EXPERIMENTS WITH AN AUTOMATIC BOWING MACHINE

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1. INTRODUCTION

Understanding the vibration characteristics of violins to the point of being capable of objectively improving their performance is an age-old problem. Although many claims have been made regarding how a violin should be constructed so that it is responsive to the player, there does not exist any single model that has been proven to describe the mechanics of the violin accurately. Further progress in the use of science in the design of a responsive violin hinges on establishing the reliability of such a model, so that it could be used to test changes in the construction of a violin. Models of varying degrees of complexity have been suggested to describe the mechanics of the bowing process [1]. To choose one such model and use it to aid in the design of a violin would require experimental validation of that model. In this paper, a novel facility for performing the required experimental validation is presented.

2. EXPERIMENTAL SETUP

2.1 CHOICE OF APPARATUS

The general aim is to build a robot that can play the violin. The most important requirement of the robot, and indeed the reason why a human violinist would not suffice, is that it must be able to repeat precisely the same bowing gesture over and over. From the point of view of testing scientific theories, it is adequate that the robot only be capable of playing a single string, and indeed only a single note, at a time. In this spirit, only the right hand of a violinist is simulated: a schematic sketch of the design is shown in Figure 1a.

A more detailed diagram of the final design for the bowing machine is shown in Figure 1b. The bow is held in a cantilever arrangement, supported only at one end by a clamp. The pin joint of Figure 1a is achieved using a leaf spring, and torque is applied by means of an electromagnetic shaker. This arrangement is specifically designed to avoid bearings and any other sliding contacts, because friction in bearings was found to impede the accuracy of the applied torque. The dynamics of the beam are monitored using an accelerometer mounted at the tip of the bow, whilst the DC force is measured using an arrangement of strain gauges on the leaf spring. The clamp is mounted on a linear motor, allowing the whole assembly to move relative to the violin with a specified trajectory. The rig can hold a normal violin bow, and it can also be used to hold a rosin-coated rod which gives a point-like contact with the string and is better suited to validating theoretical models.

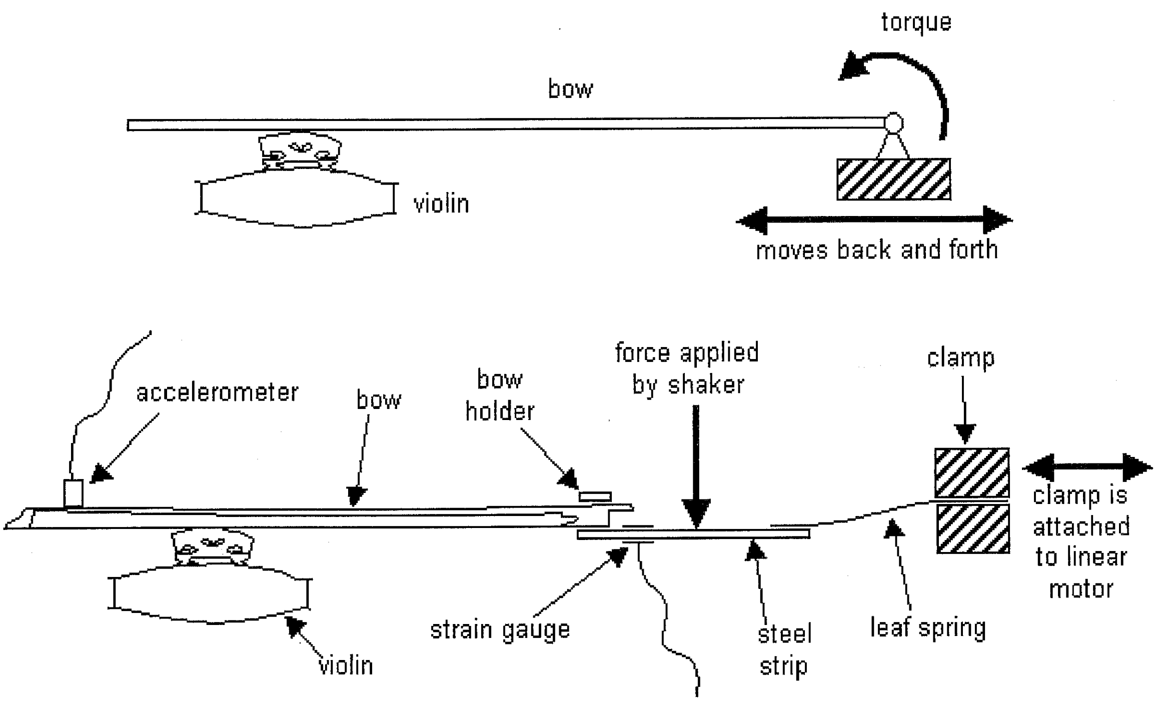

Figure 1: (a) Schematic diagram of bowing machine; the speed and force of the bow on the string are controlled. (b) Diagram of experimental setup.

2.2 DESIGN OF FEEDBACK CONTROLLERS

In order for the bowing machine to play the violin, it is necessary to control both the speed at which the bow is drawn across the string and the normal force exerted by the bow on the string. These two quantities require separate feedback controllers, and have been implemented digitally using a dedicated digital signal processor (the dSpace DS1102 Floating-Point Controller Board).

2.2.1 Control of Bow/String Contact Force

Figure 2 shows the procedure for controlling the bow/string contact force. A feedback controller is used to compensate for the dynamics of the bow and to deliver good tracking performance, which was designed using the following procedure:

(1) The impulse response of the bow and its supports was measured by applying a short pulse to the shaker, and measuring the response using the strain gauges and the accelerometer. In addition, during the testing phase a specially designed force meter was used to measure the bow force itself, which was put in the place of a violin. Because the dynamics of the bow are heavily dependent upon where the string contacts the bow (the system is rather similar to a constrained cantilever [2]), this process was repeated at different contact positions.

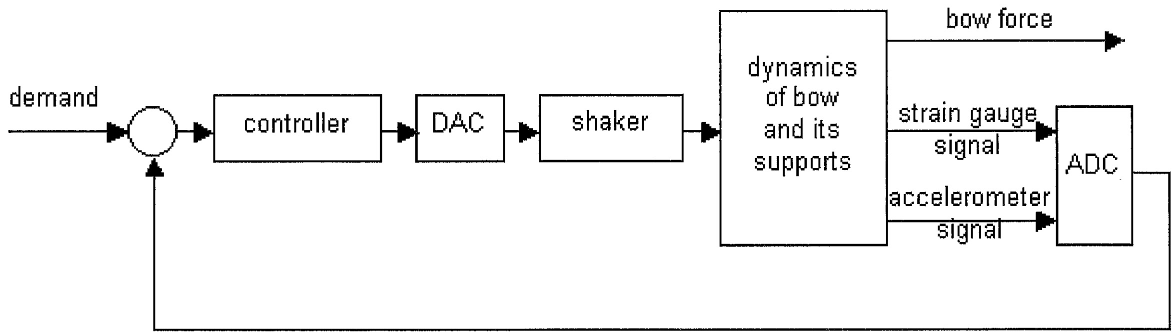

Figure 2: Configuration of feedback controller for bow/string contact force

(2) Modal fitting was used to identify transfer functions from shaker input to bow force, strain gauge signal and accelerometer signal at each contact position. For the case of a rosin-coated perspex rod acting as a "bow", the modes of the bow and its supports were

typically found to have damping factors of the order 0.1. A typical transfer function is shown in Figure 3.

(3) The H_∞ loop-shaping procedure [2] was used to design the feedback controller at ten contact positions spaced along the "bow" at 5cm intervals, with weights attached to different frequencies. This procedure guarantees a measure of "robustness", so that each controller remains stable over a finite range of contact positions.

(4) The controllers for each position were implemented in such a way that switching between them as the bow is drawn across the string did not cause any glitches.

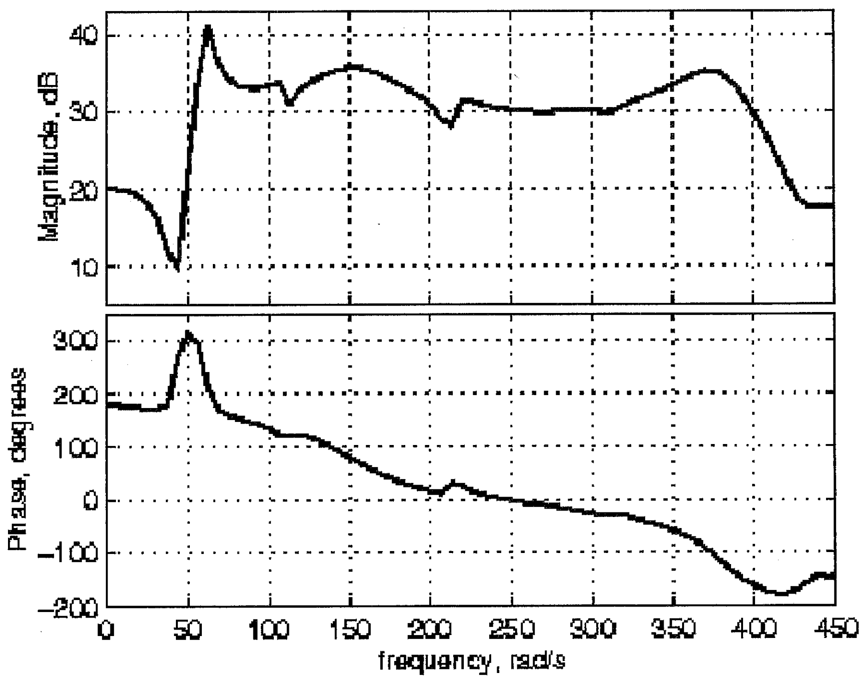

Figure 3: Typical frequency response for the (uncontrolled) bow and its supports. This data shows the response of bow force to shaker input.

2.2.2 Control of Bow Speed

The bow and its supports are mounted on a linear motor, allowing it to be drawn back and forth across the string. The linear motor is a stepper motor, where current passing through a helical coil inside the motor, wrapped around a bar that contains pairs of opposed magnets emitting a radial magnetic field, causes the motor to experience an axial force. The pole pieces are placed roughly every one inch, and cause the motion of the motor to be bumpy.

To reduce these bumps, feedback control is used. The position of the motor along its track is measured using a displacement transducer and inputted through an analogue-to-digital card to a digital controller. The controller then specifies the value of current that the linear motor should receive, compensating for bumps.

2.3 PERFORMANCE LIMITATIONS

Using the controller designs described in outline above, it was found that the following performance specifications could be met:

- **Bandwidth of force controller.** The dynamics of the bow could be controlled up to frequencies of around 250Hz. The bow and its holding system has three vibration modes in this frequency range, whose frequencies and mode shapes vary with contact position. The task of the force controller is to reduce the dynamic force variation due to transient response of these modes, and in practice they were reduced by a factor of roughly three (10dB). The input to the shaker (see Figure 1) was low-pass filtered with a cut-off frequency of 240Hz.

- **Transient response.** The force controller was found to respond to a step input with a rise time of not more than 0.2 seconds, and with no steady state error. The dynamics of the bow are controlled to an extent that the step response is considerably smoother with the controller in place than without; a typical example is shown in Figure 4.

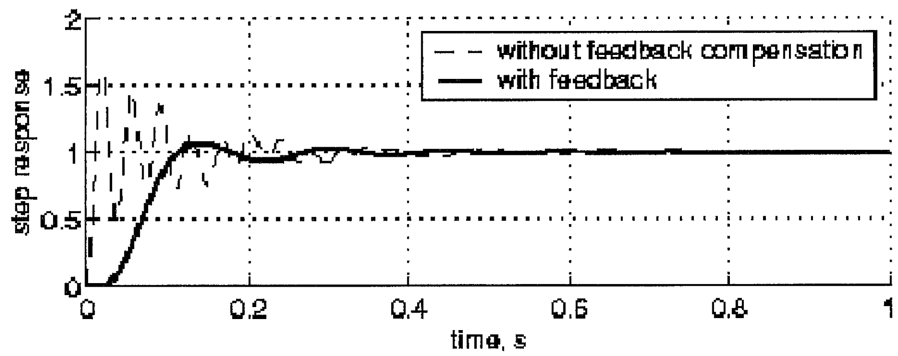

Figure 4: A typical response (in bow force) to a unit step demand signal with and without feedback compensation.

- **Smooth switching between force controllers.** Because the dynamics of the bow are heavily dependent upon the position of the bow/string contact point, it is necessary to switch between different controllers specifically designed for different contact points. It was found that the switching technique employed in the bowing machine allowed the switching to be practically seamless.

- **Velocity control.** The bow speed was found to be controllable up to a frequency of about 500Hz, given the constraints of the hardware available. The unevenness of the linear motor was reduced to acceptable levels up to that frequency.

2.4 OPEN LOOP 'TRAINING'

A human violinist learns to play the violin by means of a lot of trial and error; if one bowing gesture causes a 'crunching' noise, a different one will be tried. As such, a human violinist probably places less reliance on the active control of the bow, as is done using the force and speed controllers described above, but rather would learn more by trial and error 'training'.

'Training' the bowing machine in this same way, where performance is improved by changing the demand given to the closed loop system in light of results from past attempts, is expected to yield two advantages. First, there is the obvious possibility that the performance could be improved: for example, an exaggerated demand could be made on the bow force to compensate for a tendency to underachieve. Second, open loop training could be of interest in the study of the human learning process itself. It may also shed light on the differences of "playability" between different bows.

It is planned that open loop training will be explored once more results have been obtained using the present setup. Optimisation techniques should allow the "best" demand signal to be found for any given required bowing gesture.

3. INITIAL RESULTS

The requirement for building a bowing machine arises from the need to validate experimentally the competing theoretical models that exist to describe the mechanics of violin bowing [3]. The natural way to test the ability of theoretical/computational models to predict the behaviour of a violin is to see what string motion they predict under different conditions. Schelleng [4] has suggested that the maximimum and minimum tolerable bow force for the violin to continue speaking (i.e. to sustain Helmholtz motion [5] rather than crunching or skating etc) is of interest, when plotted for different values of bow-bridge distance. Schelleng then proposed a simple analytical model to predict that the minimum bow force would vary in proportion with (bow-bridge distance)$^{-2}$, and that the maximum bow force would vary with (bow-bridge distance)$^{-1}$ (see Figure 5). Woodhouse [3] has compared these simple power laws with results obtained using a more sophisticated computational bow-string simulation. In this section some initial results obtained using the bowing machine are presented which not only provide a further comparison, but which also illustrate the potential usefulness of the bowing machine.

Experimental results obtained using the bowing machine are shown in Figure 6. The results were obtained with a 13mm diameter perspex rod in place of a conventional bow, and with a cello in place of a violin. These modifications were made in order that the results could be directly compared with the corresponding computational results of Woodhouse [3], who modelled the bow as a rigid point contact, and used string data for a Dominant cello D-string. The bow was driven at constant speed.

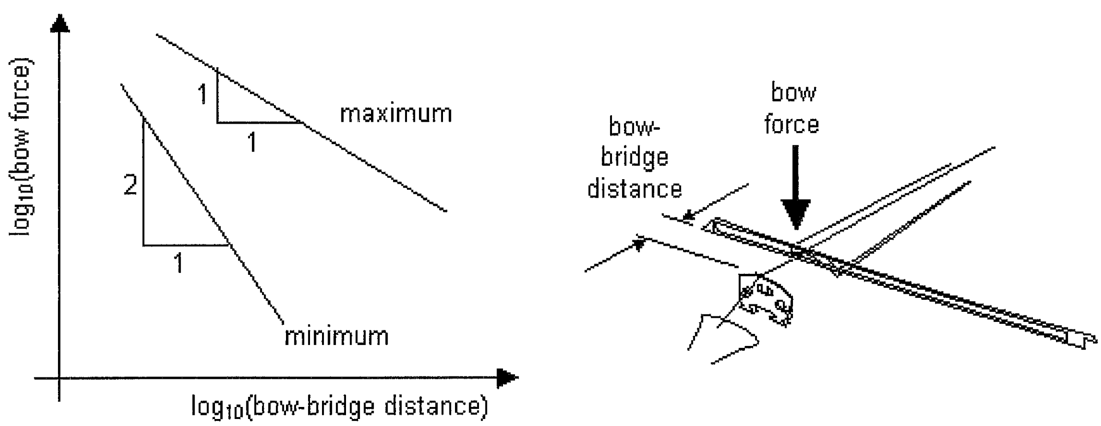

Figure 5: Schelleng predicted max bow force ∝ (bow-bridge distance)$^{-1}$, and min bow force ∝ (bow-bridge distance)$^{-2}$.

To measure the maximum bow force, the force was gradually increased until speaking ceased, and the bow force at transition from speaking to not speaking was considered to be the maximum bow force. In the case of measuring the minimum bow force, force was reduced until the point when the bow had insufficient grip to make the violin speak, and that bow force was deemed to be the minimum bow force. In all cases the judgements were made, not only by ear, but also by watching waveforms of force exerted by the string on the cello bridge using a piezoelectric sensor. Helmholtz motion gives a characteristic sawtooth waveform [5], and this breaks down to non-periodic motion (at maximum force) or multiple-slipping motion (at minimum force). It was found that values of minimum bow force were measured to an accuracy of approximately 5%, but that values of maximum bow force could only be measured to an accuracy of approximately 10%.

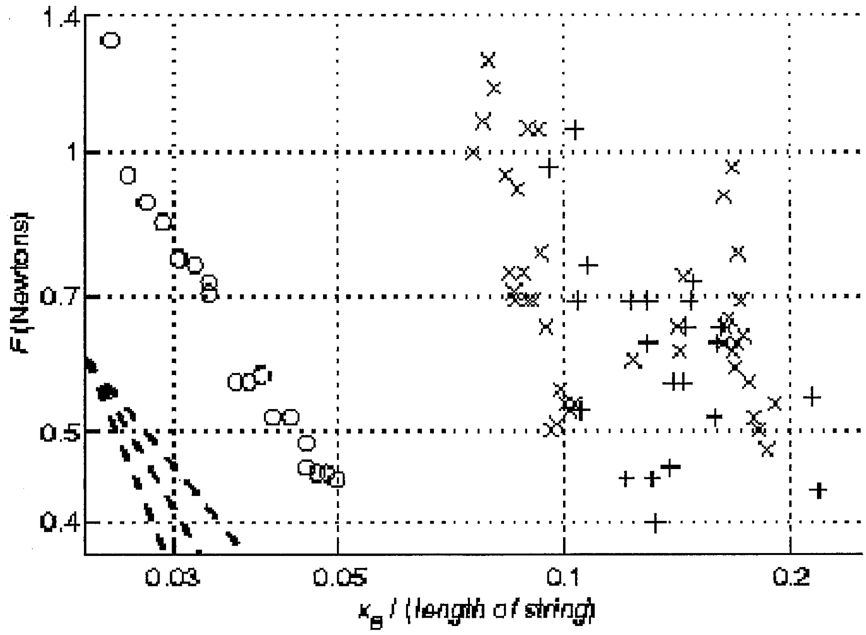

Figure 6: Experimental results, for maximum (×) and minimum (o) bow force. The dashed lines show force ∝ distance^n, with n = –2, –1.4 and –1, and are included as visual guides.

The fact that all minimum bow force data in Figure 6 lie along a straight line indicates a coherent relationship between minimum bow force and bow-bridge distance. This straight line is (min bow force) ∝ (bow-bridge distance)^n, with $n = -1.4 \pm 0.3$. The clarity of this relationship in the data is at odds with the computational results of Woodhouse [3], where a clear trend was not visible. Indeed, this observation is also at odds with the predictions of Schelleng himself, who predicted that n would be closer to –2. The results for maximum bow force in Figure 6 show much greater scatter, and it is not easy to fit a power-law trend with any confidence.

It seems that Schelleng's analytical model of the bowed string is too simple to capture the complex detailed physics of the minimum bow force, and that some details of Woodhouse's computational model may need to be modified. However, it is too early in this research project to make definite suggestions as to what these modifications should be. For now, the aim is simply to demonstrate the potential usefulness of the bowing machine.

In the immediate future it is intended that the bowing machine will be put to wide-ranging use. Examples of planned future research are as follows:

- More results will be added to those of Figure 6, allowing in particular a wider range of values of bow force to be scrutinised.
- Values of minimum and maximum bow force will be plotted against bow speed, at a fixed value of bow-bridge distance. There are early signs that a plot of bow force vs. bow speed may be of particular significance to the understanding of bow string mechanics.
- Numerous other experiments are possible in which the validity of different bow/string models could be examined using the bowing machine, because each different model predicts a different outcome to any given bowing gesture. An example of this which may again help build an understanding of the mechanics of violins, and which could also be investigated using the bowing machine, is the 'flattening effect', discussed at length in [6]. In addition the effect of changing bows or indeed strings can be explored.
- 'Playability' has been the topic of a considerable amount of research in recent years. It seems that playability, defined loosely as the ease with which a violin can be played, is the quality of a violin that is most amenable to objective analysis, and thus to scientific measurement. The bowing machine is an ideal tool for measuring the relative playability of different instruments, for example by comparing the time taken for transient noises to die away at the start of the same note played in the same way on two different violins. Indeed, a set of six specially commissioned violins with well-documented shapes and construction details are conveniently available to the authors for such a purpose.

4. CONCLUSIONS

A bowing machine has been developed that can control bow force and bow speed accurately enough to allow existing theoretical models of violin string/bow mechanics to be experimentally tested. Initial results have demonstrated one method for testing models of the bow/string friction, and many more applications for the bowing machine are envisaged. It is intended that the bowing machine be used in the future to explore a wide range of parameter space: different bowing gestures, different strings, different instrument bodies, and different bows.

5. REFERENCES

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