The Musician's Bowing Hand as a Bowing Parameter and Related Sound

Géza Horváth[1], Robert Mores[2]

[1] TU Wien, Institute of Applied Physics, Sensors and Ultrasonics Group, Email: gez.horvath@gmail.com

[2] Hochschule für Angewandte Wissenschaften Hamburg,

Fakultät DMI - Design, Medien, Information, Email: robert.mores@haw.de

Introduction

Current models of the bowed string consider three major bowing parameters. The normal force F_n acting on the string, bowing velocity v_b and β, the distance from the bridge relative to string length [1, 2, 3]. Researchers have constructed various machines to measure the response of stringed instruments with precise control of these parameters [4, 5, 6, 7]. Unfortunately we still lack in detailed understanding of what musicians do, to achieve a distinguished sound with a particular set of parameters.

Musicians are in a feedback loop with their instrument, adjusting their playing parameters on the fly to haptic and acoustic sensory cues. Teachers tell their students early on, not to press the bow onto the string. Instead, players should relax their arm and let arm and bow fall onto the string freely. A sensor measuring F_n cannot distinguish the former from the latter, and yet, any trained musician will immediatly recognize players with a strong bow grip trying to press the bow onto the string. While superior in accuracy and repeatability, bowing machines with high mechanical impedance electric motors remain similar to tight bow grip players, rather than an accomplished musician.

The hand is a good indicator of skilled bowing technique and many bowing exercises target the fingers and wrist in particular. It seems reasonable to include the player's hand in an improved model of bowing. As a starting point for this work, we think of the hand's role as some flexible coupling between the bow and the mass of the arm.

This work uses a precise bowing pendulum developed by Mores [8], where the frog of the bow was wrapped in foam to crudely imitate a relaxed bowing hand and some damping properties. An analysis of steady Helmholtz Motion at $\beta \approx 1/14$, across the normal playing parameter space of F_n, v_b and comparison of the foam-wrapped bow with a more rigid, leather-cladded bow mounting (damped and undamped bow mounting), shows measurable and audible differences in tonal quality.

Methods

Bowing pendulum. A cello's open G string was bowed and measured with a precise bowing pendulum (Figure 1) and measuring instruments as described in [8]. Key features include:

- Mass $M_1 = 3\,\mathrm{kg}$, emulating the player's arm, moves horizontally.
- Bow force F_n is precisely adjustable through the length of screws at b and c.
- Mass M_2 and its damping device with low mechanical impedance, determine the bowing speed by reacting to the friction force. This is a much closer approximation of a musician's bowing, than a high mechanical impedance electric motor.
- Sensors S_1, S_2 and S_3 measure the playing parameters v_b, friction force and F_n.
- The pendulum's bowing direction is self-stabilising, maintaining a constant bow hair to bridge distance, with less than 0.5 mm variation.

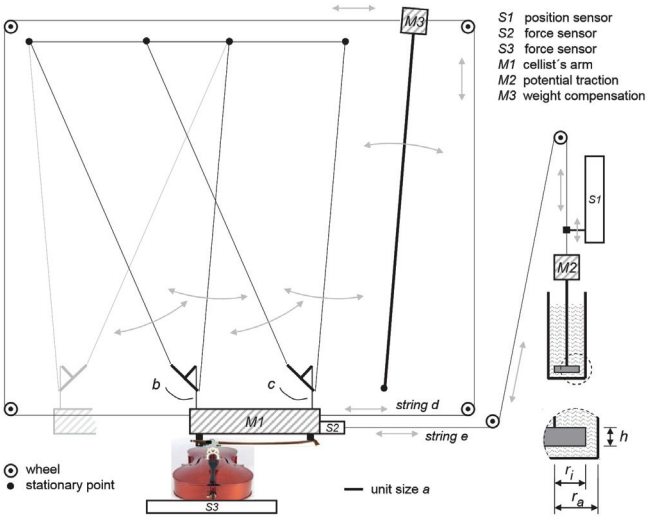

Figure 1: Bowing pendulum schematics. Due to excentric mounting brackets, mass M_1 moves horizontally. With a carefully adjusted counter mass M_3 and a disconnected string e, M_1 stays at rest at every horizontal position.

Cello and Bow. Experiments were conducted on a "teacher level" cello, crafted by *Laberte-Humbert Frères, Mirecourt*, in 1926. And a German bow by *Emil Werner*, reasonably coated with rosin, as a musician would during normal play. The string measured, was a tungsten wound *Spirocore* G string by *Thomastik-Infeld*, Vienna.

Data capturing. Each bow stroke was captured with two force sensors (F_n, friction force), a horizontal bow position sensor, a microphone placed 1 m from the bridge and a piezo sensor attached to the bridge. Bowing velocity and acceleration are derived from the horizontal bow position sensor.

Despite careful adjustment of the counter pendulum with

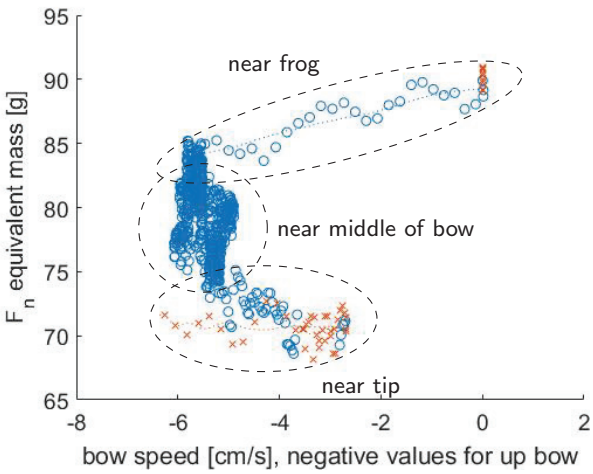

Figure 2: An example of a single stroke. Each marker corresponds to a signal averaged over 10 ms, blue circles indicate Helmholtz motion, red crosses non-Helmholtz motion. Recorded with $\beta \approx 1/14$. There is an onset with non-Helmholtz motion and quickly varying bow speed near the tip. Steady Helmholtz motion with slight variation in F_n and v_b near the middle of the bow. Bow comes to rest at the frog.

mass M_3, the bowing pendulum's damping forces are not entirely uniform across all bow positions. Also a tradeoff between the tension in string d and the friction forces at the wheels is necessary. Together with the influence of the tension in the bow hair and stick, this leads to slight variations in F_n and v_b across the horizontal pendulum positions.

Post processing. Figure 2 shows typical data for F_n and v_b recorded from a single up-bow stroke. A fundamental frequency estimating YIN-Algorithm [9] performed classification of Helmholtz and non-Helmholtz motion from the bridge-mounted piezo's signal.

As this is an analysis of steady Helmholtz motion, microphone recorded sound samples should preferrably show as little variation in F_n and v_b as possible, while data from transients near tip and frog should be excluded. Non-Helmholtz motion data tuples were discarded, while the remaining data tuples were grouped into segments, 0.34 s in length with 75 % overlap. A classic short-time Fourier transform on the microphone signal, with a Blackman window 16384 samples in length (0.34 s at 48 kHz), prepares spectral analysis. Segments whose F_n and v_b averages have standard deviations $\sigma(F_n) > 3\,\mathrm{g}$ or $\sigma(v_b) > 0.3\,\mathrm{cm\,s^{-1}}$ are discarded. To summarize, this leaves us with many steady Helmholtz motion 0.34 s sound samples, their associated frequency spectra and their respective average values of F_n and v_b with little variation.

Results and Discussion

To extract the possible impact of a relaxed bowing hand, this research attempted to cover as wide a range of normal playing parameters (F_n,v_b,β), where steady Helmholtz motion occurs, as possible. Comparing a

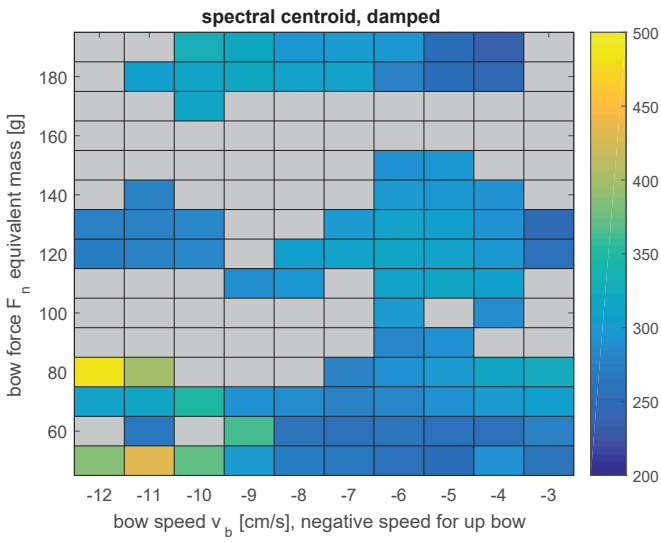

Figure 3: Recorded sound mean frequency pseudo colour plot at $\beta \approx 1/14$. Foam-wrapped (damped) bow mounting, emulating a relaxed bowing hand. Boxes are grey where there is no data available.

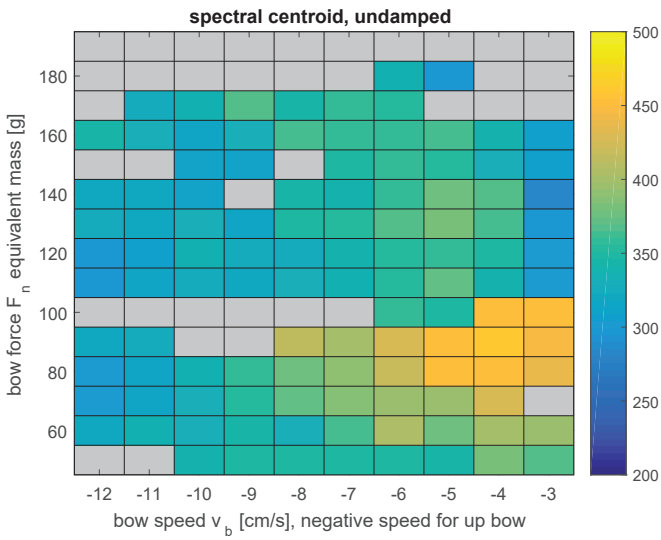

Figure 4: As in Figure 3, but with leather-cladded, rigid (undamped) bow mounting.

damped and undamped bow mounting, exhibits clearly audible differences. Visualised to some extent with the spectral centroid as a simple metric. Results of 45 damped and 60 undamped upstrokes at $\beta \approx 1/14$ are presented here. Alas, due to measuring time constraints, an exhaustive search of the parameter space is not possible.

Spectral centroid analysis. Figures 3 and 4 show spectral centroid pseudo colour plots, analysed from sound recorded with a microphone placed 1 m from the bridge. Figure 5 depicts the difference between both cases. Each rectangle represents the average over all sound samples located in its particular area of the parameter space. Grey rectangles indicate no available steady Helmholtz motion data. The fundamental frequency of the open G string is at 98 Hz.

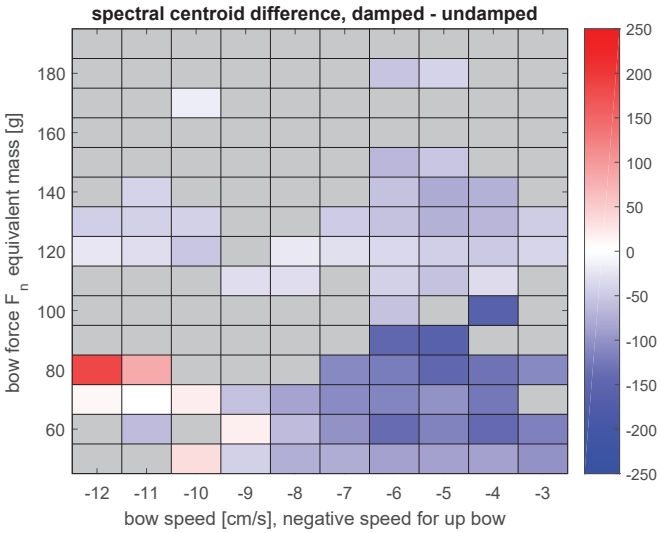

Figure 5: Recorded sound spectral centroid difference between a damped and undamped bow mounting. Note the most significant differences near $F_n = 80\,\mathrm{g}$, the bow's own mass.

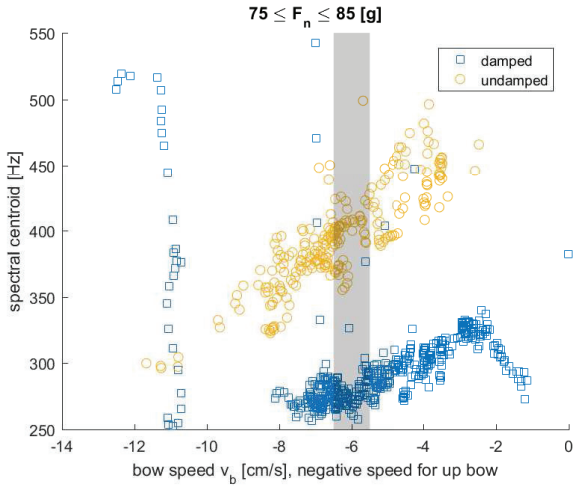

Figure 6: Spectral centroid of all sound samples in the F_n range from 75 to 85 g. Each marker represents a 0.34 s sound sample of steady Helmholtz motion. The average frequency spectrum in Figure 7, is calculated from all samples in the shaded area.

In both cases, damped and undamped, there is a trend of a spectral centroid maximum at lower v_b, gradually shifted to higher v_b with increasing F_n. The largest maximum occurs with an undamped bow mounting at a low bow speed of $-4\,\mathrm{cm\,s^{-1}}$ and low bow force equivalent mass of 85 g. At $\beta \approx 1/14$, a foam wrapped bow mounting generally lowers the spectral centroid, with the exception of high bow speeds and low bow force.

Remarkably, the most significant differences occur right around a bow force corresponding to the bow's own mass of 80 g. This would be a playing state, where the musician holds the weight of his own arm and grips the bow as lightly as possible. For a closer investigation, Figure 6 presents the spectral centroid of all sound samples in the F_n range from 75 to 85 g. The separation in spectral centroid and different dependence on v_b between the damped and undamped case, is immediatly apparent. The damped bow mounting exhibits a few outliers with high spectral centroid.

The outliers at high v_b are attributed to two particular bow strokes and are associated with a flagolet-like sound. This can be explained as a result of the limited capability of the fundamental frequency estimating YIN algorithm to classify Helmholtz motion. A definitive classification would require a look at the precise translational displacement at the bowing contact surface, to reliably identify even slight double slipping. These outliers occur near the minimum bow force, most likely right at the boundary, where differential slipping crosses into the double slipping non-Helmholtz motion regime. The undamped bow mounting shows no such outliers. Possibly there is a bow mounting dependent effect at play, related to differential slipping, requiring further investigation.

To illustrate the changing sound more precisely, Figure 7 depicts the average power spectral density envelope of all sound samples in the shaded are of Figure 6. The spectral centroid is mostly influenced by the first five to ten harmonics. Most of clearly audible differences occur within the first four harmonics. The damped second and third harmonic are lowered by more than 10 dB, while the fundamental frequency is slightly more powerful than with an undamped bow mounting. Furthermore, the undamped sound signal consistenly contains more power, it is audibly louder. This indicates, that some energy is used for bow stick vibrations, an effect musicians can feel while bowing.

These results clearly show, that two bow strokes with identical playing parameters F_n, v_b and β can produce, during sustained Helmholtz motion, significantly audible sound differences, as supported by spectral analysis. An improved bowing model requires at least one additional parameter, describing the coupling of the bow stick to its driving mass representing the player's arm.

Conclusions and Outlook

Understanding the playability of bowed instruments is a key and yet somewhat elusive goal in musical acoustics research. Musicians spend a lifetime mastering bow control, with the hand and fingers playing a major role. The experimental data of this work, suggests that string players can quantifiably control their sound's harmonic content by relaxing and tightening their bow grip. The effect is greatest, when very little arm weight acts on the bow stick and the bow's own weight force acts as the bow force F_n. While very difficult to master, among skillful musicians, this style is considered good bowing technique in a number of musical situations, *piano dolce* in particular.

An easy way to update theoretical models of the bowed string might be to include some coupling of the bow stick to the arm, e.g. a spring and dashpot. It is important to remember, that the bowing pendulum does not force a

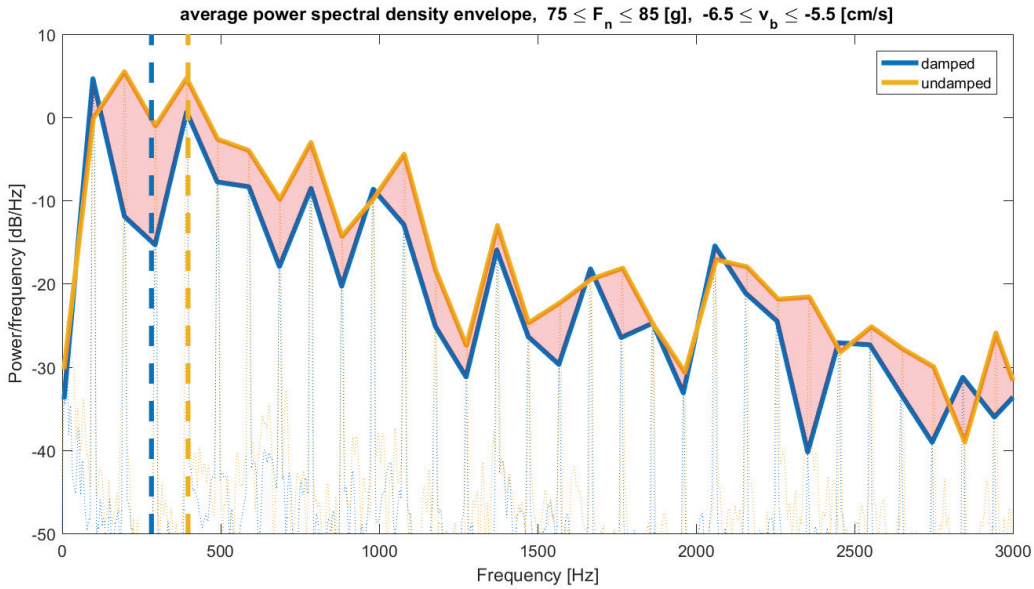

Figure 7: Average power spectral density envelope of all sound samples in the shaded are of Figure 6. The vertical dashed lines indicate the respective average spectral centroid and the red shaded area shows the difference between the damped and undamped case.

particular bow speed v_b, instead the system self adjusts according to the bow and friction forces. Just as musicians do not force a bow speed without feedback from the contact point. This was implemented in string simulations by Desvages and Bilbao [10].

A number of questions are open to further research with the bowing pendulum setup at hand. Particularly an extension of previous work by Mores on maximum [11] and minimum [12] bow force may lead to new insights on bowing hand influence. Investigating starting transients may prove to be even more insightful, as the bow stroke's attack, a major factor in playability, is strongly influenced by the bowing hand. This would require significant adaptations to the existing bowing pendulum, to reliably reproduce transients. Furthermore, the physics of the vibrational behaviour of the bow stick and hair in concert with the strings Helmholtz motion and the instruments resonances, are a possibly fruitful target for further research.

References

[1] J. C. Schelleng, The bowed string and the player, The Journal of the Acoustical Society of America 53 (1) (1973) 26–41. doi:10.1121/1.1913322.

[2] L. Cremer, Physik der Geige, S. Hirzel Verlag Stuttgart, 1981.

[3] J. Woodhouse, P. M. Galluzzo, The bowed string as we know it today, Acta Acustica united with Acustica 90 (4) (2004) 579–589.

[4] A. Askenfelt, Measurement of the bowing parameters in violin playing. ii: Bowï¿½bridge distance, dynamic range, and limits of bow force, The Journal of the Acoustical Society of America 86 (2) (1989) 503–516. doi:10.1121/1.398230.

[5] R. T. Schumacher, Measurements of some parameters of bowing including through reported In at ICA-12, October 96 (4) (1994) 1985–1998. doi:10.1121/1.410142.

[6] W. Vogl, Bogenstreichmaschine, Master thesis, Technische Universität Wien (1998).

[7] P. M. Galluzzo, J. Woodhouse, High-performance bowing machine tests of bowed-string transients, Acta Acustica united with Acustica 100 (1) (2014) 139–153. doi:10.3813/AAA.918694.

[8] R. Mores, Precise Cello Bowing Pendulum, in: Proc. of the 3rd Vienna Talk on Music Acoustics, 2015, pp. 160–161.

[9] A. de Cheveignï¿½, H. Kawahara, Yin, a fundamental frequency estimator for speech and music, The Journal of the Acoustical Society of America 111 (4) (2002) 1917–1930. doi:10.1121/1.1458024.

[10] C. Desvages, S. Bilbao, Two-polarisation physical model of bowed strings with nonlinear contact and friction forces, and application to gesture-based sound synthesis, Applied Sciences 6 (5) (2016) 1–32. doi:10.3390/app6050135.

[11] R. Mores, Maximum bow force revisited, The Journal of the Acoustical Society of America 140 (2) (2016) 1162–1171. doi:10.1121/1.4960626.

[12] R. Mores, Minimum bow force measured with a high-precision bowing pendulum, The Journal of the Acoustical Society of America 141 (5) (2017) 3873–3873. doi:10.1121/1.4988659.