow hair at the frog, and the x-axis is in the direction of the bow hair.

olin (6 degrees-of-freedom (DOF) pose). The marker configurations were associated with kinematic models of the bow and violin with a well-defined geometry, allowing for straight-forward and accurate calculation of the main bowing parameters and bow angles. The detailed marker configurations and models of the bow and the violin are shown in Fig. 2.10.

The poses of the bow and the violin during performance were obtained by fitting the kinematic models to the measured marker positions. The 6 DOF pose of the bow relative to the violin was used for the calculation of bow position (the position of the contact point with the string in the length direction of the bow), bow velocity and bow-bridge distance, as well as the distance (height) between the bow and the strings in order to determine if the bow was in contact with the string(s) or not.

Further, three bow angles were calculated: skewness, inclination and tilt (see Fig. 2.11). Skewness represents the deviation of the bowing direction from orthogonality to the string; inclination is the angle associated with playing different strings; and tilt represents the rotation of the bow about its length axis (no tilt when the bow hair is flat on the string). The three bow angles have not been measured in string performance previously.

Additional features, useful for performance annotation were also extracted, including bowing direction (down-bow/up-bow), string played (I-IV) and bow-string contact (yes/no).

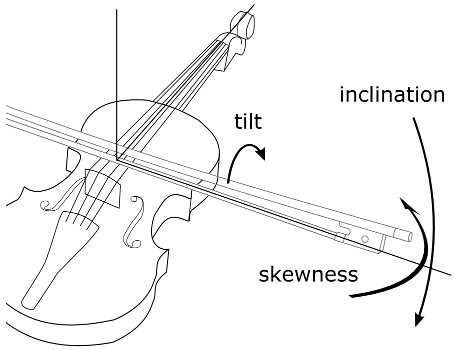

Figure 2.11: Bow angles skewness, inclination and tilt. The arrows indicate the defined positive directions.

Calibration of acceleration and bow force

The combination of motion capture and sensors allowed for efficient calibration methods. Further, the orientation of the bow obtained via motion capture could be utilized to compensate for the gravity component in the measured acceleration signal, allowing for an accurate measurement of the actual bow acceleration.

The bow force sensor basically detected the deflection of the bow hair at the frog, and consequently the output signal was a function of bow force as well as bow position. The use of the bow-force sensor in combination with motion capture data made it easy to obtain a calibration of the force signal. During the experiments, calibration of the sensor was repeatedly performed by the subjects in a playing-like situation, using a load cell mounted on a "violin-like" wooden board (see Fig. 2.12).

Discussion and conclusions

The complete measurement system turned out to perform very well. An assessment of the motion capture measurements showed that the noise levels of the measured positions and angles were quite acceptable (RMS noise less than 1 mm). Evaluation of the bow force sensor using a load cell as a reference showed that the sensor was able to reproduce detailed features in bow force. Certain difficulties in the measurements were identified and compensated for when possible. For example, tilting of the bow tended to underestimate bow force, especially close to the frog. It was found that compensation was possible, but this would require a more elaborate calibration procedure. Further, the force sensor offset at zero bow force showed small fluctuations during performance, which could degrade the accuracy, in particular at low bow forces close to the tip. For this reason the zero reference was sampled at regular intervals during the measurements, at moments when the bow was off the string.

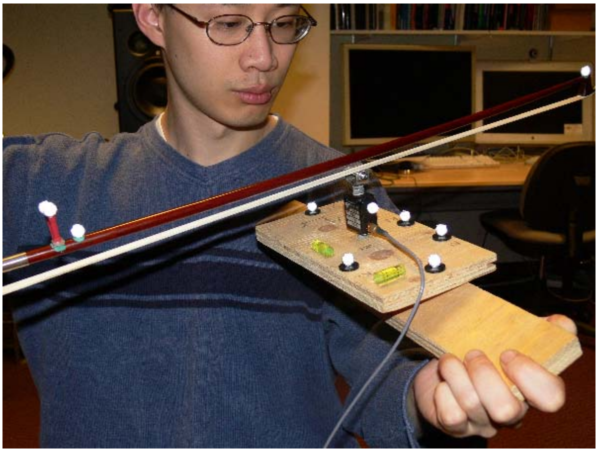

Figure 2.12: Bow-force calibration using a “violin-like” calibration device with a load cell. Bow position is obtained by motion capture.

In conclusion, the developed setup, in combination with the geometric representations of the bow and the violin and the calibration methods, allowed for a reliable, accurate and complete measurement of bowing parameters, bow angles and other features necessary for a detailed study of violin bowing, unparalleled by earlier or existing approaches [2, 72, 38]. The setup allowed for the use of any regular bow and violin (or viola), providing natural playing conditions.

2.6 Paper IV

Paper IV presents an extensive study of the use of the main bowing parameters in sustained notes in violin and viola performance, using the measurement method developed in Paper III. Also the use of the bow angles skewness and tilt were analyzed in detail, revealing systematic trends and functional strategies, among others for changing dynamic level.

Experiment

The analyses presented in this study were based on the performances of four players. Two of the players performed on both violin and viola, yielding a total of six recording sessions.

During the sessions a variety of bowing techniques were recorded, in “dry,” repeated-note conditions without musical context, as well as applied in musical fragments. For the current analyses only the “steady” parts of détaché notes were considered. The tasks consisted of repeated notes of three durations: whole notes (4 s), half notes (2 s) and sixteenth notes (0.2 s), played at three dynamic levels: *f*, *mf* and *pp*. The tasks were performed on all strings, stopping the string with the third finger in first position, a musical fourth above the open string. Furthermore, there were four half-note crescendo-diminuendo tasks (for more details see Sect. 2.6).

Use of the main bowing parameters

Figure 2.13 shows the overall distributions of the main bowing parameters bow velocity (v_B), bow force (F_B) and relative bow-bridge distance (β) in the three note-length conditions for all three violinists, revealing general trends.

The differences between dynamic levels are clearly reflected in the choice of the bowing parameters. For all players, bow force increased, bow-bridge distance decreased (and for the sixteenth notes, bow velocity increased), when changing the dynamic level from *pp* to *f*. The highest bow forces and bow velocities observed were 2.5 N and 2 m/s, respectively. Relative bow-bridge distance ranged from about 0.03 (7 mm) to 0.3 (74 mm).

Further, there was a clear difference for all players in the range in bow velocity used for the different note-length conditions. For the whole-notes and half-notes conditions bow velocity was rather constant around 15 and 30 cm/s, respectively, due to the constraints imposed by the length of the bow. Only at *pp* level lower bow velocities were used. In the sixteenth notes a large range in bow velocity was used up to 2 m/s.

The players also agreed on the general strategies for producing contrasts in dynamic level in the respective note-length conditions. In the long-note conditions (whole notes and half notes) β was the dominating factor in the v_B/β ratio, whereas in the sixteenth-notes condition it was v_B, at the expense of the range in β. The resulting dynamic contrast was higher in the sixteenth-note condition, as indicated by the v_B/β ratio, which is proportional to the string amplitude.

While the above strategies were observed in the performances of all violin and viola players, there were also notable differences between players as well. One violin player and one viola player mainly varied bow force across dynamic levels. Especially the violin player reached high forces at *f* level (visible as a bump around 2 N in the bow force distribution of the sixteenth-notes condition). The viola player consistently used low bow velocities. In contrast, another player, who performed on both the violin and viola, varied mainly bow-bridge distance, and used relatively

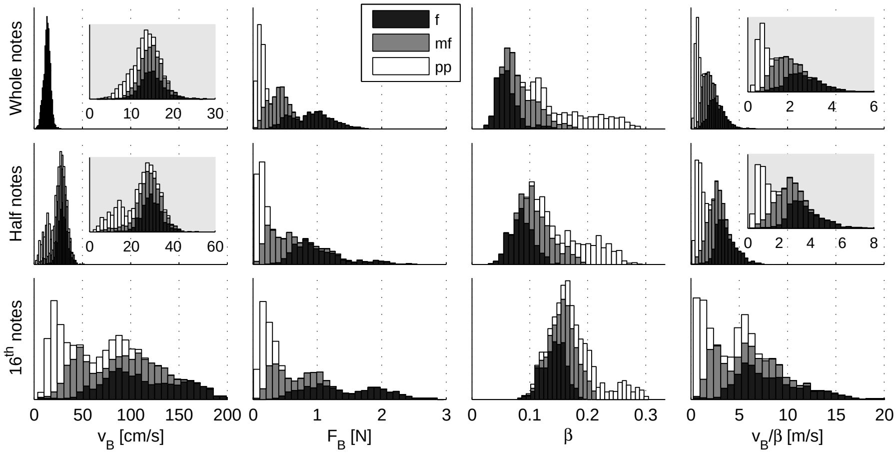

Figure 2.13: Distributions of bowing parameters v_B, F_B and β for the three violin players, specified for the three note-length conditions and the three dynamic levels. The fourth column shows the v_B/β ratio, governing string amplitude.

low bow forces. The other player performing on both instruments showed a more all-round variation of all three bowing parameters, without a clear preference for one over the others.

The conditions for playing on different strings were clearly reflected in the bowing. Figure 2.14 shows the average bowing parameters per condition used by the three violinists for different strings. The bow force used on the G string was generally higher compared to the other strings. This is in accordance with expectations as the higher characteristic impedance and the higher internal damping of the G string lead to higher upper and lower bow force limits.

Further, it could be observed that the average bow-bridge distance was slightly, but consistently, larger on the G string compared to the other strings, especially in the long-note conditions. This might be another adaption of the players to the higher bow-force limits for the G string, facilitating the overall control of bow force.

For bow velocity there were no noteworthy differences between strings in the long-notes conditions. However, the sixteenth-notes *f* and *mf* conditions showed a clear increase in bow velocity from lower to higher strings. The same was observed in the viola performances (not shown). A possible explanation lies in the control of string amplitude. If the same bow velocity as for the E string would have been used on the G string. the maximum amplitude at the middle of the string would have been 5 mm, which means that the G string would have touched the adjacent D string. Further, it was estimated that the resulting pitch increase due to such a large amplitude would have amounted to 33 cent. The different characteristic impedances of the strings might also play a role, the “heavier” strings exerting a

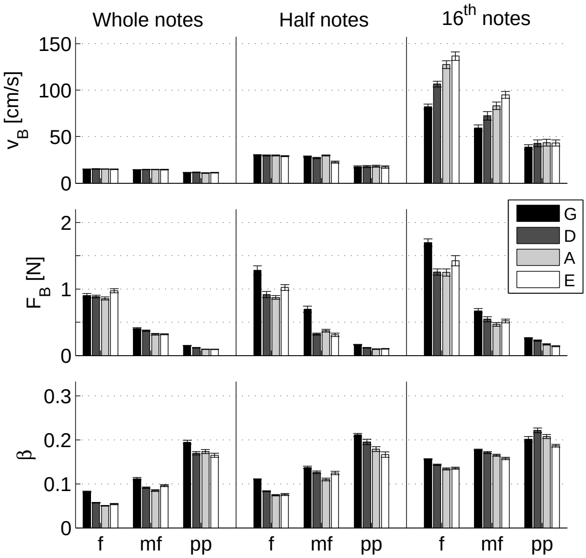

Figure 2.14: Average bowing parameters per condition and string for the three violin players. The error bars indicate the 95% confidence intervals of the mean.

higher transversal force on the bridge. The used combinations of bowing resulted in rather equal values of transverse bridge force, which indicates that there might be acoustical reasons to adapt bow velocity to the string.

Bow-force limits and playable region

Figure 2.15 shows the distributions of bow force and relative bow-bridge distance in the long-notes conditions on the violin D string, represented in Schelleng diagrams at six bow velocities. The combined data from the three players formed clear coherent regions, following the contours of the indicated bow-force limits. The distributions give a clear illustration of how the players move diagonally in the Schelleng diagram when changing dynamic level.

In general, the upper bow-force limit was respected with a reasonable margin. The bow forces used increased with increasing bow velocity, in accordance with the increase in the upper bow-force limit. This general rule did not exclude individual excursions to high forces very close to the upper limit, clearly exceeding the 10 cent pitch-flattening limit.

The lower bow force limit was not always equally well respected, in particular for the lower bow velocities. Besides some uncertainties in the determination of the lower limit (indicated by the shaded regions), the consequences of violating the lower limit are not at all as dramatic as the profound pitch flattening and

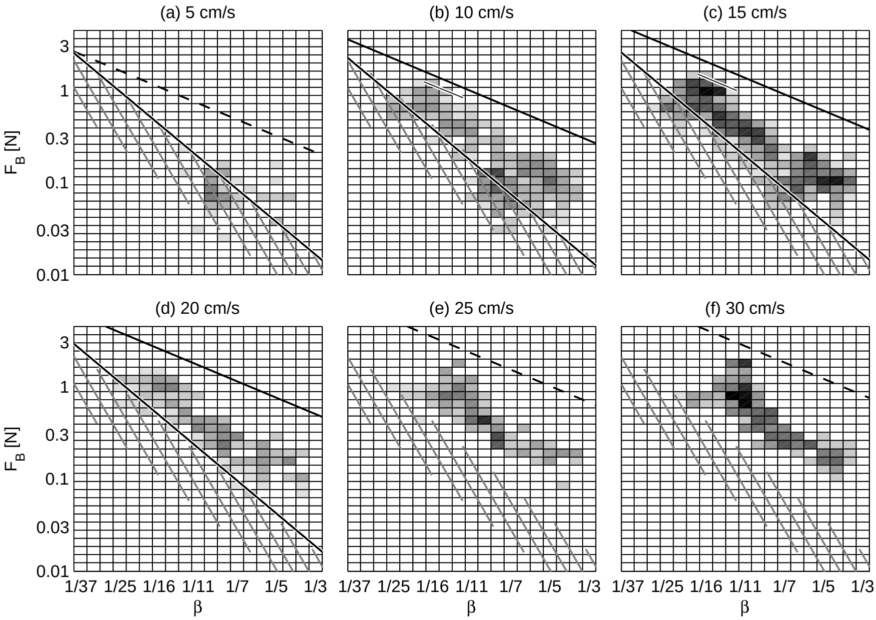

Figure 2.15: Distributions of bow force and relative bow-bridge distance represented in Schelleng diagrams at six bow velocities for long-notes conditions on the violin D string (all three players included). The gray scale indicates the density of samples. The indicated upper bow-force limits and limiting regions of lower bow force are based on measurements with a bowing machine.

breakdown of Helmholtz motion at the upper bow force limit. Some elements of multiple slipping at *pp* may not be too disturbing, particularly not in orchestra playing.

Aspects of sound quality

The string player exerts continuous control of the sound level and sound quality via the main bowing parameters. Sound level is mainly governed by the v_B/β ratio, while the spectral content has been shown to depend mainly on bow force, and to a less degree on bow velocity and bow-bridge distance (see Paper II and Ref. [24]). These relations were further investigated using the data from the current experiment.

Figure 2.16 shows the relation between sound level and v_B/β for all violinists and all conditions. The data forms a continuous distribution due to a considerable overlap between the conditions. A strong linear relation was observed ($R^2 = 0.90$). An illuminating set of outliers represent cases of multiple slipping, attributed to the

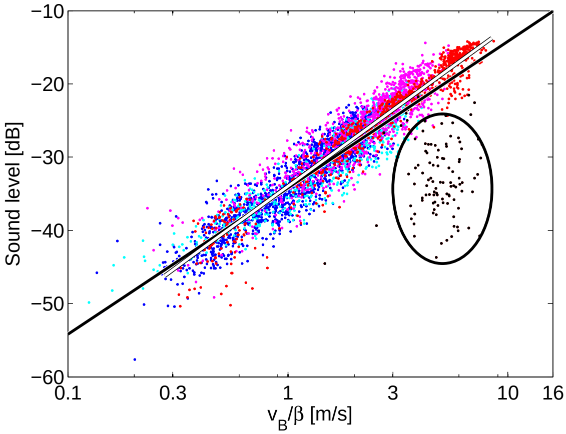

Figure 2.16: Sound level (dB) versus v_B/β (logarithmically scaled) for all conditions (whole notes (dark blue), half notes (cyan) and sixteenth notes (red) at *pp*, *mf* and *f*, as well as crescendo-diminuendo half notes (magenta)) performed by the three violinists on the G string. The black line indicates the theoretical dependence with a slope of 20 dB per decade. The black dots, marked by a circle, correspond to multiple slipping in *pp* produced by one player.

sixteenth-notes *pp* condition by one player. In case of multiple slipping, the string does not reach its full amplitude, yielding a significant decrease in sound level.

The dependence of spectral centroid on the bowing parameters F_B, v_B and β was analyzed using a similar regression model as in Paper II. The analysis strongly confirmed that bow force is the dominating factor determining the spectral centroid, followed by bow velocity and bow-bridge distance. The partial contributions of the three bowing parameters are shown in Figure 2.17. The dependencies found in Paper II were clearly confirmed: The spectral centroid (1) increases with increasing bow force, (2) decreases with increasing bow velocity, and (3) increases with increasing bow-bridge distance.

The use of bow angles

Even though the process of sound generation at the bow-string contact is well described by the three main bowing parameters bow velocity, bow force and relative bow-bridge distance, the control exerted by the player involves many more degrees of freedom. The parameters used by the player for control purposes, with an indirect relation to the produced sound, will be considered as *secondary* bowing parameters.

The bow angles inclination, tilt, and skewness are important examples of such secondary parameters. Inclination has an obvious function in selecting the string played, and can be used as an expressive element in, for example, chord playing.

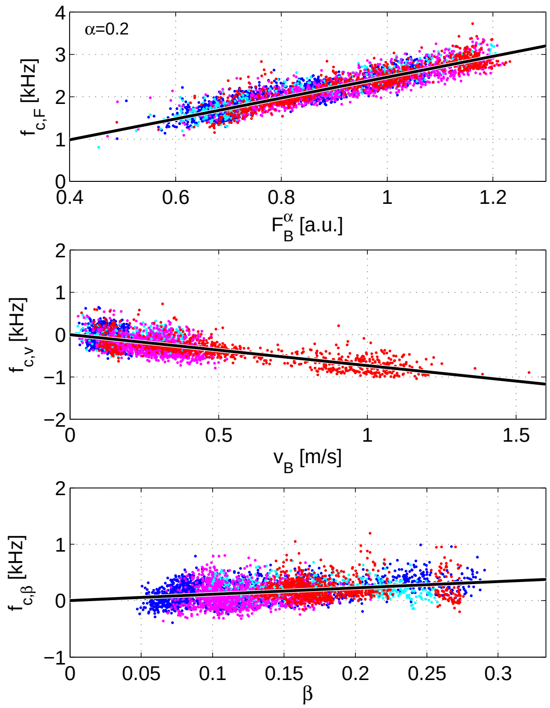

Figure 2.17: Partial contributions of F_B, v_B and β to the spectral centroid. The conditions are indicated by the same colors as in Fig. 2.16.

Furthermore, in double-string playing the distribution of bow force across the two strings involved is regulated via inclination. Inclination by itself does not have a direct influence on the sound.

Bow tilt has a certain influence on the spectrum, but it is small compared to that of the main bowing parameters [24, 54]. Tilt as a secondary control parameter, on the other hand, enables the player to modify the compliance of the bow by bringing more or less bow hairs in contact with the string. In this way, tilt can be used to influence the natural bouncing frequency in spiccato playing, and facilitate the gradation of bow force, for example during attacks and bow changes close to the frog.

Also skewness might fulfill a secondary function by controlling bow-bridge distance. When the bowing direction is not perpendicular to the string, the stick-slip interaction results in a force acting on the bow along the string, depending on the bow velocity and the skewness angle. The resulting drift velocity of the contact point can be predicted given these two quantities.

This drift effect was already observed and explained by Trendelenburg in the 1920s in connection with "crooked bowing" in double-bass playing using the German type of bow [64]. The possibility to utilize skewness to dynamically change bow-bridge distance has also been proposed by violin pedagogues, among others Galamian, Gerle and Fischer [18, 19, 14].

The straight-forward way for the player to control bow-bridge distance is by actively using force, pulling or pushing the bow along the string. The player can therefore choose between the two strategies, or even combine them, in order to achieve changes in bow-bridge distance.

Skewness

Skewness was analyzed in detail for crescendo-diminuendo conditions with *natural* and *reversed* bowing direction (a crescendo during up-bow is considered natural). An example is shown in Figure 2.18. In the natural as well as the reversed condition the main bowing parameters were varied as expected. During crescendo, bow force and bow velocity were increased, while bow-bridge distance was decreased, and vice versa during diminuendo. Interestingly, the use of skewness in the natural and reversed conditions was clearly different. The average skewness angle was negative (i.e. the bow slanted towards the player's body) in the natural condition, and positive in the reversed condition. The net result was that the predicted drift was in the appropriate direction most of the time (see the two lower panels).

This general result was observed for all crescendo-diminuendo conditions and for all players; The correlations between observed and predicted drift were generally positive and significant. However, some differences were observed between conditions and players. Skewness was generally more efficiently utilized in the natural conditions, and the use of skewness seemed to be more integrated in the bowing strategies of certain players than others.

Tilt

A typical example of the use of bow tilt is shown in Figure 2.19. It can be seen that the average tilt angle increased with decreasing dynamic level, indicating that the bow was more tilted in *pp* playing. Furthermore, a clear covariation between tilt and bow position could be observed: the tilt increased when approaching the frog. The example is representative for the performances of all players, even though there were some individual differences in the ranges and average values of tilt angles used.

The increase in tilt with decreasing dynamic level might be related to the application of bow force. At low dynamic levels the bow force used is generally quite low, typically below 0.5 N (less than the weight of the bow, mass about 60 g), and a larger tilt angle might facilitate the fine control of bow force. Concerning the covariation with bow position there are two plausible explanations. The first is that tilt serves the purpose of partly compensating for the variation in transversal

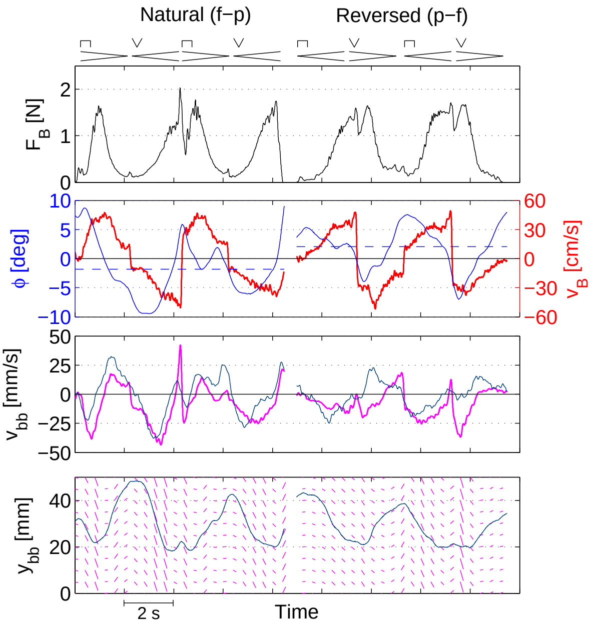

Figure 2.18: Bowing parameters, skewness and drift in natural and reversed crescendo-diminuendo tasks. The panels represent (a) bow force; (b) skewness (ϕ, blue) and bow velocity (red); (c) drift velocity of contact point (v_{bb}) as observed (dark blue) and predicted (magenta); (d) observed bow-bridge distance (y_{bb}, dark blue). The vector field (magenta) indicates the predicted course.

stiffness along the bow, allowing for a more consistent gradation of bow force.[3] The second explanation is related to the biomechanics of the player: the angle of the wrist is constrained as the arm is straightened when approaching the tip in a full down-bow stroke.

In long crescendo-diminuendo notes the natural and reversed bowing direction provide an interesting contrast with regard to the use of tilt. In the natural condition, the tendency of tilt to decrease with increasing bow force will compete with the tendency of tilt to increase when approaching the frog. Vice versa, in the reversed condition these tendencies are expected to reinforce each other. This behavior is indeed reflected in the tilt trajectories shown in Figure 2.20, the used range in tilt being smaller in the natural condition and much more expressed in both directions in the reversed condition.

A surprising observation was that the tilt angles used in viola playing were

[3]The transversal compliance of the bow mainly increases from the frog to the tip, as shown by Pitteroff [48], Chapter 2.

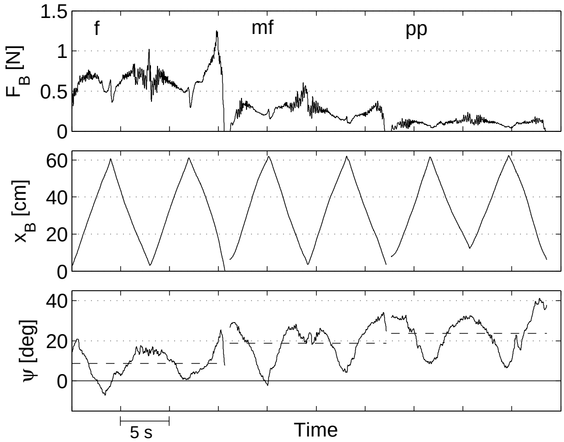

Figure 2.19: Bow force, bow position and tilt in a performance of whole notes at three dynamic levels.

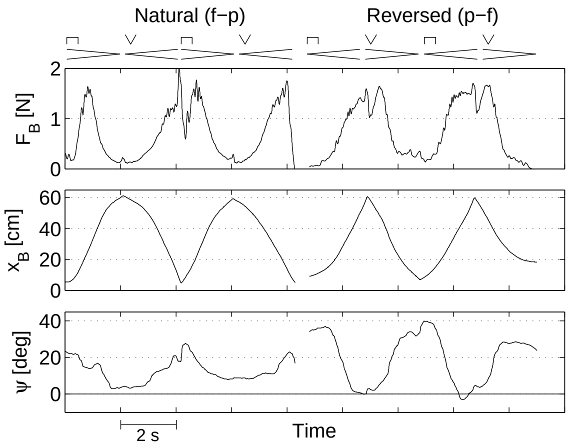

Figure 2.20: Bow force, bow position and tilt in crescendo-diminuendo notes with natural and reversed bowing direction (cf. Fig. 2.18).

generally larger. Tilt ranged from −10 to 45 deg on the violin and up to 60 deg on the viola. This counter-intuitive result might be explained by the different bows used. Whereas the violin bow was rather compliant, the viola bow was stiffer than normal. The viola players might therefore have used larger tilt angles in order to compensate for the stiffness of the viola bow and obtain a better control of bow force.

Discussion and conclusions

The analyses of the large material included in this study allowed to draw interesting conclusions about typical behaviour in violin and viola playing, both with regard to the primary control of sound generation, as well as regarding strategies for changing the bowing parameters.

It was shown that the control of dynamic level involves a trade-off between bow-bridge distance and bow velocity. In long notes, where bow velocity is constrained, bow-bridge distance was the dominating control parameter, whereas in fast notes it was bow velocity. The results confirm earlier findings by Askenfelt [2], extended to a larger range in note duration (0.2–4 s).

The results clearly showed that players adapted to the physical properties of the strings and the instrument. Players generally used higher bow forces on the lowest strings, especially the viola C string. In fast notes played forte, bow velocity seemed to be constrained by a practical upper limit for the vibration amplitude of the string. Also other instrument properties might have influenced details in the bowing strategies. The lower bow forces in forte playing on the middle strings compared to the outer strings, may be related to geometrical constraints. The yield of the string under influence of excessive bow force increases the risk for contact with adjacent strings. Further, the use of larger tilt angles in viola playing suggest that the players adapted to the stiffness of the bow.

In the analyzed conditions, bow force did not exceed 2.5 and 3 N on the violin and the viola, respectively, and the upper range of available bow force was not utilized in the sixteenth-notes condition. Substantially higher bow forces in the range of 3–4 N have been observed in violin performance of accented notes in musical fragments.

Concerning the use of bow angles, clear indications were found that skewness and tilt were actively used by the players, facilitating changes in bow-bridge distance and the gradation of bow force. It should be noted that skewness and tilt are also subject to biomechanical constraints. In case of tilt, observations by Trendelenburg [64] showed that in cello and double-bass playing tilt is normally increased when approaching the tip, in contrast to violin and viola performance. This difference is due to the different ways the instruments are held.

Regarding skewness, it is almost always more natural to make a rounded bowing movement rather than following a perfectly straight path, a basic observation made by Hodgson [27]. “Crooked bowing” can be commonly observed in string performances at all levels, including renowned violinists. Bow changes close to the tip typically give clear illustrations of the phenomenon. A general observation is that one of the main difficulties in mastering the control of bow motion lies in a sensible trade-off between biomechanical and acoustical aspects of playing.

2.7 General discussion and conclusions

Contributions

The studies included in this thesis treat the mechanics and acoustics of bowing from different perspectives. The studies were concentrated on the "steady" part of the tone, involving the maintenance of regular Helmholtz motion and aspects of sound quality under influence of the main bowing parameters bow velocity, bow force and relative bow-bridge distance. The first two studies (Paper I and II) used a bowing machine to provide a mapping of the regions of stable Helmholtz motion, timbre (brightness), and pitch deviation on the bowing parameter space available in normal playing. This systematic information is of basic importance for the understanding of the players' freedom in controlling the performance on the lowest level; the quality of the individual notes. The last study (Paper IV), which relied on the method developed in Paper III for measuring bowing gestures accurately, showed how players utilized the available parameter space in actual performance under various conditions.

The results of the studies provided a number of new or deepened insights. Paper I shed more light on the mechanism of breakdown of Helmholtz motion at low bow forces, with implications for the formulation of the lower bow force limit. It appeared that Schelleng's equation for minimum bow force [52] was not based on correct assumptions. Even though Schelleng's equation was found to provide a good qualitative description of the lower bow-force limit at fixed bow velocity, it failed to predict the empirically found dependence on bow velocity correctly.

In Paper II a systematic investigation of spectral centroid and pitch level was provided. Mapping on Schelleng diagrams provided a deepened insight in the dependence of spectral centroid (correlated to perceived brightness of the tone) on the main bowing parameters, as well as the role of pitch flattening as a practical upper bow-force limit in string performance.

Paper III described a complete measurement system for all bowing parameters and other aspects of bowing. Clear geometrical definitions of the spatially defined bowing parameters, as well as bow angles relevant to violin performance were provided. The methods and definitions will be helpful for the development of standards for the measurement and representation of bowing gestures, facilitating the exchange of data and analysis methods [30].

The results in Paper IV provided in-depth analyses of the use of the main bowing parameters in violin and viola performances under the influence of different types of constraints (acoustical, biomechanical and musical). Even for the relatively simple tasks included in the experiments, the need and importance of trade-offs between the individual bowing parameters due to the constraints was clearly demonstrated.

Such trade-offs rely on realistic judgments of what is possible to achieve acoustically, how the bowing parameters need to be combined to reach the particular sound (stable tone, dynamic level, timbre), and a clear strategy for how the bowing parameters should be changed to meet the requirements of the following note or bow stroke. In this connection, the systematic use of the bow angles skewness and tilt, which not have been possible to measure reliably before, was shown to be of great value in continuously adapting the bow force and bow-bridge distance to the current needs.

The measurement method described in Paper III allows for a detailed insight in the control of even very complex bowing gestures. The analyses in the included studies have been limited to the steady part of bowing, but the quality of the measurements makes it possible to extend the studies to more complex aspects of bowing, including attacks, bow changes, string crossings as well as dynamic bowing patterns with a bouncing bow (spiccato, sautillé, ricochet). Some preliminary analyses and further possibilities regarding overview of large amounts of data by visualizations and animations will be reported in Part II.

Future directions

In future studies it would be interesting to include body movements in the analyses in order to shed more light on biomechanical functions and constraints in bowing, as well as the influence of posture on the efficiency of bowing technique. There are many subtleties in the coordination of the different parts of the bowing arm. For example, Rasamimanana showed that there was a clear transition from one coordination pattern to another in accelerated and decelerated détaché note sequences, involving a transition from in-phase to anti-phase relation between the elbow and wrist angles [51].

Also the use of the left arm should be further investigated, including fingering, position shifts, as well as aspects of bimanual coordination. Measurements of the use of finger force in violin playing by Kinoshita [33] revealed interesting details, for example that the exerted finger force was related to dynamic level. With regard to tone production, finger force influences the damping of the string, and therefore also the sound. Details in the bowing constraints, including minimum bow force and the conditions during the attack, are also strongly influenced by the conditions at the string terminations. Further, Baader et al. [3] have reported interesting results on the relative timing of fingering and bowing. All together these findings demonstrate that bowed-string performance involves many levels of coordination, worthy of further study.

Many scientific performance studies, including those presented in this thesis, focus on classical playing. For a more differentiated picture, the scope should be expanded to other playing styles. Preliminary analyses of measurements of bowing in fiddlers (French-Canadian style), using the setup described in Paper III, revealed a highly expressive and dynamic use of the bow, including ornamentations and specific techniques not present in classical performance. A more multifaceted approach is therefore important for obtaining a complete picture of the possibilities in bowing.

Another interesting and important aspect of bowing is related to haptics. Haptic feedback plays an important role in bow control, as it allows the player to feel the frictional interaction between the bow and the string. It has been shown in haptic experiments that such feedback facilitates the control of sound production in virtual instruments [44, 43, 16]. Most likely, other haptic cues related to the mechanics of the bow, such as the transversal compliance ("stiff /soft bow"), also play an important role in the control of bouncing bowing techniques and bow changes.

The study in Paper II has provided a basic link between spectral centroid and the main bowing parameters. In the psychophysical literature there is a general agreement on that spectral centroid is correlated with perceived brightness [20, 39, 9]. However, the spectral centroid is a rather crude spectral measure, and the perception of the timbre of the violin is associated with many more dimensions [59, 58]. The relation between the control parameters of the sound and the perceived tone is still essentially unexplored. Measurements of the kind presented in the included studies, combined with perceptual experiments, could shed more light on this relation, in a similar way as has been reported for the guitar [63].

A better understanding of the relation between the bowing parameters and the properties of the sound is of paramount importance for continued progress in the study of the bowed-string instruments, including the synthesis of violin sound. Recent studies have shown that the perception of synthesis is as much determined by the control of bowing as by the level of detail of the model [12]. The magic of the violin sound may be less determined by the proverbial "The Secret of Stradivari" than by the gestures of the performer.

Part II

Prospects

Chapter 3

Visualization of bowing gestures

The method for measurement of complete sets of bowing parameters described in Paper III generates a wealth of data, including the bowing parameters bow position, bow velocity, bow-bridge distance, bow force, bow acceleration, as well as the bow angles inclination, skewness and tilt. The recording sessions for the performance experiment described in Paper IV lasted typically two hours with an estimated effective playing time of about half an hour. With a total of eight recording sessions the processing and representation of the large quantity of collected data are far from trivial. Considerable effort was spent on methods for overview and access of selected subsets of the data.

A good presentation of the data greatly facilitates the understanding of what has been measured. The sheer amount of data involved a number of challenges; (1) to provide a complete overview allowing for easy comparison, e.g., between the performances of different players, (2) identification of relevant features, systematic behavior and coordination of bowing parameters, e.g., during bow changes and string crossings, and (3) to provide insight in the connection between the bowing patterns and sound. Another challenge was to present the data in such a way that a wider audience, including violin teachers, students and other interested string players without a technical background, could benefit from the results. These challenges were faced by implementing different ways of visualizing the data.

3.1 Picture book

To create an overview of the data, "picture books" were created for all recorded sessions, containing aligned graphs of the most relevant parameters as a function of time. Paging through the books allows to quickly skim over the data. Furthermore, performances of different players can be easily compared, and the influence of different conditions on the bowing parameters, such as dynamic level on bow force, can be easily identified.

An example is shown in Fig. 3.1. Each performance is represented by a total of

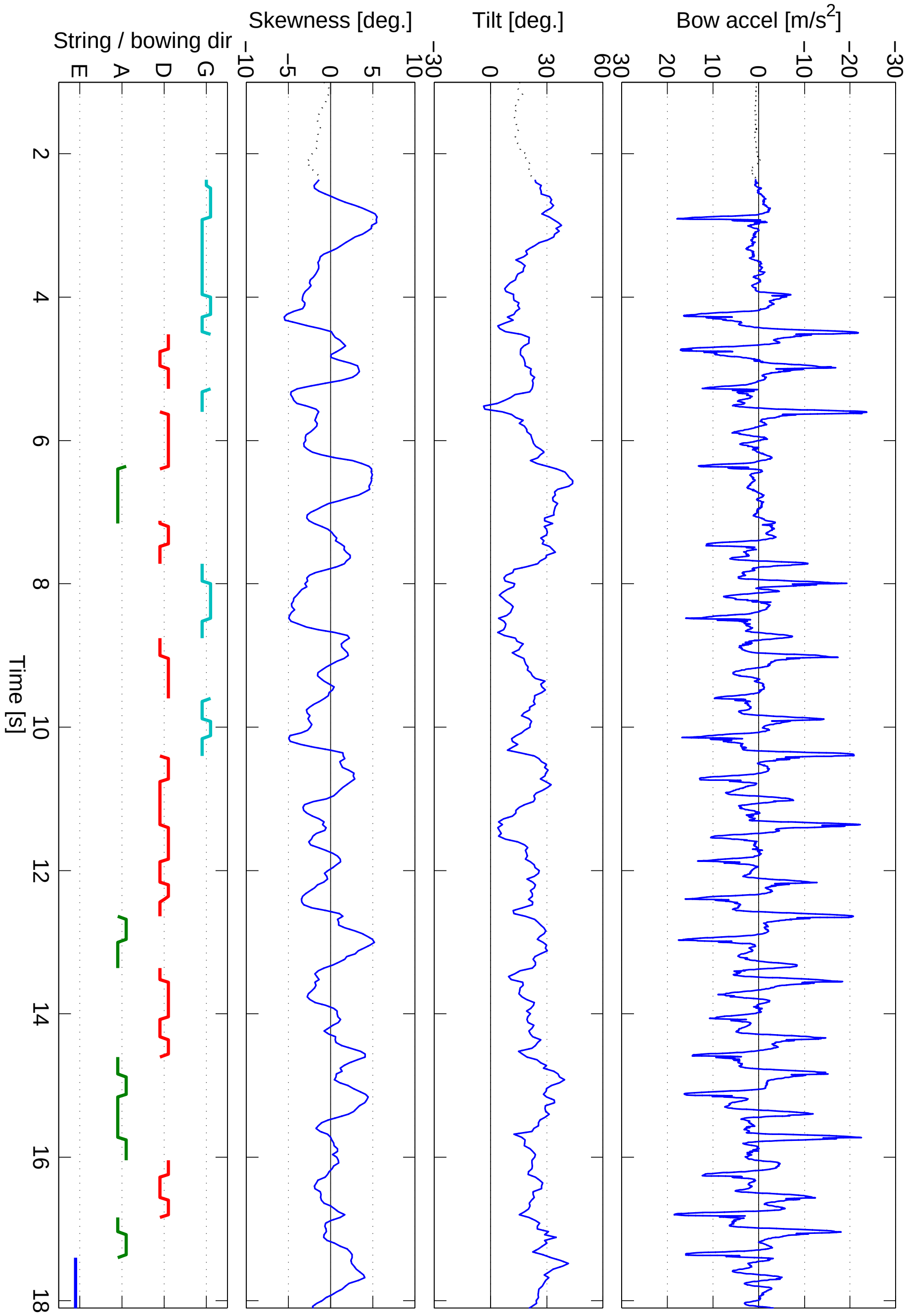

Figure 3.1: Page from the picture book. A performance is shown of the first 4½ bars of J. S. Bach's Allemande from the second Partita for solo violin (player P4, violin). See the text for an explanation of the panels.

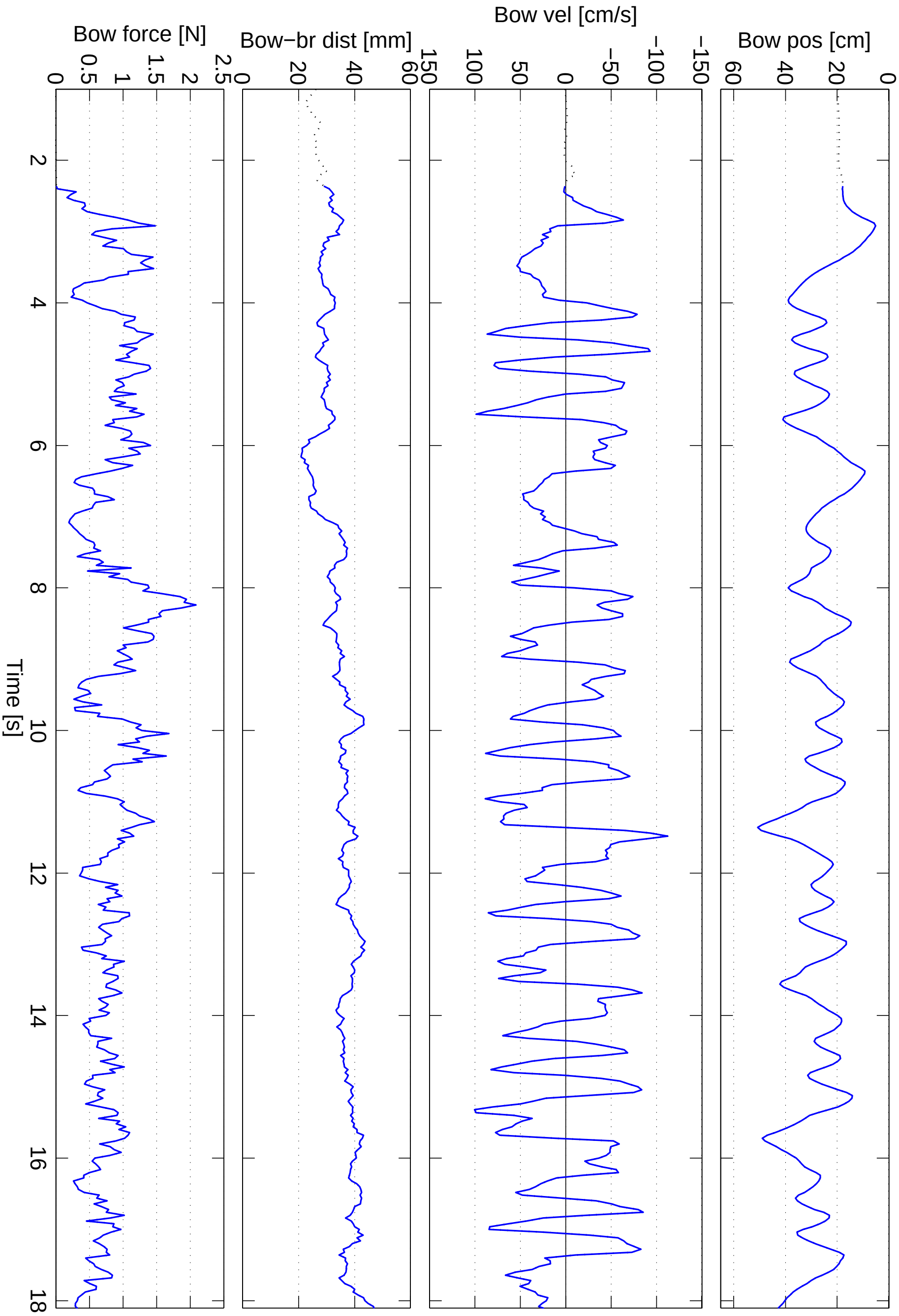

Figure 3.1: continued

eight panels distributed across two adjacent pages. The first seven panels, starting from the top, represent bow position, bow velocity, bow-bridge distance, bow force, bow acceleration, tilt and skewness. The lowest panel represents the basic "bowing state," showing string played and bowing direction. The level of the line shows which string is played (grid lines, color), as well as the bowing direction (down-bow when the line is hanging slightly below the grid line, and up-bow when the line is slightly above). In all panels the lines are printed as solid lines when the bow is in contact with the string, and as thin dotted lines when the bow is off the string.

The polarity (direction) of bow position, velocity and acceleration (panels 1, 2 and 5), as well as the levels of the lines in the lowest panel have been chosen for an intuitive representation of the bowing. For this reason the y-axes of panels 1, 2 and 5 are inverted. In the lowest panel the highest level corresponds to the lowest string, and the level decreases when switching to the higher strings, resulting in an inverted relation with pitch.[1] These choices might seem odd at first sight, but the meaning becomes clear when trying to mimic a violin performance from the display. For example, it is more intuitive to follow the bow position curve when a down-bow is represented by a downward direction in the graph.

An inherent limitation of the picture book is that it is not always easy to appreciate the relations between bowing parameters across all the panels, and for long recordings fine details become obscured. Furthermore, time history plots do not always provide a good "feel" for the data. For these reasons, alternative visualizations of the data were developed.

3.2 Hodgson plots

The first effective visualizations of real bowing gestures were performed by Hodgson in the 1930s [27]. He recorded bowing gestures by so-called cyclegraphs, photographic records of spatial trajectories. This was done by attaching a light source to the object to be traced, for example the wrist of the player, and capturing the motion on a photographic film while playing in a dark environment. A typical example is shown in Fig. 3.2.

The visual displays developed in this work show similar information as Hodgson's cyclegraphs, and are therefore referred to as "Hodgson plots." In the current implementation, the Hodgson plots typically show the spatial trajectory of the frog of the bow during a certain time span (typically 1 s). This provides a simple, yet informative, representation of bowing gestures with a direct relation to the actions of the right hand of the player.

The 3D motion capture data, in combination with calibrated geometrical models of the bow and the violin described in Paper III, allow for some important additional features. First, the motion of the bow can be shown relative to the violin, displaying the effective bowing gestures related to sound production. There is no

[1] Despite the apparent resemblance, this combined string – bowing direction representation should *not* be confused with piano roll notation.

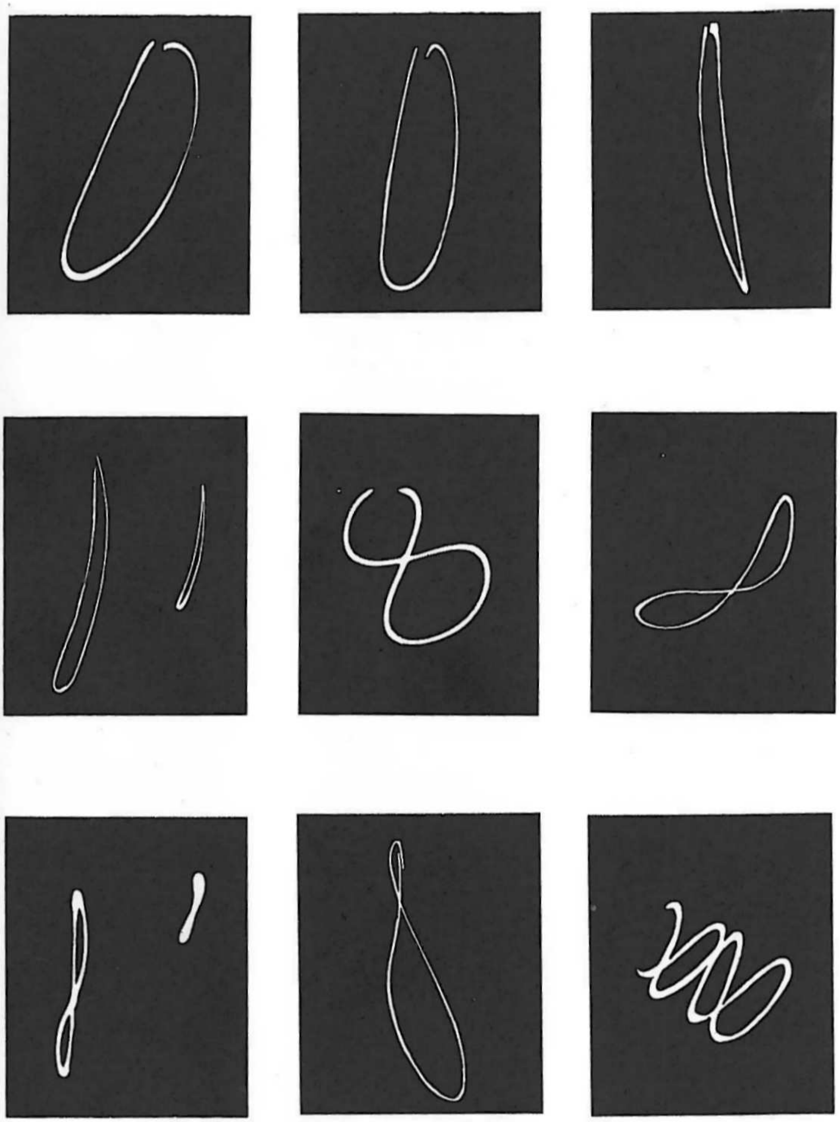

Figure 3.2: Cyclegraphs of typical bowing patterns. (Adapted from Hodgson [27])

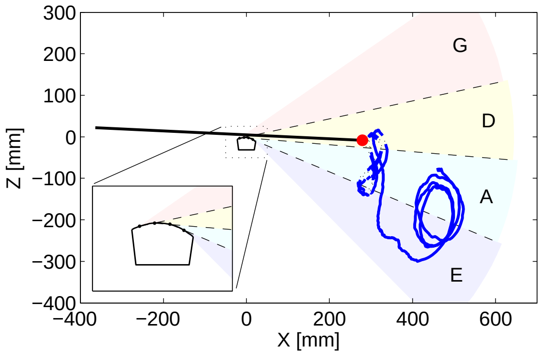

Figure 3.3: Hodgson plot in back projection (xz-plane). The red dot indicates the position of the frog at the "present" moment (i.e., at the end of the shown time interval). The solid black line represents the bow-hair ribbon. The spatial trajectory of the bow frog is indicated by a blue line, shown as solid and fat when the bow was in contact with the string, thin and dotted otherwise. In the background, the bridge, string positions and string crossing angles are shown (see close-up for more detail), forming a functional context of the displayed bowing gestures. The string crossing angles (dashed lines) subdivide the space into four angular zones associated with bowing different strings.

need to constrain the movements of the player during the measurements, allowing for natural playing conditions. Secondly, the same data can be shown in different projections. This allows for example to show the bowing gestures from the perspective of the player in order to strengthen the association with her/his own actions. Furthermore, it is possible to display important landmarks on the violin, such as the bridge and the strings, as well as the string crossing angles, in order to provide a functional visual context for the bowing gestures.

Two particular projections were considered most useful to cover the main aspects of bowing: The "back" projection, showing the bow motion from the perspective of the player, and the "top" projection, showing the violin from above. Typical examples are shown in Figs. 3.3 and 3.4.

The back projection is especially suitable for showing complex bow coordination patterns involving bow changes and string crossings (see Hodgson [27] for an extensive overview of typical patterns). Fig. 3.3 shows a selected fragment of about three seconds of a performance of F. Kreisler's "Praeludium and Allegro." The fragment contains two clearly distinguishable coordination patterns: a circle-shaped pattern corresponding to a détaché passage across two strings, and a figure-of-eight pattern (played closer to the frog), corresponding to a spiccato passage across three strings. A variety of information can be obtained from the displayed patterns, for example about the use of the accessible length of the bow (bow position, amount of bow

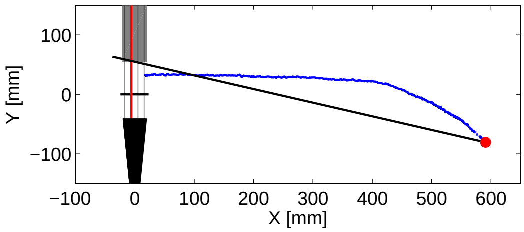

Figure 3.4: Hodgson plot in top projection (xy-plane). The bow and the spatial trajectory of the frog are shown in a similar way as in Fig. 3.3. The context is formed by the four strings (vertical lines), the bridge (bold horizontal line), the fingerboard (gray rectangle) and the tailpiece (black shape), based on the specific measures of the instrument. To enhance clarity, the string played at the "present" moment is highlighted in red.

length used on each note), the regularity of the motion, and the efficiency of the string crossings.

The top projection gives a good sense of bow-bridge distance and skewness of the bow. The frog trajectories are particularly useful for illuminating details of changes in bowing direction, which according to empirical observations follow curved rather than straight paths [27, 66]. The example in Fig. 3.4 shows an example of a long diminuendo note played down-bow. It can be seen that at the end of the bow stroke the bow was far from perpendicular to the string, clearly showing how skewness was utilized to drive the bow towards the fingerboard (see Paper IV).

One important aspect of bowing, not covered by the two Hodgson projections, is bow tilt. Tilt can be intuitively visualized in a clock-like display, showing the angle of the frog relative to the string. An example is shown in Fig. 3.5. During normal playing, the bow is often tilted with the stick towards the fingerboard, corresponding to a clockwise rotation in the tilt display. The tilt angle is easily quantifiable, realizing that an angle of 30 degrees corresponds to 5 minutes on the clock. In *pp* playing close to the frog bow tilt can reach values up to 45–60 deg.

3.3 Alternative displays

Even though a direct visualization of bowing gestures in a functional context can be highly informative, it still fails to reveal certain subtle, but vital, aspects of the coordination of the bowing parameters. For example, Demoucron [12] showed that systematic patterns in the details in bow acceleration and bow force during bow changes could be better understood by plotting the parameters versus bow position instead of versus time.

An illustration of such a representation is given in Fig. 3.6 for bow skewness. The example clearly shows how bow skewness was varied during repeated long notes.

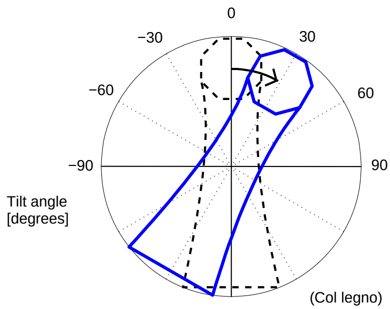

Figure 3.5: Visual display for bow tilt. The keyhole-like shape represents the bow frog when looking in the direction of the stick. Tilt is shown as a rotation of the frog in a clock-like display. When the stick is tilted towards the fingerboard (as during normal playing), this is shown as a clockwise rotation. For *col legno* playing tilt angles of 90 degrees or more are employed, clockwise or anti-clockwise depending on the preference of the player.

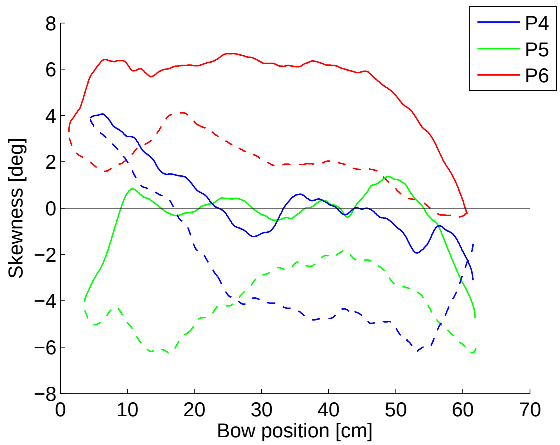

Figure 3.6: Skewness versus bow position in long (4 s) notes at *mf* level, played with the full bow by three players (P4, P5, P6, see Paper IV). For all players a full cycle is shown, consisting of an up-bow (dotted line) followed by a down-bow (solid line and arrows). Positive skewness corresponds to the case with the bow frog slanted away from the player.

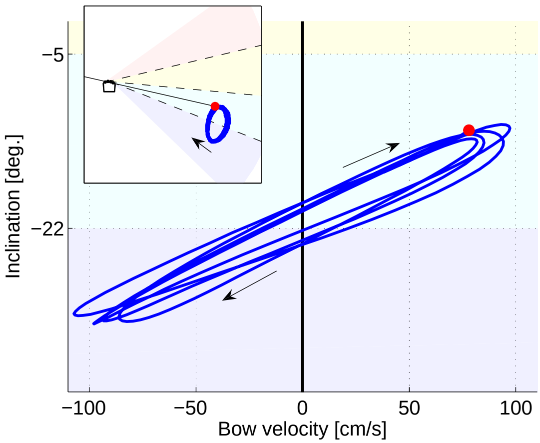

Figure 3.7: Inclination versus bow velocity in a fast détaché passage with coordinated string crossings and bow changes. The example is taken from a performance of J. S. Bach Preludio from the third Partita for solo violin. The corresponding bow motion (circular pattern) is indicated in the small Hodgson plot.

A number of interesting aspects are revealed. First, there was a clear asymmetry between up-bows and down-bows for all players: during up-bows the bow frog was generally slanted more towards the body (lower skewness values) compared to down-bows. Furthermore, during an interval before and after the bow change at the frog the skewness increased continuously, probably reflecting a rotation of the wrist in order to facilitate a smooth bow change. The reverse motion was seen for bow changes at the tip. Another interesting detail is that the individual players showed different average skewness values. For example, player P6 tended to use positive skewness angles consistently, slanting the bow slightly away from the body all the time. It is noteworthy that, except for large parts of the down-bows by players P4 and P5, the bow was not drawn parallel to the bridge, even though the notes were played at constant dynamic level.

Another useful visual representation, in particular for bowing patterns involving coordinated string crossings and bow changes, is a plot of inclination versus bow velocity. An example is given in Fig. 3.7, showing a fast détaché passage (about 8 notes per second) with coordinated string crossings and bow changes. This leads typically to circular patterns of bow motion, as shown in the corresponding Hodgson plot. It can be seen that rather high peak bow velocities of about 1 m/s were reached. The alternative representation clearly reveals the relative phase of bow velocity and inclination of the bow in this type of cyclic patterns, and will therefore be referred to as “phase plot.”[2] A further explanation of the shown example will

[2]The term “phase plot” is often used in connotation with the behavior of dynamic systems,

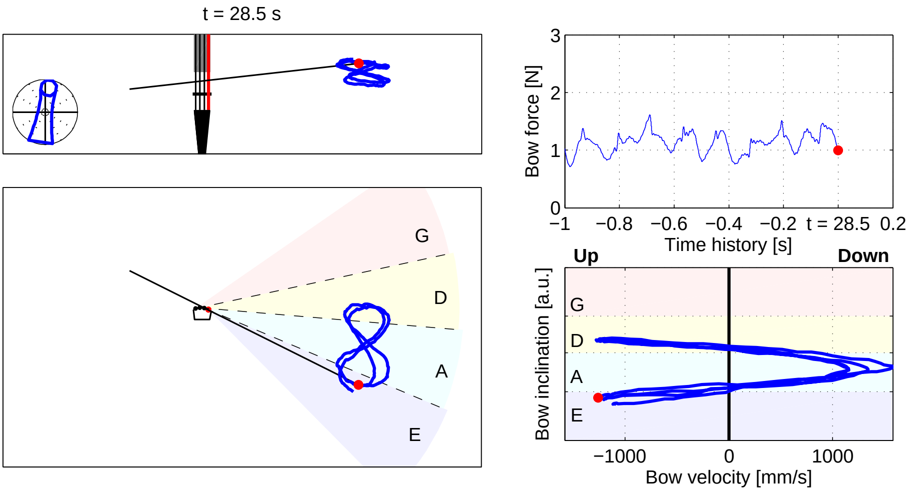

Figure 3.8: Screenshot of combined animated displays. The panels on the left side show the Hodgson plots in two projections, as well as bow tilt. The two panels on the right side show additional information on the use of the bow. Depending on the purpose of the visualization different types of display might be placed here. In this example bow force as a function of time (present moment and history) is shown in the upper-right panel, and a phase plot of bow inclination versus bow velocity is shown in the lower-right panel. The background colors reinforce the association with the Hodgson plot.

be provided in Sect. 4.2.

3.4 Animations and further improvements

The described displays allow the study of various aspects of bowing gestures, but the connection with sound is missing. This was achieved through animation, combining several displays in synchrony with the recorded sound (see Fig. 3.8 for a screenshot). The animations are rendered as QuickTime movies, making it possible to play them using a standard media player. This feature makes it possible to scroll fast through a performance, looking for interesting passages. The animations are therefore highly suitable for teachers and students for analysis of performances, and might contribute to a deepened understanding of several aspects of bowing. Moreover, the animations have proven to be a powerful research tool, greatly facilitating the discovery of many interesting aspects of coordination of the bowing parameters in performance.

indicating a plot of position and momentum variables as a function of time.

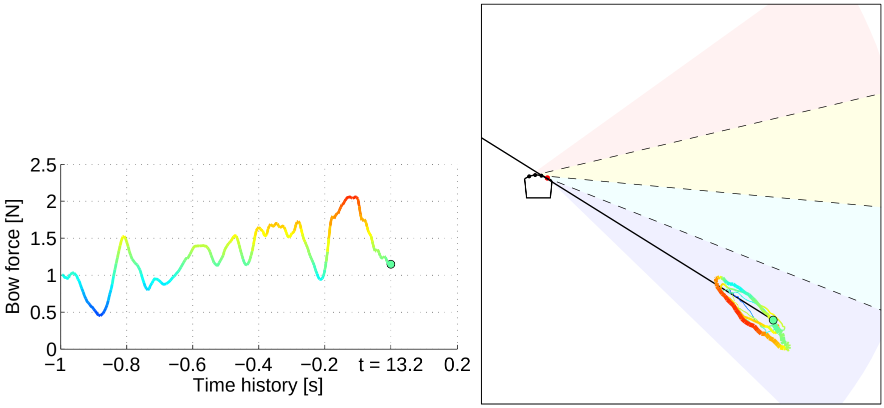

Figure 3.9: Time history of bow force and Hodgson plot with added color information. The color is mapped to bow force and visualized in both displays. In addition, the trajectory in the Hodgson plot is faded with time for a better distinction in cyclic bowing patterns. The example shows a performance of a fast and loud détaché passage on the E string from J. S. Bach's Preludio from the third Partita for solo violin. The most recently played note was accentuated, using a combination of a high bow velocity and bow force.

In the animated displays background colors were utilized to reinforce the association between different displays. In the latest state of development, the option to use color as an additional dimension to the motion trajectories has been added. This can be used to provide a better insight in the coordination between the bow motion and other parameters such as bow force. Fig. 3.9 shows an example of this way of using color. The fragment shows again a fast détaché passage from Preludio by J. S. Bach. By varying the line color as a function of bow force in both the force time-history display and the Hodgson plot, the relation between the two becomes much clearer; It can be immediately seen *where* exactly in the bow stroke the bow force is varied, which is much harder to appreciate from the two separate panels. This particular example shows an accentuated note, characterized by a peak in bow force. The colored trajectory shows clearly how bow force developed during the note.

Chapter 4

Extensions of the current work

The measurements of violin and viola playing reported in Paper IV provided a wealth of performance data. Only the “steady-state” aspects have been analyzed so far as described in Paper IV. In this part some preliminary observations and analyses on dynamical aspects of bowing, including attacks and string crossings will be presented to further illuminate the informative power of the developed type of measurements.

4.1 Attacks

Background

Attacks and bow changes play an important role in the articulation of the notes. In analogy with speech the steady part of the tone can be compared with vowels, while the consonants are formed by the attacks and bow changes. In this section a preliminary analysis of attacks is given, supplementing the extensive analyses of the “steady-state” parts of sustained tones in Paper IV.

The analyses in Paper IV were limited to the “steady” part of notes in relatively simple repeated note patterns. The player’s main task was to control the quality of the sound, which in most cases involves the maintenance of Helmholtz motion. Within these constraints the player has the freedom to choose the specific combination of bowing parameters (bow force, bow velocity, bow-bridge distance) providing control of loudness and timbre of the sound. Even the seemingly simple task of drawing a good steady string tone requires surprisingly much skill. Still, the production of steady tones represents a basic level of continuous bow control, characterized by relatively slow modulations of the control parameters.

The situation is different in attacks and bow changes, which typically take place during a short period of time. As shown by Guettler [22], the quality of the transient is critically dependent on the coordination of mainly bow-bridge distance, bow force and bow acceleration, and the production of a good attack therefore requires a refined control of these parameters by the player on a short time scale.

The bowing gesture experiment described in Paper IV included a part dedicated to the attack. Here some preliminary results will be given. A more detailed analysis of the attacks will form a separate study.

Experimental method

The task consisted of playing repeated notes, separated by pauses to make sure that the string was at rest before the next attack. Three types of attacks were included; soft, neutral and strong. To clarify the instruction, the attack types were associated with consonants; "w", "b" or "d", and "k" or "t". The tasks were performed at three dynamic levels (*f*, *mf*, *pp*) on all four strings, both open and stopped (third finger in first position). Each condition consisted of six repeated notes, resulting in a total of 432 attacks per recording session.

In the analysis the onsets of the notes were determined using a semi-automatic procedure. For all attacks the bow acceleration and bow force were calculated by taking the average over the first 10 ms after the onset. Bow-bridge distance and bow tilt were measured at the onset.

Hypotheses

The different attack types and dynamics were chosen to obtain a large spread in the used parameter space, avoiding the need for direct reference to bowing parameters in the instructions. The hypothesis was that the players would adapt bow-bridge distance to dynamic level, whereas the used combinations of bow force and acceleration were expected to depend mostly on attack type.

For the different strings it was expected that the players would adapt the combination of bowing parameters to the physical properties of the string. From the highest to the lowest string, the characteristic transverse impedance Z_0 increases (see Table IV in Paper IV). It was therefore expected that players would use higher bow forces and lower accelerations on lower strings.

Furthermore, damping plays an important role in the creation of Helmholtz motion during the attack. A larger damping leads to more rounding of the Helmholtz corner. As a result, the "echoes" of the reflected corner (secondary waves) are weaker and therefore less likely to initiate additional slips. This leads to more favorable conditions for an acceptable attack, with less risk of multiple slipping. By stopping the string the damping is highly increased. The hypothesis was thus that the parameter space in the Guettler diagrams would be narrower for the open strings compared to the stopped strings.

Preliminary results

Figure 4.1 shows seven Guettler diagrams for different values of relative bow-bridge distance β for attacks played on the D string, obtained from the recordings of three violinists. The combination of conditions (dynamic level and attack type) and players yielded a large spread in the parameter space. The combinations of bow force and acceleration used formed clear triangular areas, corresponding to the conditions for a good attack according to Guettler's criteria [22]. The "inclination" of the triangular areas was clearly dependent on bow-bridge distance. For small values of β relatively high forces were used, whereas for large values of β bow acceleration was relatively high. This is also in agreement with the predictions by Guettler.

The strong attacks could be clearly distinguished by the high values of acceleration and force. The soft and neutral attacks showed more overlap, the average acceleration and force of the neutral attacks being higher. Interestingly, it can be seen that the players used different bowing strategies, similar to the individual "signatures" found in Paper IV. Player P5 used relatively high bow-bridge distances and low bow forces, player P6 used a relatively limited range of bow-bridge distance, and player P4 showed the largest overall variation in bowing parameters.

Some preliminary observations could be made regarding the dependence of relative bow-bridge distance β, bow force and bow acceleration on the conditions (attack type, dynamic level, string played, open or stopped string). As hypothesized, dynamic level was the dominating factor in the choice of relative bow-bridge distance, the value of β decreasing with increasing dynamic level. A bit surprisingly, in violin performances the average absolute bow-bridge distance was the same for stopped and open strings, leading to higher values of β for stopped strings. In the viola performances the average absolute bow-bridge distance was slightly smaller for stopped strings, but not enough to obtain a similar value of β. This is contrary to expectations, in view of that the open string is less "forgiving," and that higher values of β would lead to more critical conditions for the combination of bow force and acceleration.

The combination of force and acceleration was mainly dependent on attack type and less on dynamic level, in accordance with expectations. For open strings, the average values of bow force and acceleration were generally larger compared to stopped strings. This yields a higher tolerance, possibly to compensate for the more critical conditions on open strings.

On the lower strings higher bow forces were used, especially on the viola C string. The differences between strings were clearest for the strong attacks at *f* level. Also acceleration was on average highest on the lowest strings.

Finally, some interesting observations on bow tilt could be made. Tilt depended stronger on attack type than on dynamic level. For strong attacks the average tilt angles varied from 5 to 15 deg between dynamic levels, compared to 20–25 deg for soft attacks. For open strings smaller tilt angles were used (bow hair flatter on the string). This might be related to the higher bow forces used, providing a better "grip" on the string.

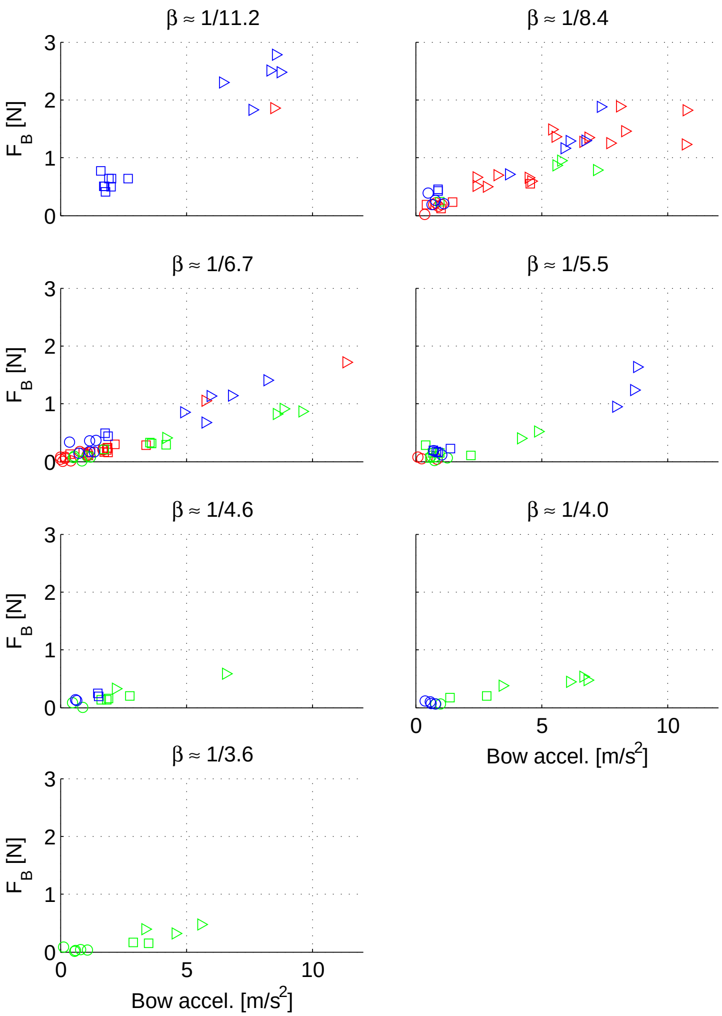

Figure 4.1: Guettler diagrams of bow force F_B versus bow acceleration for seven values of relative bow-bridge distance β for the stopped violin D string at three dynamic levels. The data are from three players (total of 162 attacks). The players are indicated by color; P4 (blue), P5 (green), and P6 (red). The symbols indicate the three types of attacks; strong (▷), neutral (□), and soft (○).

Discussion and conclusions

The above observations on attacks show clearly that players adapted the bowing parameters bow-bridge distance, bow force and bow acceleration, as well as tilt, to the physical properties of the string and the musical requirements (attack type, dynamic level). Figure 4.1 provides a clear indication of that the players adapt to the conditions of a proper attack as formulated by Guettler [22]. Further analyses, including assessment of the quality of the attacks, are needed to shed light on the details of bow control during the attack, as well as on the players' ability to adapt to the conditions for a proper attack.

4.2 Coordination in complex bowing patterns

Complex bowing patterns involving bow changes and string crossings form an interesting case in analyses of bow control. Typical aspects of coordination can be readily observed in the visualizations of repetitive bowing patterns. The phase plot showing bow inclination versus bow velocity, introduced in Sect. 3.3, is highly suitable for detailed analysis of the coordination between string crossings and bow changes. An example of a détaché passage across two strings was shown in Fig. 3.7. The example was taken from Preludio from the third Partita by J. S. Bach, which contains typical examples of cyclic bowing patterns, showing up as circles and figure-of-eights in the Hodgson plots (back projection, shown inserted in the figure).

The détaché passage consistently resulted in a narrow ellipse in the phase plot. The elliptical shape might be surprising at first consideration. For a perfect synchronization between bow changes and string crossings, one would expect that the trajectory would form a straight diagonal line. The hysteresis clearly indicates that the bow changes lag behind the string crossings. There are, however, good acoustical reasons for this lag. In order to obtain a proper start of the note on the new string after the string crossing, the bow force needs to be sufficiently high, especially at the high bow velocities (about 1 m/s) and accelerations (20–40 m/s^2) reached in the current example. The necessary build-up of force is achieved by crossing the string just before the bow change.

A more complex bowing pattern involving three strings is shown in Fig. 4.2. This bowing pattern results in a figure-of-eight trajectory in the Hodgson plot. It is clearly more difficult to perform, and requires devoted practice even by advanced players. The current example shows a performance of a player who mastered this passage very well. The resulting shape in the phase plot is quite different compared to Fig. 3.7. However, the coordination between bow changes and string crossings shows the same type of hysteresis; the bow changes lag behind the string crossings.

These examples show clearly how the coordination of the components of the bow motion by the player is influenced by the acoustical requirements of tone production. They are exemplary for expert behavior, characterized by a high precision and consistency, and are therefore interesting evidences of complex coordination in motor control.

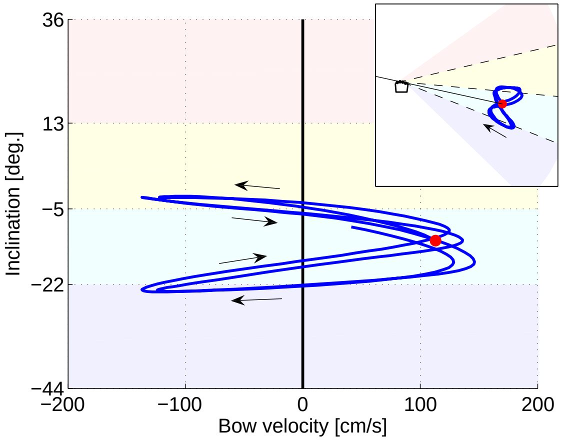

Figure 4.2: Phase plot of a fast détaché passage involving three strings (arpeggios). The example is taken from a performance of J. S. Bach Preludio from the third Partita for solo violin. The corresponding bow motion (figure-of-eight pattern) is indicated in the small Hodgson plot. At the current moment shown (indicated by the red dot), a down-bow is played on the A string (green area) while the bow inclination is changing towards the E string (blue area) in preparation for a string crossing.

The movements in both examples are composed of two components; a to-and-fro motion (up- and down-bows) and a pivoting motion around the strings. The resulting patterns are highly reminiscent of Lissajous figures. Figure 4.3 shows the basic Lissajous figures corresponding to the above examples of bow motion. The apparent similarity indicates that the two movement components constituting the complex bowing patterns can be well approximated by simple sinusoids. For the circle-shaped bow motion the frequencies of the up- and down-bow motion and the pivoting motion are equal. For the figure-of-eight patterns the up- and down-bow motion has twice the frequency of the pivoting motion.

It was noticed that the bow changes lagged behind the string crossings in both bowing patterns. This can be introduced in the Lissajous figures as a phase lag of the x-coordinate, as shown in Fig. 4.4 for a phase lag of 10 degrees. The resulting patterns clearly provide improved descriptions of the corresponding bowing patterns. In the right panels the diagonal line becomes an ellipse, and the parabola shape splits up in two lobes, in agreement with the phase plots shown in Figs. 3.7 and 4.2. In the left panels the circle becomes flattened and the figure-of-eight becomes more butterfly-shaped.

The above examples show that advanced violin bowing requires non-trivial coordination patterns, including certain phase relations which are kept constant across

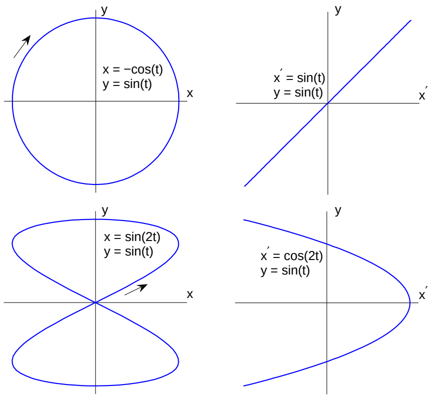

Figure 4.3: Typical Lissajous figures, corresponding to the bowing patterns shown in Fig. 3.7 (upper panels) and Fig. 4.2 (lower panels). The left panels represent the bow motion as shown in the Hodgson plots. The right panels are comparable to the phase plots and can be obtained by differentiation of the x-coordinate of the corresponding left panels with respect to time (i.e., from position to velocity). The parametrization of x and y with respect to *t* (time) is indicated in the panels.

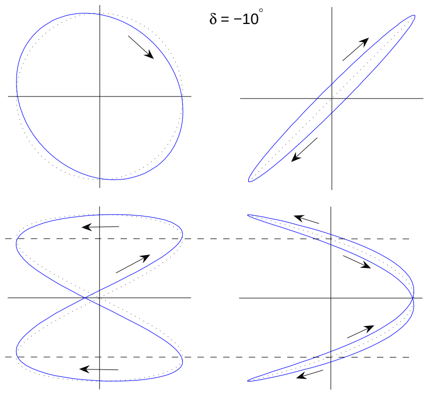

Figure 4.4: Similar Lissajous figures as shown in Fig. 4.3 including a phase lag of the x- and x′-coordinates of 10 deg. The basic Lissajous figures are indicated by dotted lines. The dashed lines in the lower panels indicate the inclination corresponding to the string crossings. In the upper panels the string crossing angle corresponds to the abscissa.

a specific bowing pattern. Further, in music performance players can easily switch swiftly from one bowing pattern to another, for example as shown in Fig. 3.3 for the two typical bowing patterns described in this section. It seems safe to conclude that violin bowing belongs to the top achievements in human motor control, worthy of further study.

Chapter 5

Music pedagogical perspective

5.1 Informed teaching and practicing

An important underlying goal of the studies presented in this thesis was to provide a link between the scientific studies of the bowed string, and the praxis of playing the violin and other bowed-string instruments. It is clear that both areas can benefit greatly from a close, mutual relationship. Practitioners and teachers of music can profit from the results of acoustical, physiological and psychological research related to music performance, and researchers can formulate informed and musically relevant research questions.

In violin performance there is a close connection between the physics of the bowed string and the actions of the player, as pointed out in Paper IV. A basic knowledge of these areas is therefore indispensable in modern string teaching, both for teachers as well as for students, facilitating learning and practicing. First, this type of understanding can greatly facilitate (self) diagnosis of technical problems and inhibitions. Further, it allows teachers to explain the relevant control aspects of sound production in violin playing in a pedagogically efficient way, based on true facts rather than on beliefs and metaphors.

Studies like the ones presented in this thesis provide a deepened insight in the mechanics and acoustics of bow-string interaction, as well as in bow control and coordination of bowing parameters in playing. These results have direct relevance to string performance. Awareness of the playable parameter space, including the constraints and their relations to loudness and timbre (Papers I and II), can serve as a guide for a conscious, systematic exploration of the possibilities in tone production. This will be helpful in increasing the contrast in performance and optimize bowing strategies, depending on the musical requirements.

Regarding popular beliefs and idées fixes in string teaching the measurements presented in Paper IV give some thoughtful facts. In particular "straight bowing" and the use of the bowing angles in playing present some striking illustrations of how conflicting arguments based on facts and beliefs respectively, can give rise to long-lasting debates. For example, Hodgson's conclusions after having studied thousands of cyclegraphs that "In no case did the movement [of the bow] remain absolutely parallel with the bridge," was received sceptically.[1] Even at present day, many teachers and players are still convinced that "crooked bowing" always leads to a degradation of tone quality. This is, within certain limitations, not necessarily true, as pointed out by Trendelenburg [64], who made a distinction between skilled and unskilled skewness in bowing ("künstlerischen Schrägstrich" and "schülerhaften Schrägstrich," respectively): the sound quality does not necessarily have to suffer from skewness as such, as long as the player does not oppose the natural drift of the bow.

Another example of a strongly rooted popular belief is that bringing the bow closer to the bridge would in itself cause an increase in brightness of the tone. The true explanation is that the player makes a coordinated change in bow-bridge distance and bow force. A decrease in bow-bridge distance requires an increase in bow force in order to respect the limits in bow force. As a result the player actually moves diagonally in the Schelleng diagram.

The results in Paper IV showed that players generally utilize the bow angles skewness and tilt in a systematic way. The role of the bow angles skewness and tilt as secondary control parameters for controlling bow-bridge distance and the gradation of bow force is not always explicitly understood by players and teachers, and is therefore often neglected in teaching. Problems in tone control can often be related to wrong applications of the bowing angles. A higher awareness and explicit training of these aspects could therefore contribute to a more efficient development of basic bowing skills.

5.2 Enhanced feedback

According to Ericsson et al. [13] three requirements need to be fulfilled in a learning task in order to qualify as deliberate practice: (1) a well-defined task, (2) informative feedback, and (3) opportunities for repetition and correction of errors. Feedback can hereby be understood as a "process by which an environment returns to individuals a portion of the information in their response output necessary to compare their present strategy with a representation of an ideal strategy" [4]. It has been shown that technology can successfully enhance teaching of complex musical skills when implemented according to these criteria [31].

With regard to bowing, the second requirement (informative feedback) can be particularly difficult to meet, given the complexity and the many degrees of freedom involved. The visualizations of bowing gestures as described in Chapter 3 might provide an effective solution, allowing for specific feedback on various aspects of bowing.

[1] An anonymous critical review of Hodgson's book "Motion study and violin bowing" [27], questioning his conclusions, appeared in The Musical Times (Vol. 76, pp. 347–348, 1935).

As a means of feedback, the visualizations might be implemented in different ways. The visualization methods as such are not normative, as they just reflect the movements of the player without any inferences. Visualization can therefore in the first place be used as an explorative tool, providing an extra layer of information between the actions of the player and the resulting sound. This type of implementation is sometimes metaphorically considered as an “augmented mirror” [17, 42].

Going one step farther, it is possible to build in norms, for example based on thresholds. In this way, explicit knowledge can be implemented in the form of rule-based performance criteria. This can be particularly useful for teaching of basic musical skills [53], or in specific tasks with an obvious optimal strategy. Examples of such normative evaluations in violin bowing, based on similar techniques for the measurement of bowing gestures as in the current work, were developed in the i-Maestro project [34]. However, there are also some dangers involved in making assumptions of “ideal” strategies. Normative evaluation methods should therefore be implemented with great care, making sure that the performance criteria are based on correct assumptions, and not on false beliefs.

An alternative way to assess a student’s performance is by comparison with one or more reference performances, for example the teacher’s. Insight in the differences in bowing strategies related to the produced sound might provide an informative form of reflection. There are, however, some potential dangers. It is for example not directly obvious which features are useful to consider, and to determine the appropriate level of detail for comparison. In any case, an effective utilization requires a good understanding of the mechanics and acoustics of bowing by the teacher, which also needs to be conveyed to the student.

Another important trade-off involves real-time versus off-line presentation of the feedback. Providing feedback in real time gives the advantage that other modalities of perception are included in the feedback loop, particularly touch (haptic and vibro-tactile feedback) and proprioception (“muscle sense”), allowing for a richer and more direct interaction. However, the amount and level of detail in feedback which can be effectively taken into account in real time is limited, due to the cognitive load [60, 46, 62]. An off-line presentation might therefore be more advantageous to provide detailed analytic feedback.

5.3 Conclusions

The integration of scientific findings and technology in string teaching forms an interesting and challenging issue, and can only be successfully achieved by intensive multidisciplinary research and development. Novel ways of providing feedback and their pedagogical implementation need to be further explored and assessed in field studies, requiring an active participation of scientists, music teachers and students. An interesting example of such a multidisciplinary environment for the piano is the Piano Pedagogy Research Laboratory at the University of Ottawa.[2] Another interesting example is the singing voice, where it has been shown that knowledge of the physiology and acoustics of the singing voice can form an important contribution to teaching [61, 6, 7].

String playing builds on a tradition which has evolved over centuries, and has led to the development of advanced playing techniques and violin schools. Teachers and players possess an extensive, often intuitive knowledge and understanding of string playing. Nevertheless, science and technology can provide a useful complement to pedagogy when they relate to the players' world of experience.

[2] http://www.piano.uottawa.ca/

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