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REAL-TIME BOWING PARAMETER SENSING METHODS FOR ARTICULATED BOW-STRING PHYSICAL MODELLING

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ABSTRACT

This paper presents bowing parameter estimation techniques developed specifically for real-time control of bowed-string physical models. By placing the sensors on the resonator instead of on the bow, the ability to seamlessly employ traditional bowing techniques is preserved. The sensing methods presented here are part of a larger project that aims to design and develop stage-ready virtual-acoustic bowed-string instruments.

The proposed approach utilizes load cells mounted beneath the string supports to sense bowing force and position in real time. An automatic offset adjustment algorithm is implemented to counter sensor drift, which enhances accuracy and long-term reliability. A Kalman-like feedback loop that implements level-dependent adaption of the bowing position was designed to avoid noisy estimates at small bowing forces. Experimental validation shows that this approach provides robust, usable estimates of bowing force and position with minimal calibration.

Bow velocity is inferred from string velocity data captured by an electromagnetic pickup system, utilising an approximation of the short-time probability density function. Preliminary bow velocity estimation results were obtained with an offline algorithm, showing promising capability for real-time application.

Keywords: Instrument Design, Physical Modelling, Sensor-Based Interface Design, Bowing Parameter Sensing

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1. INTRODUCTION

Among sound synthesis methodologies, physical modelling stands out for its distinctive advantage: its control parameters bear a direct physical correspondence to those of the acoustic instrument being simulated [1]. Recent advances in bow-string interaction modelling have yielded significant progress, including improved alignment with measurements [2, 3], guaranteed passivity [4, 5], and enhanced computational efficiency [6]. Although the accurate modelling of frictional dynamics at the bow-string interface remains an open challenge (see, e.g., [7]), these ongoing developments are steadily advancing toward real-time implementations that faithfully reproduce the salient acoustic characteristics of bowed-string interaction. Realising the full potential of such models, however, also requires the development of robust, real-time estimation techniques for bowing control parameters.

The excitation of a bowed-string physical model requires the specification of several key control parameters. This study concentrates on three primary bowing parameters: bowing force, bowing position, and bow velocity. Bowing force denotes the normal force applied by the bow at the point of contact with the string; bowing position specifies the location along the string where this contact occurs; and bow velocity corresponds to the relative tangential speed of the bow perpendicular to the string. Together, these parameters capture the dynamics at the bow-string interface, where frictional interaction gives rise to sound production. Although secondary factors such as bow tilt and inclination angle can influence the character of the interaction, the aforementioned primary parameters are generally sufficient to drive physically based bowed-string models with high fidelity [8].

Bowing parameter estimation has been the subject of

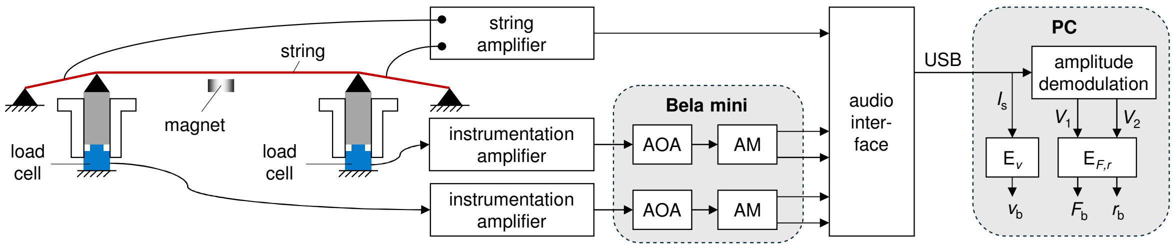

Figure 1: Bowing parameter estimation apparatus - system schematic.

extensive research for the past 40 years, driven by different motivations across disciplines. Researchers studying musical acoustics and gesture analysis aim to understand and quantify the mechanics of bowing, often prioritizing accuracy to capture the nuances of the bow-string interaction [3, 9–11]. In these areas of study, bowing parameter estimation is usually performed offline to achieve greater accuracy [3, 10, 11]. In the realm of pedagogy, bowing parameter estimation is pursued to enhance learning and teaching methods for string players. By analysing bowing techniques in real-time, educators and students can receive immediate feedback, fostering more effective practice and skill development [12–14]. Accuracy remains important in this context, but the primary concern is ensuring that the system is relatively non-intrusive and that the instrument retains familiarity with the traditional acoustic instrument being learned. The same holds for studies focused on instrument innovation, with additional emphasis on developing systems that are robust and capable of functioning in diverse performance environments. While precision is important, these systems do not require the same level of accuracy as those used in musical acoustics or gestural studies. They must be designed to accommodate different playing styles and instrument variations without requiring extensive calibration or modifications to the bow, allowing musicians to leverage their existing bowing techniques seamlessly [15, 16]. This paper is concerned with the latter research area, and as such, the methodology presented here reflects the priorities of developing a stage-ready bowed-string physical model interface.

2. METHODOLOGY

2.1 Selected Sensing Systems

Figure 1 provides an overview of the sensing system for bowing parameter estimation presented in this paper, illustrating the bowed-string interface and how the sensors are arranged, as well as the signal processing and routing.

In prior work, Lampis et al. [11] employed two load cells positioned beneath one of the string boundaries to estimate both the normal and transverse components of bowing force in controlled musical acoustics experiments. Building on this approach, we introduce a modified configuration in which a single load cell is placed beneath each of the string's boundaries (Figure 1). This arrangement enables simultaneous estimation of the normal bowing force and inference of the bowing position. Each load cell is mechanically coupled to its respective string boundary via a cylindrical shaft guided by a linear ball bushing, which constrains motion to a single plane – parallel to the shaft and perpendicular to the string. This mechanical design ensures accurate transmission of the normal component of bowing force while maintaining consistent coupling between the string and the sensing elements. The full assembly is mounted onto a 20×20, 55 cm-long aluminium profile using custom-designed, 3D-printed fixtures (Figure 6). While the current setup does not capture the transverse component of the bowing force – potentially leading to a slight underestimation when the bow is applied at an angle – this trade-off enhances structural rigidity and ensures robust sensor-string coupling, with the introduced difference being minor enough for musicians to adapt to comfortably. Each load cell operates on the Wheatstone bridge principle, producing millivolt-range output signals proportional to the applied force, which are subsequently amplified using AD620 instrumentation amplifiers.

In contrast to many existing methods for bowing parameter estimation, our approach eliminates the need for sensors to be mounted directly on the bow, thereby preserving the natural feel and freedom of motion familiar to string players. This design choice ensures that performance remains as unencumbered and authentic as possible. Although alternative bridge-force sensors – such as piezoelectric discs – have been employed in prior studies, their AC-coupled nature renders them ineffective for capturing low-frequency or quasi-static variations in bowing force. Load cells, by contrast, provide DC-coupled measurements, enabling the accurate detection of both rapid transients and slow, gradual changes in applied force [11].

For bow velocity estimation, we propose a sensing methodology inspired by the work of Pardue et al. [16], which employs an electromagnetic pickup system to measure string velocity. This method again offers a non-intrusive means of acquiring bowing data without requiring direct modification of the bow. A neodymium magnet is positioned beneath the string at a fixed location, with one end of the string connected to the analogue input of a low-noise string amplifier, and the other end of the string connected to ground. In accordance with Lorentz force principles, the induced current in the string is directly proportional to its velocity at the location of the magnet. This string velocity information can then be used to infer the bow velocity at the point on the string directly above the magnet (see Section 2.5).

Alternatives to the above sensing techniques include the indirect estimation of parameters from AC-coupled sensor signals, which for example has been successfully applied to the estimation of plucking position in plucked-string instruments [17–21] and to tracking bowing parameters [15, 16]. However, all these methods share the disadvantage of relying on a particular structure in the waveform or spectrum, which may not be generally present under playing conditions. For estimating bowing parameters, machine learning techniques have been applied successfully for a specific set of notes [22], but with no follow-ups demonstrating more general estimation robustness covering a wide range of oscillation regimes.

Also worth noting here is that fully external sensing solutions such as camera-based motion tracking systems [8] offer high-resolution data in controlled laboratory settings, but their reliance on line-of-sight, controlled lighting, and computational overhead make them less suitable for real-time applications and live performance contexts – the target scenarios for our system.

Despite the advantages offered by the chosen sensing methodologies, several challenges must be addressed to ensure reliable and accurate parameter estimation. Although load cells are capable of capturing both rapid transients and slow variations in force, they are susceptible to signal drift over time, potentially compromising long-term measurement stability. Moreover, fluctuations in string tension and shifts in the string's equilibrium position introduce variability into the measured force signals, thereby affecting the accuracy of both bowing force and position estimations. Potential non-linearities in the load cell response further complicate matters and necessitate rigorous calibration procedures to ensure measurement fidelity.

The signal quality is also constrained by the limitations of the amplification stage. The employed load cell amplifiers exhibit a relatively poor signal-to-noise ratio, particularly at small force levels, where reliable data acquisition becomes more difficult. Electromagnetic pickups are particularly vulnerable to noise and interference from external electromagnetic sources. Mitigation strategies – such as the low-noise string amplifier developed by Pardue et al. [12] – have proven effective in reducing such interference, and as such has been implemented in the system presented here.

A further challenge arises due to the semi-chaotic nature of bowed-string interaction – particularly under expressive or unsteady bowing – which complicates the use of typical indirect sensing methods. This unpredictability demands a system that is robust across a wide range of performance conditions.

To address these challenges, a series of compensatory strategies have been implemented, detailed in the following sections.

2.2 Automatic Offset Adjustment

The load cell output, $V(n)$, represents the instantaneous voltage reading at time $t = n\Delta_t$, reflecting the combined effect of all forces acting on the system, including string tension and any external load. During startup, a calibration period occurs in which no external forces are applied, and the offset voltage $V_0(n)$ is calculated as an average over $M = 4410$ samples. This value serves as the baseline for adjusting the estimated applied force by subtracting $V_0(n)$ from $V(n)$. Ideally, $V_0(n)$ would remain constant; however, in practice, $V(n)$ does not always return to the same value upon bow release due to sensor drift, changes in string tension, and changes to the string's equilibrium state.

To counteract this artifact, an Automatic Offset Adjustment (AOA) algorithm is implemented. This Kalman-filter-like algorithm, illustrated in Figure 2, employs a feedback loop to update the offset voltage during periods of inactivity. Inactivity is defined as periods where the variance of both load cells falls below a threshold – set at 5% above a calibration-period variance reading taken

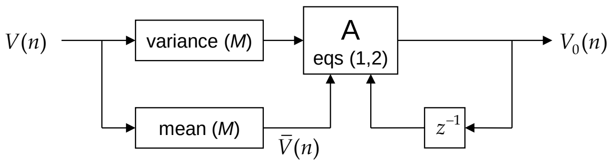

Figure 2: Schematic diagram of the automatic offset adjustment (AOA) algorithm. The variance and mean are calculated over M samples.

when the system is left undisturbed.

During these periods of inactivity, the following adaptation calculation is performed:

$$V_0(n) = V_0(n-1) + \Delta_V(n)\, \underbrace{g\, \Delta_t\, W(\Delta_V(n))}_{\gamma(n)}, \quad (1)$$

where:

$$\Delta_V(n) = \bar{V}(n) - V_0(n-1) \quad (2)$$

The term $\gamma(n)$ represents the effective adaptation rate at each step, and is composed of the scaling factor g – which statically determines the overall responsiveness of the adaptation, the time step Δ_t – ensuring proper temporal scaling, and the weight function $W(\Delta_V(n))$ – which dynamically modulates the adaptation rate based on the magnitude of $\Delta_V(n)$. This weight function is defined as:

$$W(\Delta_V(n)) = e^{-\psi\,|\Delta_V(n)|}, \quad (3)$$

where ψ is a tunable weight control factor. This formulation ensures that adaptation occurs more quickly for small deviations and more gradually for large deviations, preventing instability while still allowing for long-term drift correction.

2.3 Signal Routing

As illustrated in Figure 1, a Bela Mini is used to sample the amplified load cell signals at audio rate, maintaining high temporal resolution. To preserve this fidelity, the signals are transmitted at audio rate to a laptop via the Bela mini's audio outputs. This method leverages the Bela mini's low-latency audio path rather than relying on USB communication. Since many standard audio interfaces AC-couple their inputs – effectively filtering out DC components – an amplitude modulation (AM) scheme is used to encode the signals within the audio band. To mitigate phase misalignment issues that can arise between modulation and demodulation stages, each load cell signal modulates two carrier signals in quadrature. This approach enables robust demodulation in Max/MSP, ensuring accurate signal reconstruction for real-time bowing parameter estimation.

2.4 Bowing Force and Bowing Position Estimation

Equations for bowing force and bow position estimation are derived from heavily simplified acoustics of the string-assuming constant string tension, small string vibration, ideal string behaviour, and simplified boundary conditions. Under these assumptions, the force exerted on the string by the bow at the point of contact, $\tilde{F}_\mathrm{b}(n)$, is equal to the sum of the forces exerted by the string on the string's fixed boundaries, $\tilde{F}_1(n)$ and $\tilde{F}_2(n)$:

$$\tilde{F}_\mathrm{b}(n) = \tilde{F}_1(n) + \tilde{F}_2(n), \quad (4)$$

and these forces are distributed in such a way that:

$$\hat{r}_\mathrm{b}(n) = \frac{x_\mathrm{b}(n)}{L} = \frac{\tilde{F}_2(n)}{\tilde{F}_\mathrm{b}(n)}, \quad (5)$$

where $r_\mathrm{b}(n)$ is the relative bowing position, $x_\mathrm{b}(n)$ is the distance from the left string boundary to the bowing position, and L is the distance from one string boundary to the other-the effective length of the string.

Simulations were used to verify that these equations remain valid in the presence of stiffness and with different boundary conditions. However, it is less straightforward to predict whether they remain accurate under larger bowing forces, which induce large string deflections and significant increases in tension. In such cases, the resulting string slopes at the supports mean that the applied force is no longer purely parallel to the shafts, and thus is not fully captured by the load cells.

More importantly, the reliability of the estimates resulting from applying equation (5) deteriorates for small bowing forces, in which case the sensitivity to noise becomes extremely high, leading to large estimation errors. In practice, this can result in significant drift from the true position, occasionally producing values outside the expected range. To address these challenges, a feedback loop-similar in structure to the AOA algorithm is introduced. This adaptive mechanism improves stability when bowing forces are small and ensures that, in the absence of force input, the system retains the last reliable position estimate.

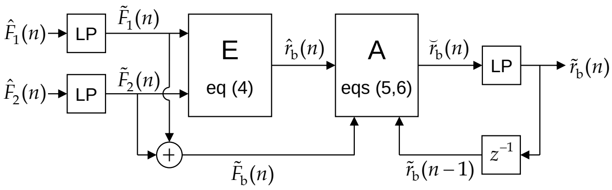

Figure 3: Bowing force and position estimation block diagram.

The following adaptation calculation is performed within the adaptation block A shown in Figure 3:

$$\breve{r}_{\mathrm{b}}(n) = \tilde{r}_{\mathrm{b}}(n-1) + \Delta_r(n)\, \underbrace{g\, \Delta_t\, W(\tilde{F}_{\mathrm{b}}(n))}_{\gamma(n)}, \quad (6)$$

where,

$$\Delta_r(n) = \hat{r}_{\mathrm{b}}(n) - \tilde{r}_{\mathrm{b}}(n-1). \quad (7)$$

Here the term $\gamma(n)$ once again represents the effective adaptation rate at each step, only in this case the weight function $W(\tilde{F}_{\mathrm{b}}(n))$ dynamically modulates the adaptation rate based on the magnitude of $\tilde{F}_{\mathrm{b}}(n)$. The weight function is defined as:

$$W(\tilde{F}_{\mathrm{b}}(n)) = 1 - e^{-\psi\, \tilde{F}_{\mathrm{b}}(n)^2}, \quad (8)$$

where ψ is again a tunable weight control factor. This formulation ensures that adaptation occurs more quickly for large bowing forces and more gradually for small bowing forces, preventing wild fluctuation at small bowing forces where the noise can begin to affect the accuracy of the bowing position estimation.

2.5 Bow Velocity Estimation

The characteristic sound of a bowed string arises from a periodic cycle of ‘sticking’ and ‘slipping.’ The bow hairs grip the string momentarily, pulling it in one direction until friction is overcome, causing the string to slip back – only to stick again. This repeating motion, known as the Helmholtz motion, produces the characteristic sound of a bowed string [23]. Even when a periodic Helmholtz motion is not established, the bowed string’s sound still results from instances of sticking and slipping. Our envisaged bow velocity estimation methodology relies upon the fact that the string velocity and the bow velocity are equal to each other during periods in which the bow hairs stick to the string. By measuring the string velocity, the bow velocity can be extrapolated by way of a probability density function – under the assumption that the sticking velocity is the dominant velocity in the signal, while slipping plays out over a more distributed range of velocities.

3. EXPERIMENTAL PROCEDURES AND RESULTS

A series of experiments were conducted to evaluate the efficacy of the proposed bowing parameter estimation methods.

3.1 Calibration and Validation with Static Forces

A bench experiment was devised to record load cell signals for various forces and positions along a 20cm string. A series of weights were suspended from the string using a 3D printed cradle to apply known static forces. The cradle was suspended in 5 known locations along the length of the string, limited to the middle 40% of the string due to the physical dimensions of the cradle and the strings supports.

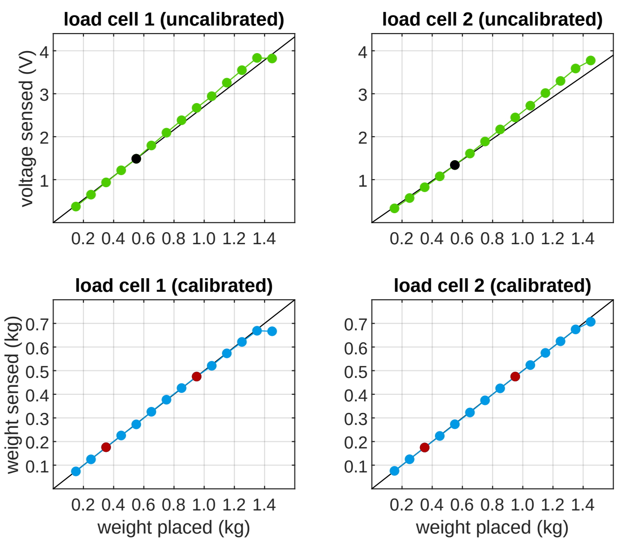

Figure 4: Load cell signals before and after logarithmic scaling calibration procedure. Black dots represent an arbitrary reference reading through which the linear black line is drawn. Red dots represent the calibration reference weights.

The load cell signals were recorded post-demodulation in Max/MSP. They were then rescaled to match the voltage read by the Bela mini, and a calibration scheme was devised to estimate the applied weight, as illustrated in Figure 4.

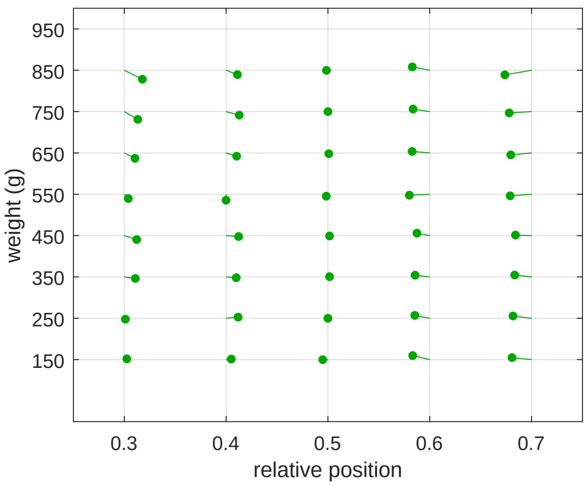

Figure 5: Estimation results for a known set of static weights and positions. Green dots show how estimation compares to nominal values at the grid line intersections.

Figure 6: Monochord in cello orientation.

Two reference weights are selected at the midpoint of the string, plotted as red points, upon which to scale the data logarithmically to correct for the slight nonlinearity observed in the uncalibrated data. In accordance with the project's overall goal of musical instrument implementation, the calibration procedure is intended to be practical and time efficient, so using as few calibration weights as possible is preferred. In this particular arrangement, we observe the beginning of saturation occurring in the upper region of the plot around 650g for load cell 1, or roughly 6.5N. As these plots represent the readings at the midpoint of the string, we can expect to measure a maximum of 6.5N at all points along the string, while larger forces can be measured the closer one bows to the centre of the string, up to 13N at the centre – double the maximum bowing forces measurable at the ends of the string.

The position estimation data is then calculated using equation (5) with the calibrated force data. Figure 5 illustrates the general accuracy of the bowing force and position estimation across a range of the string. As observed in Figure 5, the estimation errors can be largely described by an inward trend indicating lower accuracy for positions nearer the string ends. This can be attributed to the simplifications underlying equations (4) and (5), as discussed in section 2.4. While our calibration process ensures precise results at the center of the string, part of the total force remains unaccounted for when weights are hung away from the center, as variations in slope angles affect the proportion of the total force captured by the load cell. Consequently, the position estimation is less accurate when applying a load nearer to the string ends.

3.2 Bowing Experiment

In order to observe how the proposed estimation methods perform in the context of bowing practices, the third author, who is a cellist, bowed the experimental rig in an upright angled cello orientation using an *NS Design* electric cello stand, as shown in Figure 6.

Four short passages were recorded, where the cellist used four different cello bow strokes. As illustrated in Figure 7, the signal from a contact microphone placed on the monochord (green), bowing force estimation (blue), and bowing position estimation (red) were recorded in real-time. In these examples, the bowing force peaks at around 4N during *martelé* playing, well away from our saturation range of 6.5N, indicating that this will be enough headroom to capture most typical bowing techniques. We can also observe the slight inertia in bowing position estimation – for example, at around 7.5 seconds – when force is applied to the string and the bowing position estimation takes a few milliseconds to reach the new bowing position.

3.3 Preliminary Bow Velocity Sensing Results

In order to observe and validate the dominance of the sticking velocity in the string velocity signal, string velocity measurements were taken at a fixed position along the string using the apparatus detailed in Section 2.1 and illustrated in Figure 1. These measurements, as shown in Figure 8, illustrate that even when bowing away from the location of the magnet, the sticking velocity – and therefore the bowing velocity – can be estimated by finding the

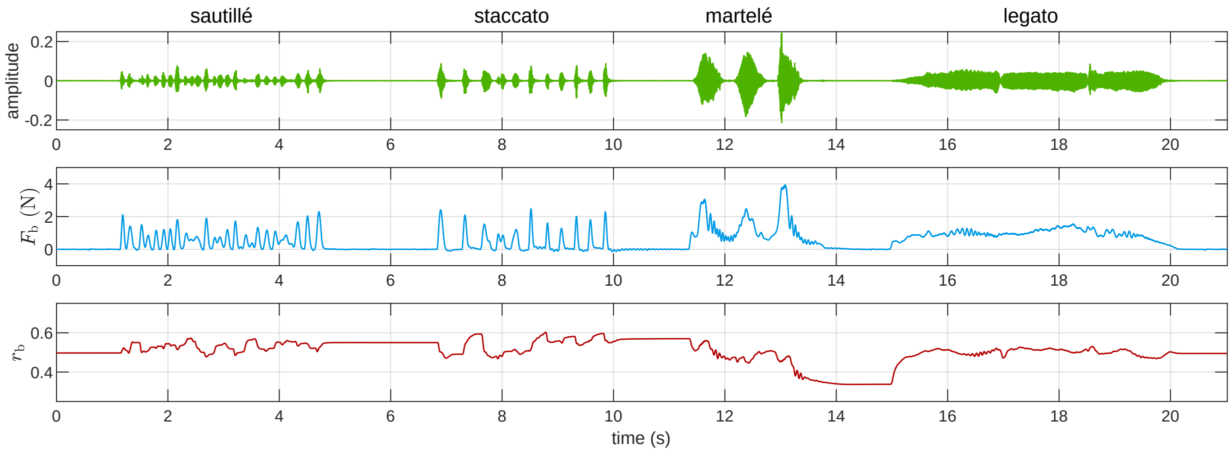

Figure 7: Real-time bowing force and bow-bridge distance estimation for four short cello bowing techniques performed on experimental rig.

peak of a probability density function. These preliminary results were calculated offline.

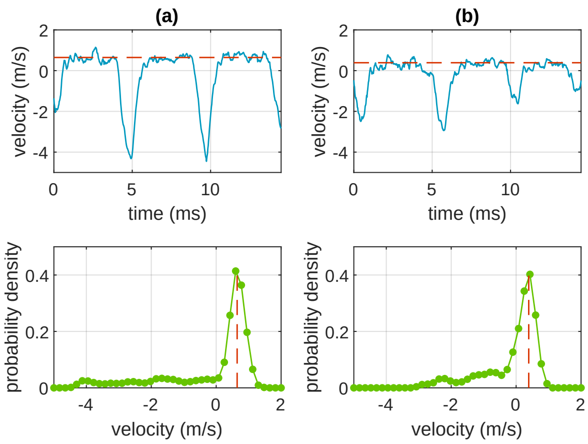

Figure 8: Bow velocity estimation - preliminary offline results. (a) - bowing above the magnet. (b) - bowing 2cm away from the magnet. Dashed red lines represent the estimated bow velocity.

4. CONCLUSION

This study contributes to the ongoing development of a sensing methodology for bowed-string instruments that avoids the limitations of on-bow sensing by positioning all sensors at the string interface. By eliminating the need for sensors on the bow itself, this approach preserves natural bowing technique and ergonomics – key considerations for integration into robust, stage-ready digital musical instruments with minimal calibration overhead. Our results demonstrate that load cells, when appropriately configured, can reliably estimate bowing force and position in real time within a compact, instrument-compatible design.

Experimental results indicate that accurate bowing force estimation can be achieved using only two calibration weights, offering a practical and time-efficient setup. Bowing position can be accurately tracked in the region around the string midpoint, with small errors arising for bowing nearer to the string ends. Preliminary investigations into bow velocity estimation via the string's sticking velocity – extracted using a probability density function – show promising potential.

Future work will focus on improving the calibration procedure to enhance relative bowing position estimation while preserving short setup times. Robust real-time estimation of the bow velocity for a wide range of bow-string interaction regimes remains an open challenge. Success in these areas would enable full real-time control of bowed-string physical models, unlocking new possibilities for expressive digital instrument design and performance-oriented applications in computer music.

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