Proceedings of the 2002 Conference on New Instruments for Musical Expression (NIME-02), Dublin, Ireland, May 24-26, 2002

The Hyperbow Controller: Real-Time Dynamics Measurement of Violin Performance

Diana Young
M.I.T. Media Lab
20 Ames St.
Cambridge, MA 01239
U.S.A.
diana@media.mit.edu

ABSTRACT

In this paper, the design and construction of a new violin interface, the *Hyperbow*, is discussed. The motivation driving the research of this instrument was the desire to create a violin bow capable of measuring the most intricate aspects of violin technique–the subtle elements of physical gesture that immediately and directly impact the sound of the instrument while playing. In order to provide this insight into the subtleties of bow articulation, a sensing system has been integrated into a commercial carbon fiber bow to measure changes in position, acceleration, and the downward and lateral strains of the bow stick. The sensors were fashioned using an electromagnetic field sensing technique, commercial MEMS accelerometers, and foil strain gauges. The measurement techniques used in this work were found to be quite sensitive and yielded sensors that were easily controllable by a player using traditional right hand bowing technique.

Keywords

Hyperbow, Hyperviolin, Hyperinstrument, violin, bow, position sensor, accelerometer, strain sensor

INTRODUCTION

The violin is widely considered to be one of the most compelling and complicated musical instruments, as its range and richness of tone and capacity for nuance are unsurpassed. Of course, the violin interface also presents many great challenges to a musician. Traditional violin repertoire and technique require extremely subtle articulations and sophisticated coordination of gestures, most of which are not easily understood by non-players. Because of the complexity and range of control, as well as the possibility of illuminating such aspects of musicality for audiences, the violin is a wonderful source of inspiration for new music controllers and playing techniques.

The question of how to develop a new musical interface for an experienced bowed string player in order to create new methods of musical expression was addressed in the *Hypercello* and subsequent *Hyperinstruments* work at the M.I.T. Media Lab [6, 5, 3, 4]. Later, projects such as the *Bossa* (Princeton) were developed [7]. These endeavors used measurements such as bow position, pressure on the bow stick, and acceleration of the bow to alter the sound produced by the bowed string.

The *Hyperbow* project discussed in this paper is a music controller similar to those mentioned above, as the sensing system on which the controller is based includes sensors for bow position and acceleration [8]. However, in order to provide greater insight into the subtlety of gesture demanded of and used by violinists, different types of strain in the bow stick are also measured. The downward and lateral (indicative of angle of bow) strains on the bow stick are closely related both to the experience of a violinist while playing and to the immediate changes in the sound produced by the string when bowed.

The sensing system implemented to take the desired measurements is comprised of a minimal number of carefully placed hardware additions to the original carbon fiber bow. These include a printed circuit board containing custom circuitry (and accelerometers) and a 3V battery mounted to the frog of the bow, foil strain gauges adhered to the bow stick, and a resistive strip (also attached to the stick) for the position measurement that spans the length of the bow hair. Data from the position sensor is sent to a computer via a cable connected to the antenna mounted on the violin (attached to the tailpiece of an acoustic violin or situated directly behind the bridge of an electric violin), while the acceleration and strain data is transmitted using an RF module. Therefore, the *Hyperbow* remains wireless.

This paper presents the *Hyperbow* controller and the design and implementation of the three sensing subsystems–position, acceleration, and strain–that enable (directly or indirectly) the *Hyperbow* to collect data reflecting bow position, speed, acceleration, downward force, and angle of the bow. Applications are also discussed.

Figure 1: The electrode antenna is mounted behind the bridge of a Jensen electric violin.

DESIGN AND IMPLEMENTATION

Position Sensing

The method of sensing the position of the bow relative to the bridge of the violin presented in this paper is an adaptation of the system used in the development of the *Hypercello* [6].

In this method, two square wave signals of different frequencies are produced. The signals are connected to opposite ends of a resistive strip that spans the length of the bow. A simple electrode antenna is placed behind the bridge of the violin. The electrode is connected to a circuit that amplifies the combined signal received from the bow. This signal is then sent via a cable to a remotely mounted printed circuit board, whose task is to separate the two signals from each other and measure their varying strengths as the bow moves with respect to the bridge of the violin. Bow position is then be determined from the data in software on a computer connected to the output of the board.

Because the other sensing subsystems discussed in this paper were completed before the inclusion of the bow position measurement in the *Hyperbow*, the implementation of the position sensor was completed with as little alteration of the rest of the existing system as possible. So as to add a minimal number of hardware components to the small printed circuit board mounted on the bow, the two square wave signals mentioned above are generated by the PIC16LF877 manufactured by Microchip Technology, Inc. A 100KHz signal is produced using the PIC's `Timer2` module in PWM mode, and a 50KHz signal was produced using the built-in `Timer1` oscillator.

The board that receives the signal from the antenna on the violin consists of two bandpass filters (created using two LTC1562-2 chips (manufactured by Linear Technologies) that have been designed to separate the two different signals of different frequencies from each other, peak detectors that convert the signals to analog DC voltages equal to the signal amplitudes, and a PIC16F877 (powered with 5V rather than the 3V supply used to power the PIC16LF877 on the bow board) microprocessor with a built-in 10-bit A/D converter that receives these voltages and sends them to a computer in the form of a serial data message (see Figure 2).

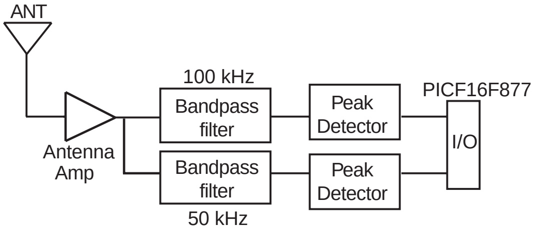

Figure 2: The amplified signal from the antenna board on the violin is a combination of the two signals sent from the bow. In order to determine the position of the bow, the combined signal first must be separated into two signals once again. This function is performed by directing the combined signal into two bandpass filters, one designed to pass 50KHz signals and one for 100KHz signals. The outputs of these filters are then converted into DC voltages by two peak detectors and sent to the PIC16F877 microprocessor.

Acceleration Sensing

In order to sense the acceleration changes of the bow, two ADXL202 accelerometers from Analog Devices, Inc. are used. This accelerometer is capable of measuring accelerations with a full-scale range of ±2g. Because the ADXL202 is a 2-axis accelerometer, two of these devices, one mounted orthogonal to the plane of the electronics board containing the other, are used in the design in order to attain acceleration data along all three axes. This accelerometer has a digital output for each of its two axes of sensitivity that has a maximum resolution of around 14 bits. The acceleration measured by the accelerometers is encoded in the digital output signal by modulating the duty cycle linearly with the acceleration. The acceleration is thus retrieved by simply counting the duty cycle in a software loop.

Strain Sensing

Because of its direct effect on the violin string and its close relationship to the experience of a violinist while playing, a technique for measuring the downward and lateral forces on the bow stick was developed. This measurement is similar to that used in the original *Hypercello* project, which employed a force sensitive resistor to indicate the pressure of the right hand index finger on the bow stick. However, in this method we measure the relative changes of the different strains on the carbon fiber material of the bow stick itself. This basic technique was also employed by Askenfelt [2, 1].

Figure 3: These two uniaxial strain gauges (EK-06-250BF-10C) each have nominal resistances of approximately 1000Ω and are 6.35mm long and 3.18mm wide each. The winding of the metal alloy wire that composes the gauge can be seen running back and forth in the direction parallel to the bow. The terminals of this wire are connected to solder tabs.

Strain Gauge Operation The sensors used in this project are commercial foil strain gauges from Vishay Measurements Group, Inc. The gauges are two-terminal devices that behave as variable resistors. Therefore, the proper operation of the gauges demands that they be securely and permanently affixed to the material that is under strain such that the stretching of the gauge is identical to the stretching of the material. The strain gauges used in this project possess a uniaxial pattern designed to measure strain along one axis (in the direction of the grid lines), as in a bending beam. In adhering the strain gauges to the surface, special care had to be taken because of the requirement to conform to a cylindrical surface rather than a flat surface (see Figure 3). These high-precision foil strain gauges presented many implementation issues and constraints. Because the strain gauge measurement could easily degrade when operating at high temperatures (due to thermal expansion of the alloy), special care had to be taken when choosing appropriate operating current levels to avoid generating large amounts of power dissipation in the form of heat. Also, a foil strain gauge relies on the material on which it is mounted to assist in heat conduction away from the gauge body itself. The gauges are temperature-matched to either steel or aluminum due to their high heat conductivity. Because this work was done on a carbon fiber bow, whose heat dissipating capabilities were not nearly as good as those of metals, the supply voltage for the sensor circuits was set much lower than that suggested for typical applications. The electronics that comprised these sensors used a 3 Volt power supply, in the form of a lithium battery, which was capable of operating both the PIC16LF877 microprocessor and the Linx TXM-900-HP-II transmitter, the crucial components of the bow board.

Wheatstone Bridge Configuration The strain gauges were arranged in a Wheatstone Bridge configuration with the midpoints of each "leg" of the bridge connected to a differential operational amplifier. So as to allow for the best measurement possible, a full bridge configuration, i.e., two strain gauges in each of the two legs of the bridge, is implemented.

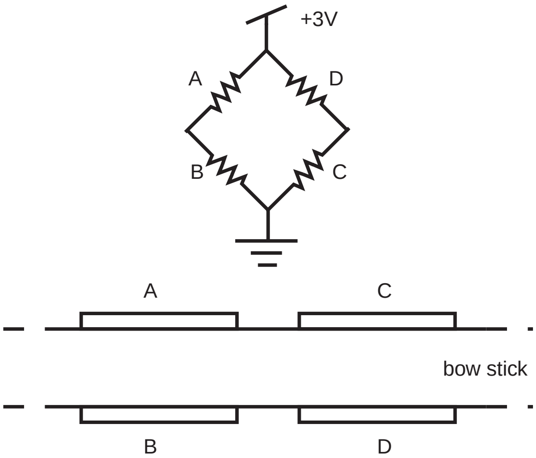

Figure 4: The arrangement of the strain gauges that comprise the Wheatstone Bridge circuit on the bow stick has been designed so that the sensor measures the strain roughly halfway between the two legs of the bridge (A/B and C/D). In the case that a lateral (parallel to the strings) force is applied to the bow, gauges A and C are compressed and therefore decrease in resistance, while gauges B and D expand and therefore increase in resistance. Therefore the voltage drop over B increases while the drop over C decreases, resulting in a nonzero differential voltage between the two midpoints of the legs of the bridge. If a force is applied to the bow in the opposite direction, the opposite changes occur in the resistances of the gauges, causing a differential voltage measurement of opposite sign.

The sensor measures the strain at the point located approximately halfway between the two sets of gauges (see Figure 4). At rest, the resistances of all of the gauges are approximately equal, and so the corresponding voltage values between the midpoints of the bridge and ground are also approximately equal, resulting in a voltage difference of zero at the output of the differential amplifier. So, as the bow is laterally strained in one direction, the gauges on one side of the stick are compressed and decreased in resistance, while the gauges on the opposite side of the stick expand and increase in resistance. Thus, the left "leg" of the Wheatstone bridge experiences an increase in the upper resistance value and a decrease in the lower, while the right "leg" experiences the opposite. The voltages at the midpoints of the bridge are shifted in opposite directions. The voltage difference between these two points is then taken as the sensor value.

A principle advantage of the full Wheatstone Bridge configuration is that it renders the strain sensors unaffected by temperature changes in the bow. If a half-bridge configuration had been used, for example, such that resistors A and C were strain gauges, while B and D were fixed precision resistors (see Figure 4), the gauges would have experienced temperature changes affecting their values while the fixed resistors would have been unaffected. In this case, the Wheatstone Bridge might have been quite unbalanced. Therefore, the gauges have been arranged on the bow such that two of the gauges are placed directly above the other gauges in opposite legs of the Wheatstone Bridge circuit. Therefore all four gauges in each bridge experience approximately the same changes in temperature and expansion of the bow, as heat is dissipated through the carbon fiber bow.

Amplification The voltage difference between the two midpoints of the Wheatstone Bridge is amplified using a differential amplifier to yield a voltage value within the range of 0-3 Volts, as this is the range of the A/D converter in the PIC16LF877. The goal is to ensure that when the bow is idle the voltage value is stable at approximately the midpoint of this range, and when the bow is in use the voltage value exhibits significant deviation without risk of saturation. This amplification is achieved after adjusting the external resistors of the differential amplifier appropriately. The differential amplifier is constructed using an INA2321 instrumentation amplifier manufactured by Burr-Brown Corp., which has a maximum gain of 1000. In most cases, the strain sensor voltages are amplified by 500 or 750.)

Power Consumption One of the greatest concerns of the strain sensing hardware was that of power consumption. In each "leg" of each Wheatstone Bridge, the current drawn is equal to $I = V/(2 \cdot R_{\text{rest}})$, where V is the power supply voltage.

In order to reduce the power consumption of the system so as to extend the lifetime of the battery, strain gauges with a nominal resistance of 1000Ω are used for the strain sensors. The current through each leg of each Wheatstone bridge is

$$I = 2(3V/(2 \cdot 1000\Omega)) = 3\text{mA}. \qquad (1)$$

Application and Alignment Proper installation of foil strain gauges is critical to the performance of the sensor. Some major difficulties arose in the process of adhering strain gauges to the surface of the bow. The first was found in the task of simply achieving a solid bond between the strain gauge (by carefully preparing the surface of the bow, abrading it, applying fast-curing adhesive and catalyst between the gauge and bow surface, and then applying pressure until set) and the bow surface and the second was found in the task of properly aligning the devices (see Figure 4).

The accuracy of a strain gauge measurement is highly sensitive to the relative alignment of the group of strain gauges along the bow surface. Any difference of the angle made between individual strain gauges and the axis of the test object alters the effective lengths of the strain gauges along the strain axis and therefore affects their relative rest and strained resistances. Discrepancies between the orientations of the individual gauges and how they conform to the surface of the bow contribute to the difference between their nominal resistance values, and this in turn creates problems in the performance of the bridge. Since the measurement taken is really the voltage difference between the two voltages at the midpoints of each leg of the bridge, when the gauges are not closely matched this value at rest is nonzero and the dynamic range of the measurement is impaired.

Figure 5: The *Hyperbow* consists of a modified CodaBow *Conservatory* violin bow. This bow was enhanced with strain sensors and a resistive strip used for position sensing. A PCB mounted to the frog houses the accelerometer sensors as well as control circuitry for sending data wirelessly to a remote receiver (see text).

Therefore, though considerable pains were taken to ensure that the devices were well matched from the onset, there were seemingly unavoidable deficiencies in the balancing of the bridge in its rest position due to differences in the nominal resistances of the strain gauges after installation. Despite this fact, the performance of the strain sensing subsystem was found to be quite satisfactory.

System Overview

The goal of the *Hyperbow* project was to create a new kind of violin bow with capabilities unlike any other, and therefore the form of the *Hyperbow* was expected to differ from that of the traditional bow as a result. However, it was important to maintain certain traits of the physical interface so as to enable a player to use the same postures of the right hand wrist and fingers on the bow. Therefore, the hardware implementation of the *Hyperbow* measurement system was designed so as to provide the performer with an instrument as similar to a traditional bow in size, weight, and weight distribution as possible.

In addition to the requirements of the physical interface of the bow itself, there were several basic requirements for the architecture of the sensing system. Though the printed circuit board on the bow performs the functions necessary to attain and send strain and acceleration data, it acts as only part of the position sensor. The second part of the position sensor is the antenna described above. Because the progress of the position sensing subsystem was separate from that of the rest of the project and the subsystem was designed for use in musical applications different from those of the strain and acceleration sensing subsystems, the hardware created to receive position data is isolated from the other subsystems. Ultimately, the data from the bow sensors was intended to be viewable by both a workstation running a Microsoft Windows variant for the purposes of analysis, and

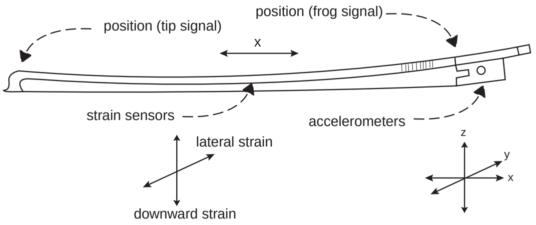

Figure 6: The *Hyperbow* system includes accelerometers, mounted at the frog of the bow, to give acceleration data for all three axes of bow movement, two strain sensors, mounted around the middle of the stick, for downward (normal to the strings) and lateral (parallel to the strings) strains, and the outputs for the two signals necessary for position sensing (parallel to the bridge), located on the stick at the extreme ends of the bow hair.

a Macintosh workstation for the development of music applications. A serial protocol is used to carry the combined strain/acceleration data stream and the position data stream to an external computer.

A crucial design objective was that the bow remain wireless, free of power or data cables. The small electronics board mounted to the bow is powered by a lithium battery and sends the sensor data from its transmitter to a receiver on a separate electronics board. This data transfer is performed via a Linx HP-SeriesII RF module, manufactured by Linx Technologies, Inc. This module operates in the 902-928MHz band, is capable of transmitting data for distances up to 1000ft, and has eight selectable channels (making it possible to adapt this sensing system for use in several instruments simultaneously). The antenna for the transmitter is a simple $\frac{1}{4}$ wave whip antenna made from a piece of solid conductor wire cut to the appropriate length.

RESULTS

Sampling Frequencies

A serial protocol is used to carry the combined strain/ acceleration data stream and the position data stream to an external computer at 19200 baud. The sampling rate of the position sensing subsystem is approximately 142.86samples/sec. and the sampling frequency for the acceleration and strain subsystems is about 41.67samples/sec.

Power Budget

The total current drawn by the *Hyperbow* bow board was measured to be 26mA: the Linx 900MHz transmitter draws 15mA, the strain gauge bridges draw 3mA each, the microprocessor draws 0.6mA, the accelerometers draw 0.6mA each, and the remaining components draw 3.2mA total. This large power consumption of the system necessitates the use of a large 3V lithium battery.

Weight and Balance Point

The overall weight of the *Hyperbow* is 89.751g, an increase from the original weight of 60.930g for the unchanged carbon fiber bow. The balance point was shifted from approximately 25.5cm (measured from the frog end of the bow stick) to about 22cm. Though the weight is considerably increased, the shift in the balance point toward the right hand seems to ameliorate the effect of a heavier bow.

In future, the weight might be reduced by replacing some of the larger components currently used in the bow board, such as the battery, which is the heaviest single part (approximately 11g), with smaller and lighter substitutes. Though much work can be done to strive toward an improved weight, balance, and overall “feel” of the interface, the play-ability of the *Hyperbow* was evaluated by several accomplished players and two professional violinists and found to be adequate by all.

APPLICATIONS

The *Hyperbow* was first played in public performance by a professional violinist in January 2002 in Dublin, Ireland, and it is currently featured in *Toy Symphony*, a new piece written by Tod Machover (MIT Media Lab) for full orchestra, children’s chorus, and solo violin. *Toy Symphony* was premiered in February 2002 (Berlin, Germany), and upcoming performances are scheduled for April (Dublin, Ireland) and June (Glasgow, Scotland) of 2002. In these applications the *Hyperbow*, using chosen gestures, controls various enhancements of the solo violin part in real-time, such as activating and altering sounds and effects (no samples) on the audio output of a Jensen electric violin.

Though it was designed to be an interface for a virtuoso violinist with a traditional classical music background, the *Hyperbow* is meant to be an alternative for any violinist, or indeed, for any player of a bowed string instrument. By offering possibilities for the real-time alteration of acoustic or electric sound though gestures familiar and learned by the player, the *Hyperbow* offers an endless supply of new sounds and musical options. The *Hyperbow* enables players to view, inspect, and exploit the subtlety of their bowing.

As the *Hyperbow* is a new instrument, with different capabilities than a tradition bow, it is hoped that future experimentation with the *Hyperbow* may lead to altogether new bowing techniques.

FUTURE WORK

There is much exciting progress to be made in improving the interface of the *Hyperbow* in order to make it more comfortable to play, to reduce the vulnerability of the sensing system, and to better accommodate the technological enhancements within the form of the bow. Small improvements made be made by the advent of smaller components to enable the design of a smaller bow board. However, a truly significant change in the mechanical design cannot occur until the hardware becomes more closely connected to the structure of the bow or even contained within the bow itself. For instance, the resistive strip for the position strip, or the strain gauges and accompanying wires may, one day be installed inside the bow stick. The construction of a custom designed bow that better houses the sensing system may also necessitate the design of custom devices, such as new strain sensors, whose form factor and material properties are better suited to this application.

Research may be done to exploit the sensing techniques to help create models of bow gestures. The two strain sensors currently present can be consciously controlled by the player somewhat independently of those actions essential for producing sound on the violin. Therefore, these sensors are extremely valuable as music controllers. However, from a scientific viewpoint, there is value in investigating the manner in which the bow flexes and strains along its length during play. Additional strain sensors may be added to the bow stick in order to measure these behaviors.

Also, the possibility of using the *Hyperbow* to play already existing models of bowed strings, or indeed models of altogether different sounds, may be pursued. This might enable a person who has particular skill playing a violin to play other instruments in a style that is somewhat violinistic.

One might also hope that the design and construction of new bows would inspire the development of new stringed instruments. For instance, new instruments that perhaps require less proficiency of the left hand, or even no left hand technique whatsoever, may be built to complement the complexity of new bowing techniques.

ACKNOWLEDGEMENTS

I would like to thank Tod Machover for suppoting this project, Joshua Bell for his valuable feedback, and Matthew Reynolds for his technical advice.

REFERENCES

1. A. Askenfelt. Measurement of the bowing parameters in violin playing. II. bow-bridge distance, dynamic range, and limits of bow force. *Journal of the Acoustical Society of America*, 86(2):503–16, Aug. 1989.
2. A. Askenfelt. Measurement of bow motion and bow force in violin playing. *Journal of the Acoustical Society of America*, 80(4):1007–15, Oct. 1986.
3. T. Machover. Hyperinstruments: A progress report 1987-1991. Technical report, MIT Media Laboratory, 1992.
4. T. Machover and J. Chung. Hyperinstruments: Musically intelligent and interactive performance and creativity systems. In *Proceedings of the 1989 International Computer Music Conference*, pages 186–190, San Francisco, CA, 1989. Computer Music Association.
5. J. Paradiso. Electronic music interfaces: New ways to play. *IEEE Spectrum*, 34(12):18–30, 1997.
6. J. Paradiso and N. Gershenfeld. Musical applications of electric field sensing. *Computer Music Journal*, 21(3):69–89, 1997.
7. D. Trueman and P. R. Cook. Bossa: The deconstructed violin reconstructed. In *Proceedings of the ICMC*, Beijing, 1999.
8. D. S. Young. New frontiers of expression through real-time dynamics measurement of violin bows. Master's thesis, M.I.T., 2001.