A Haptically Accurate Practice Carillon

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Abstract

Mastery of musical instruments remains both a rewarding and challenging haptic task. The carillon is a particularly difficult instrument to practice due to its public nature and variability from location to location. A dynamic model of the carillon key (baton) is presented and a design for a haptically accurate practice carillon is proposed. The Passive Dynamics Practice Carillon (PDPC) is able to emulate a range of actual carillons using adjustment of passive masses and a spring. To evaluate the necessary fidelity of such a design, a study was conducted in which participants were asked to discriminate between batons with differing impedance parameters.

The results showed that subjects are more sensitive to the force parameter and less sensitive to the stiffness and inertial parameters. In all cases, the passive adjustment increments on the PDPC were well below the sensitivity of the test participants. This leads us to two conclusions: a) a passive dynamic system is sufficient for a haptically accurate practice carillon and b) the Passive Dynamics Practice Carillon can be simplified to be less accurate but more cost effective while still sufficiently matching the haptic feel of real carillons.

Keywords: carillon, haptics, passive dynamics

Index Terms: H.1.2 [Models and Principles]: User/Machine Systems—Human Factors;

1 Introduction

Mastery of musical instruments is one of the most challenging haptic tasks that humans undertake. Many musical instruments, whether string, woodwind or percussion rely on precise control of force, timing and muscle impedance. Depending on the instrument, it may require precise control of the fingers or recruit larger muscle groups in the arms and torso. The majority of instruments are practiced in relative privacy and students master certain skills before performing. The carillon is an instrument that consists of bells of varying sizes (20 – 7000 kg) that are struck by clappers or weighted pendulums. The clappers are connected by wires to wooden batons that are arranged similarly to a piano keyboard in a playing cabin typically just below the bellfry (Figure 1). The carillon presents a particularly interesting training challenge in that each instrument is physically unique with the masses of the bells and clappers varying from note to note and from carillon to carillon. Students of the carillon must learn how much force to give each baton in order to achieve the appropriate note velocity and timing. Because the instrument is impossible to silence, every session is a public performance. Practice carillons are able to replicate the arrangement of keys but the mechanical impedance of the batons rarely matches that of the real instrument, and therefore does not provide a realistic practice experience.

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Figure 1: The Yale Memorial Carillon resides in Harkness Tower (a). All 54 bells (43 tons in total) are arranged in a space in the tower called a bellfry. A medium-sized bell with clapper in rest position is depicted on the upper right (b). When a carillonneur plays this note on the keyboard in the playing cabin (c), the clapper will swing towards the bell and impact, producing a sound.

In this paper, we present a design for a practice carillon that emulates the haptic feel of a real carillon. The proposed design is adjustable so that it may be configured to match the characteristics of a variety of real carillons. We also present the results of a haptic fidelity experiment in which we measured carillonneurs' and non-carillonneurs' ability to discriminate between various impedance parameters. From this work, we were able to understand the design requirements for haptic fidelity in practice carillons and make suggestions that are likely to extend to other physical tasks that require arm coordination and timing.

2 Background

The carillon is a public instrument. Whether listeners are purposefully attending a concert or just passing by the tower, they are always part of the carillonneurs audience. The fact that the carillon is always heard is both a joy and a curse. Most musicians are eager to share their art with the public, but all musicians need to practice. For a carillonneur to practice privately, he must play a practice carillon.

A practice carillon consists of manual keys (batons) and pedals arranged similar to a real carillon. The batons are tied to small tone bars that produce quieter sounds. A player may use a practice car-

illon to acquaint himself with the geometry of a particular carillon keyboard, but timing and dynamics are not easy to learn on a practice carillon due to the lack of haptic fidelity. Transitioning from instrument to instrument can be challenging even for professionals since each carillon has a unique design with varying numbers of bells, musical transposition, keyboard geometries, and mechanical impedances.

Practice carillons have improved substantially in audio quality over the last decade. State-of-the-art practice carillons have done away with tone bars and are now electronic MIDI instruments that play samples of real bells, often recorded on the matching carillon. While the fidelity of audio has improved a great deal, the haptic feel of most practice carillons has not.

Adjustable practice carillons have received some attention in the recent past. A practice carillon developed by Timothy Hurd [8] has adjustable key geometry, allowing the user to set the instrument to the geometry of many different carillons.

Some newer commercial practice carillons come "weighted" [3]. Generally, this means adding small weights to the batons that represent the heaviest bell clappers, a little bit less weight to the octave above, and so on. The result is a practice carillon that feels very smooth but unrealistic.

Mimicking the haptic feel of a real carillon in practice carillons is challenging and a few different designs have been proposed. The literature describing these attempts is sparse and in some cases anecdotal. Recently, the haptic dynamics of carillons have been analyzed by Havryliv et. al. [6, 7, 8, 9]. A detailed analytical model of the carillon dynamics as well as a design for an electromechanical, actively controlled single baton is presented in [8].

Examples of research merging haptics and the piano can be found in patents [15, 18, 17], and an actively controlled piano simulator [5, 10]. A tactile stimulator that simulates plucking a guitar string is described in [2], interactive music modules are proposed in [1], and work with a theramin-like device is described in [14].

In this paper, we describe our efforts to design, fabricate and evaluate a practice carillon with accurate and adjustable mechanical dynamics that can recreate the haptic feel of the real instrument. Our objectives include the ability to rapidly adjust the instrument to replicate the feel for a wide range of real carillons. In the next section, we propose a dynamic model for the carillon baton as experienced by the player. From this model, we were able to analyze a number of existing carillons and propose a design that uses adjustment of passive masses and springs to recreate accurate haptic dynamics – The Passive Dynamics Practice Carillon (PDPC). We conclude with a preliminary assessment of players' sensitivity to the various impedance parameters.

3 Dynamic Model

We present a dynamic model of a typical carillon bell in this section. A single carillon bell is shown in Figure 2. Variables in this figure are defined in Table 1 in the Appendix. The clapper hangs from the middle of the bell at an angle offset to the vertical, θ_0, and extends a distance L_2 from the fulcrum. A wire is attached from the clapper to a bell crank that connects another wire to the baton on the keyboard. As the carillonneur plays the baton, the baton is deflected a distance y_d (measured at the wire) and the clapper moves towards the bell until it makes contact, sweeping out an angle θ_d. The clapper then bounces off the bell, allowing the bell to resonate freely.

To obtain a relatively simple model, we make several assumptions. First, our model is used to describe the motion of the bell and baton from the time the player makes contact with the baton until the player releases the baton or the clapper strikes the bell. During this time, the wires, bellcrank and transmission parts are assumed to be massless, rigid and frictionless. This is a reasonable assumption because the clapper is being accelerated as the player "throws" the baton and the pivots are relatively small compared to the masses

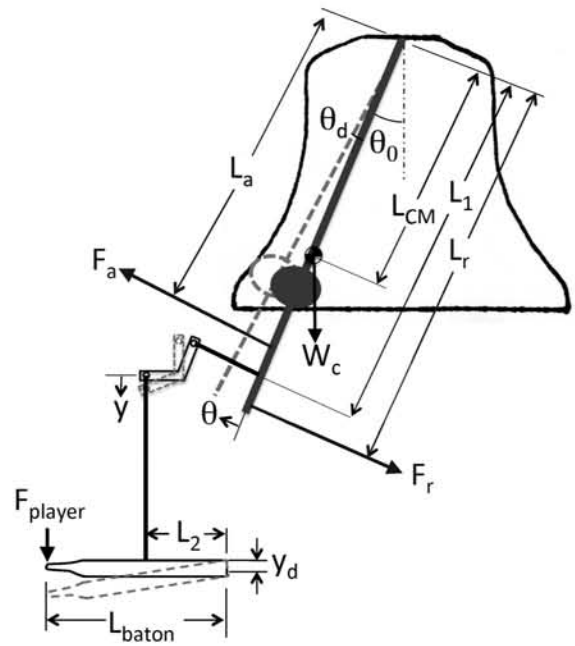

Figure 2: Model of the carillon mechanism. Wires, bellcrank and transmission parts are assumed to be rigid and frictionless since the mass of the clapper is quite large and the stiffness of the human hand and arm is much lower than that of the wire. This model is used to predict optimal haptically accurate practice carillon clapper parameters. Many carillon bells do not have the assist and return springs represented by F_a and F_r.

and forces in the system.

In order to replicate the feel of the mechanism shown in Figure 2, we need to obtain an equation for the force between player and baton, F_{player}. If the PDPC is capable of mimicking this force, then the instrument will be haptically accurate under the assumptions outlined above. The derivation of F_{player} begins by presenting the second-order linear equation of motion of the carillon mechanism.

$$W_c \sin(\theta_0 + \theta) L_{CM} - F_{player} \frac{L_2}{L_{baton}} L_1 + F_r L_r - F_a L_a = I_c \ddot{\theta} \quad (1)$$

To calculate I_c, we assume that the clapper is a solid bar rotating about one end with a point mass for the bulge in the clapper. Some carillon bells will have a return spring applying a force F_r on the clapper and others will have a return spring applying a force F_a in the opposite direction. These springs are typically constant force springs but may be extension or torsion springs as well. F_r and F_a can be split into two components, a constant term and a displacement dependent term:

$$F_r = F_{r_0} + k_r x_r \quad (2)$$

$$F_a = F_{a_0} + k_a x_a \quad (3)$$

For a constant force spring, $k_r = k_a = 0$. Many carillon bells will have neither return springs nor assist springs, in which case $F_{r_0} = F_{a_0} = k_r = k_a = 0$.

After applying the double angle formula, we can then simplify using small angle approximations for θ and use the following substitutions:

$$y = L_1\theta \qquad \ddot{y} = L_1\ddot{\theta} \qquad x_r = \frac{L_r}{L_1}y \qquad x_a = \frac{L_a}{L_1}y \tag{4}$$

Rearranging and solving for F_{player}:

$$F_{player} = F + Ky - M\ddot{y} \tag{5}$$

$$F = \frac{W_c L_{CM}\sin(\theta_0) + F_{r_0}L_r - F_{a_0}L_a}{L_1}\frac{L_{baton}}{L_2} \tag{6}$$

$$K = \frac{W_c L_{CM}\cos(\theta_0) + k_r L_r^2 - k_a L_a^2}{L_1^2}\frac{L_{baton}}{L_2} \tag{7}$$

$$M = \frac{I_c}{L_1^2}\frac{L_{baton}}{L_2} \tag{8}$$

When the carillonneur begins a key stroke on the baton, the baton is in rest position ($y = \ddot{y} = 0$) and the impedance felt by the player reduces to $F_{player} = F$. If the carillonneur were to hold the baton at the bottom of its stroke ($y = y_d$, $\ddot{y} = 0$), the impedance would become $F_{player} = F + Ky_d$. The M term only becomes significant when the baton and clapper are accelerating.

Each bell on every carillon has a unique F, K, and M value, defined by the clapper properties and dimensions of that particular bell. The PDPC clapper design recreates the haptic feel of a real carillon by matching each parameter as accurately as possible. The model we propose represents the baton's mechanical impedance as experienced by the player during hand strike and up to clapper impact. The simplifications we introduce in our model allow us to evaluate the mechanical properties of real carillons and recreate them using our practice carillon.

4 Empirical F, K, M Measurements

The impedance felt by the player is parameterized by the F, K, and M values defined in Equation 5. To characterize the range of possible values, we traveled to five different carillons at universities and churches in New England to measure the values.

F and K were measured directly on the carillon batons using a tension scale accurate to 0.02 lbs. As described in Section 3, Equation 5 reduces to simple cases when the system is not accelerating and the baton is at the top or bottom of the stroke. By directly measuring F_{player} on the baton in these two positions, we can then estimate the F and K values of that note. M, on the other hand, could not be measured directly and is an estimated value. To obtain an estimate for M for a particular bell, we measured L_1, L_2, and L_{baton} for that bell, approximated the inertia of the clapper by taking several length measurements, and used these values with the density of bronze in Equation 8.

Figure 3 depicts F, K, and M values for the five different carillons that we measured: Yale Memorial Carillon at Yale University, Dorothea Carlile Carillon at Smith College, Trinity Singing Tower at Trinity United Methodist Church in Springfield, Massachusetts, The Philip B. Stanley Carillon at the Congregational First Church of Christ in New Britain, Connecticut, and Gordon Stearns Memorial Carillon at the Congregational First Church of Christ in West Hartford, Connecticut.

We used the data in these plots to assist the clapper design for the PDPC. The plots also nicely illustrate the motivation for the project; all carillons are different, and practice carillons have very poor haptic feedback.

F, K, and M compose a 3D vector space, which we call *FKM space*. Our design challenge is to maximize the range of values that the PDPC can achieve in FKM space that coincide with real carillons. Obtaining the data points and understanding this vector space motivates our clapper design by presenting a a portion of FKM

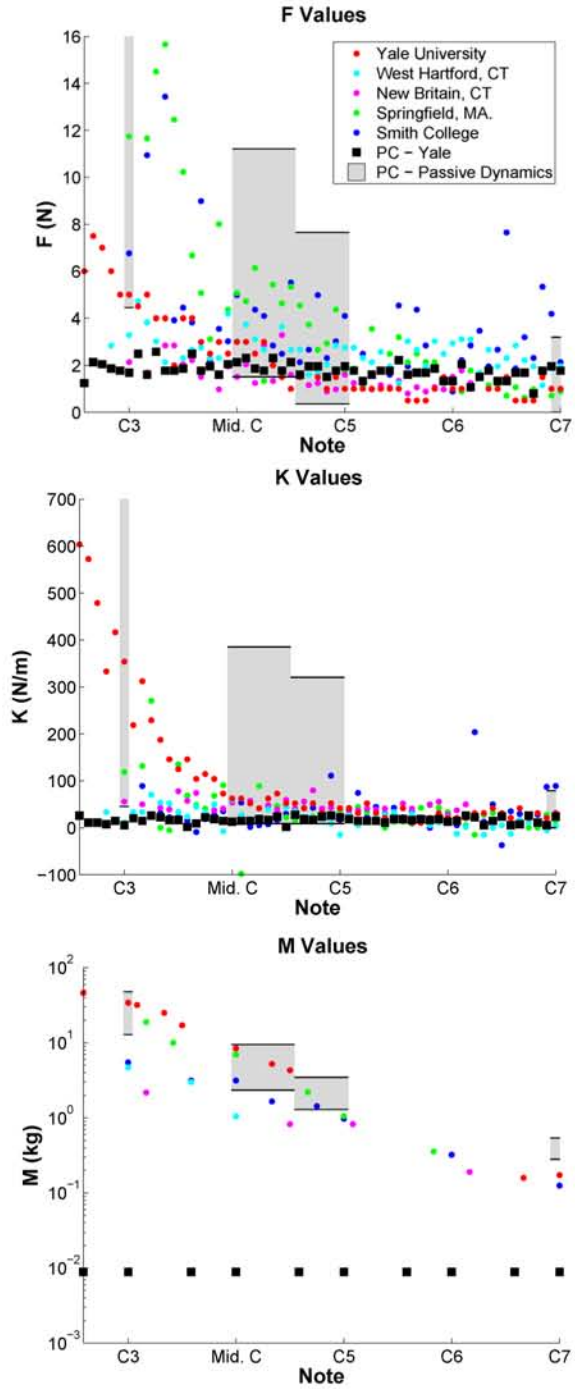

Figure 3: F, K, and M values for 5 different carillons: Yale Memorial Carillon at Yale University, Dorothea Carlisle Carillon at Smith College, Trinity Singing Tower at Trinity United Methodist Church in Springfield, Massachusetts, The Philip B. Stanley Carillon at the Congregational First Church of Christ in New Britain, Connecticut, and Gordon Stearns Memorial Carillon at the Congregational First Church of Christ in West Hartford, Connecticut. Black squares are shown for the practice carillon at Yale. The grey shaded regions represent the range of values that the PDPC can achieve.

space that we want our instrument to replicate. The grey shaded regions shown in Figure 3 represent the range of values that the PDPC can achieve.

5 Haptic Practice Carillon and Clapper Design

The mechanical impedance felt by the player in a real carillon is a function of clapper size and mechanism. The challenge in creating a haptically accurate practice carillon is to recreate the mechanical impedance of the real carillon in a much smaller volume and with less mass. Our approach changes the transmission ratio between the baton and the practice carillon clapper so that the system could be designed with lower mass and volume while maintaining the correct impedance.

A primary consideration for any practice instrument is cost. A typical 4-octave practice carillon will have about 47-50 keys. The use of electromechanical actuators for each key would make such a device very expensive. Furthermore, actively rendering inertia presents a greater technical challenge than rendering stiffness or force. Since it is still not known how sensitive players are to various impedance parameters, we chose to design a system using adjustable passive elements and evaluate the ability of players to discriminate between the various parameters before committing to the higher cost of actively controlling the impedance.

Our method for evaluating possible clapper designs for the PDPC was based on the ability to achieve F, K, and M values for a particular note, in addition to physical volume constraints and ease of adjustability. We considered several combinations of adjustable masses and springs that would allow adjustment over the desired range. After several design iterations, a two mass / one spring design was selected for its minimal size and weight, few adjustable components, and haptic fidelity. One clapper size alone for the entire desired range would have been impractical. Instead, we decided on two clapper sizes for the octave spanning C4 (middle C) to C5 in addition to one large clapper for C3 and one small clapper for C7. We then wrote a MatLab script that calculated the F, K, and M values of every possible clapper size within the available volume and chose the four that covered the largest desired range in FKM space. Four clapper sizes were fabricated ranging from $35cm$x$30cm$ to $55cm$x$50cm$.

There are three easily adjustable components on each clapper that can be used to set the desired F, K, and M value: D_1, D_2, and D_3 control the position of steel block B_1, steel block B_2, and spring S, respectively. Figure 4 shows the location of the three adjustments on the clapper.

D_1 and D_2 are adjusted by lifting a spring-loaded toothed piece out of the interlocking teeth on the clapper, then moving the piece to slide the coupled block down the length of the channel. The spring S is fixed to a wire attached to a custom made nut that slides up and down the channel as the user turns the knob above, adjusting D_3. The nut moving up and down the channel changes the lever arm that the spring is attached to. As the three adjustments D_1, D_2, and D_3 are changed, the values of F, K, and M change as well. Equations 9 – 11 relate the three adjustments on the clapper to F, K, and M values.

$$F_{pc} = F^*_{pc}(D_3) + W_{B_1}\frac{L_2(D_1 - D_{1_{min}})}{RL_{baton}} \tag{9}$$

$$K_{pc} = K^*_{pc}(D_3) - W_{B_1}\frac{L_2(D_1 - D_{1_{min}})}{y_d RL_{baton}} + L_2\frac{W_{B_1}\cos\theta_d(D_1 - D_{1_{min}}) + W_{B_2}\sin\theta_d(D_2 - D_{2_{min}})}{RL_{baton}} \tag{10}$$

$$M = I_{pc}(D_1, D_2)\frac{L_2}{R^2 L_{baton}} \tag{11}$$

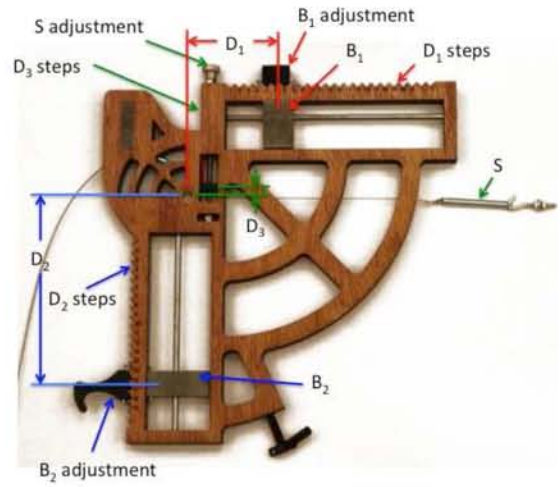

Figure 4: Three adjustments (two blocks, one spring) control the F, K, and M value of each clapper, allowing the clapper to feel like a range of notes on a variety of different carillons.

where:

$F^*_{pc}(D_3) = F_{pc}$ as a function of D_3 when $D_1 = D_{1_{min}}$, $D_2 = D_{2_{min}}$

$K^*_{pc}(D_3) = K_{pc}$ as a function of D_3 when $D_1 = D_{1_{min}}$, $D_2 = D_{2_{min}}$

$I_{pc}(D_1, D_2)$ = Rotational inertia of clapper as a function of D_1 and D_2

In these equations, $F^*_{pc}(D_3)$ is the F_{pc} value of the clapper, measured directly on the baton like the real carillons, when $D_1 = D_{1_m}in$, $D_2 = D_{2_m}in$, and D_3 is varied across its range of values. Similarly, $K^*_{pc}(D_3)$ is the K_{pc} value of the clapper set to these adjustments. Measuring these values directly allows us to avoid modeling the spring S. The remaining variables are described in Table 2 in the Appendix. Although we have such a model, the semi-empirical model above was much simpler and more accurate on the fabricated assembly.

The clapper frame is made from 4 sheets of laser-cut plywood that are laminated together with epoxy to produce a 20mm thick clapper. Pockets, channels, and holes are cut in the plywood to allow weights, adjustments, bushings, and wires to fit in. Several stationary components are labeled in Figure 5. On the top left of the clapper, the bias mass is sized and positioned to decrease F and K and increase M to the desired minimum values. The short arm on the bottom right of the clapper is the impact location, the point on the clapper that hits the hard-stop crossbar on the frame. The optical beam trip sits below the impact location and passes through two optical sensors as the clapper swings through its range of motion.

The 15 clappers were assembled onto a single steel shaft spanning the length of the PDPC. The batons were manufactured from maple according to the World Carillon Federation (WCF) standard. The manual key stretcher that holds the batons also complies to WCF standards. A final picture of the PDPC is shown in Figure 7.

Two rear support plates on the instrument hold the spring-termination crossbar, the hard-stop crossbar, and the circuit board. The hard-stop crossbar spans the length of the instrument; as a note is played and a clapper swings through its range of motion, the impact location on the clapper collides with the hard-stop crossbar to simulate a real carillon clapper striking a bell.

The circuit board contains 30 optical sensors (Sharp GP1A57HRJ00F), 2 sensors per clapper. When one of the optical beam trips passes through the two sensors (Figure 6), an Arduino Mega calculates an estimate of the speed of the clapper. This speed is converted into a MIDI dynamic (0-127) and sent

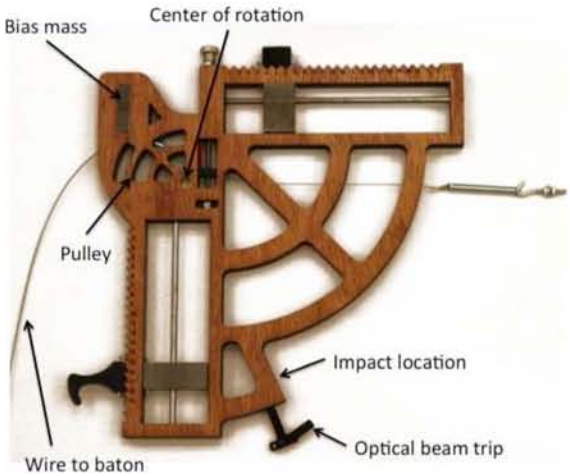

Figure 5: Some of the clapper components. The bias mass is sized and position to set the desired minimum F, K, and M values. When the baton coupled to this clapper is played, the clapper swings through its range of motion until the impact location makes contact with the hard-stop on the PDPC.

to a personal computer via USB. The PDPC communicates in standard MIDI format and is compatible with any MIDI synthesizer (Garageband, Logic, Audacity, etc).

6 Evaluation of F, K, M Detection Thresholds

As mentioned earlier, carillon characteristics vary from instrument to instrument and a goal of this project was to create an adjustable haptically accurate practice carillon. Knowing that carillons vary is not enough. We aim to know how much variation in impedance players (both novice and expert) are able to detect. The practice carillon we constructed allowed us to perform several tests to evaluate players' sensistivity to different impedance parameters. If players have an acute sensitivity to these parameters, an active-dynamics actuator may be necessary to accurately mimic the feel of a real carillon. On the other hand, if players are insensitive to one or more of these parameters, then our design for a passive-dynamics haptically accurate carillon could be further simplified.

The following test does not evaluate the accuracy of the PDPC compared to the real carillon. The PDPC produces similar F, K, and M values to those of real carillons within the limitations of our model. We chose to evaluate the player sensitivity to these parameters before comparing the PDPC to a real carillon since there is little value in being more accurate than the limits of human perception. To evaluate player sensitivity to the three parameters, we implemented a 3-alternative forced choice (3AFC) test method on one of the PDPC clapper sizes. This method is commonly used in psychophysics to determine the just-noticeable difference (JND) threshold of a psychophysical variable of interest [4, 11, 13, 16]. In this test, subjects were asked to play three adjacent batons and identify which one of the three feels different from the other two. An adaptive algorithm for the 2-down, 1-up staircase method [12, 13] was used to determine F_{pc}, K_{pc}, and M_{pc} threshold values above fixed reference F_o, K_o, and M_o values. The area below the reference values was not tested in order to focus on the area above the reference values. The choice of reference values for F_o, K_o, M_o was based on regions in Figure 3 that overlap with real carillon data. When modifying an impedance parameter, the other two parameters were held constant.

When the subject accurately identified the baton that felt different from the other two batons two trials in a row, the step size was decreased on the next trial. However if he chose the wrong baton, the step size was increased on the next trial. Note that the clapper dynamics were adjusted after each trial so the location of the "different" baton may have changed even if the subject correctly identified it in the previous trial.

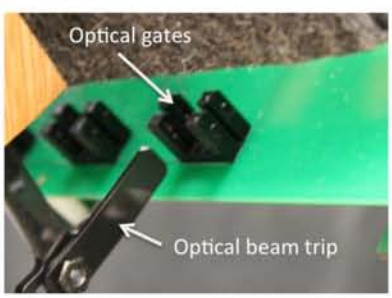

Figure 6: Just before the impact location on the clapper makes contact with the hard-stop on the PDPC, the optical beam trip passes through two optical gates. These gates communicate with an Arduino Mega that records the speed of the clapper. The information is then sent to a personal computer that reads the Arduino like a MIDI instrument and will convert the speed of the clapper into a note velocity.

Figure 7: The Passive Dynamics Practice Carillon. 15 batons and clappers line the instrument, covering a musical range of C3, C4-C5, and C7.

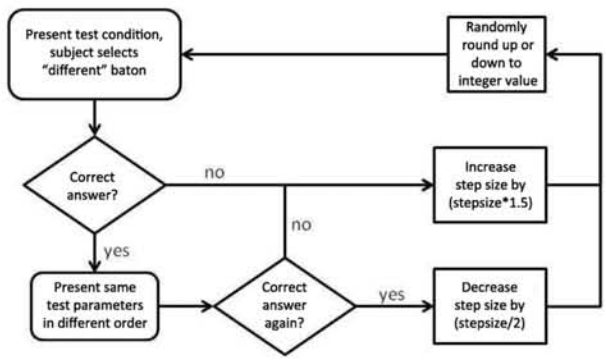

Figure 8: Flowchart for the 2-down, 1-up algorithm.

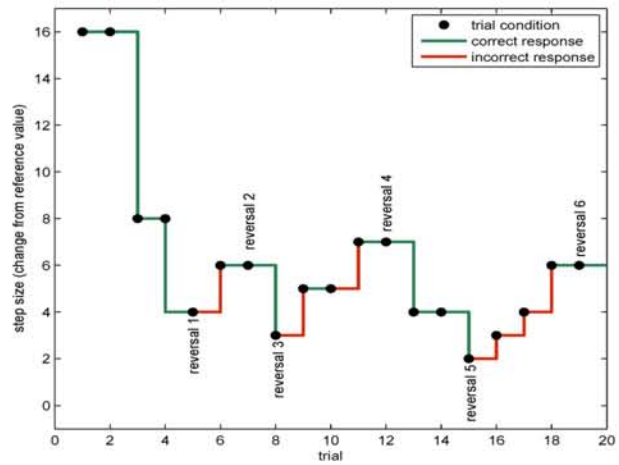

Figure 9: An example of the 2-down, 1-up staircase method showing a hypothetical test case. For illustration purposes only, trials are labeled as dots, correct responses are indicated by green staircases, and incorrect responses are highlighted by red staircases.

In psychophysics, typically a 2-down, 1-up staircase method for a threshold test terminates after 12 reversals and the average of the last 10 reversal values are used to determine the threshold. (A reversal is when the subject's answer switches from correct to incorrect or vice versa (see Figure 9). However preliminary testing on the PDPC showed that subjects' thresholds reached a near-constant value after 3-4 reversals. Since we are interested in optimizing the clapper design and are not primarily concerned with psychophysical measures, we decided to terminate the test after 6 reversals and average the last 4 reversals to obtain the threshold value. The first two reversals were excluded from analysis to account for the learning curve of the test.

6.1 Equipment and Setup

The haptic practice carillon shown in Figure 7 was used for the experiment. A black curtain was drawn across the frame to cover the carillon clappers so that test subjects would not be able to see the locations of B_1, B_2, and S on each clapper. These discrete positions of B_1, B_2, and S, denoted D_1, D_2, and D_3, correspond to the various F_{pc}, K_{pc}, and M_{pc} values for the clappers, as related by Equations 9 – 11.

A computer running a script in Matlab was used by the experimenter to enter test subjects' baton selections. When a baton selection was entered, the algorithm output D_1, D_2, and D_3 values that correspond to the new positions for B_1, B_2, and S, respectively, that the experimenter needed to adjust to for the next trial.

6.2 2-down, 1-up Adaptive Staircase Test Algorithm

An adaptive test algorithm was coded in Matlab for the 2-down, 1-up staircase test method. "Step size" was the main variable in this algorithm; it determined how many discrete "steps" the B_1, B_2, and S positions need to be away from the reference location. The discrete positions of B_1, B_2, and S (denoted D_1, D_2, and D_3) determine the corresponding F_{pc}, K_{pc}, and M_{pc} values for each carillon clapper.

A flowchart of the 2-down, 1-up algorithm is shown in Figure 8 and an example of a hypothetical test case is shown in Figure 9. In this algorithm, if the test subject correctly selects the "different" baton two trials in a row, the next step size decreases by half of the current step size and B_1, B_2 or S move to their new D_1, D_2, and D_3 values. However if the subject incorrectly identifies the "different" baton, the next step size is the current step size multiplied by 1.5.

Psychophysical experiments that utilize the 2-down, 1-up staircase test method use either fixed or variable step sizes. In our case we wanted to quickly home in on a subject's threshold and test near their threshold values. Hence we divided the step size by 2 after two consecutive correct responses. We began with a step size in the middle of our possible range.

Step size was an integer value since the passive elements were adjusted along discrete displacement intervals. As such, we developed a subroutine that randomly called the Matlab "ceil" and "floor" functions to round "step size" up or down to the nearest integer. Rounding was randomized in order to mitigate against loops in step sizes that would prevent intermediate step sizes from being tested.

The test generally terminated after six reversals, however there were two special conditions that also merited termination. One condition was at the maximum step size; if a test subject answered incorrectly at the maximum step size, the same stimulus was presented four more times to ensure that their detection threshold was truly above the maximum step size. The test terminated if the subject answered one of two tests incorrectly three times in a row at the maximum step size. The other condition was at the minimum step size; if a test subject answered correctly twice in a row at the minimum step size, the same stimulus was presented four additional times for verification. The test terminated if the subject answered correctly six times in a row at the minimum step size.

Selection of a single operating point (F_o, K_o, M_o) for all sensitivity tests presented a challenge. We had two objectives to satisfy. The first was to use a clapper configuration that would permit variation in one parameter over a large range while holding the other parameters constant. A second objective was to use an operating point that might be typical of a real carillon bell. Due to the nonlinear coupling between F_{pc}, K_{pc}, M_{pc}, $D1$, D_2 and D_3, it was difficult to satisfy both objectives with a single set of F_o, K_o, M_o. Instead, we chose slightly different operating points for each test to maximize the available adjustment range on the parameter of interest while holding the others constant.

7 Results and Discussion

The subject population consisted of a pool of 15 carillonneurs and 15 non-carillonneurs from our home university. There were 22 females and 8 males. The average age of all 30 subjects was 22±3.3 years. On average, the group of carillonneurs had 2 years of carillon experience.

The F_{pc}, K_{pc}, M_{pc} detection thresholds for carillonneurs and non-carillonneurs are presented in Figure 10. The black vertical bar shows the F_o, K_o, and M_o values. The red bars indicate subthreshold range for carillonneurs while the blue bars indicate subthreshold range for non-carillonneurs. The grey dots are the F_{pc},

K_{pc}, or M_{pc} values that correspond to discrete positions on the clapper that were adjusted for the experiment.

In the results that follow, the threshold values are reported in SI units and the thresholds are also expressed as a percentage of the initial parameter value in parentheses.

We found that the average F_{pc} threshold was $4.4N$ (26% of F_o) for carillonneurs and $4.6N$ (34% of F_o) for non-carillonneurs. This means that clapper F_{pc} values between $3.5N$ and $4.4N$ felt the same for carillonneurs, and F values between $3.5N$ and $4.6N$ felt the same for non-carillonneurs. At supra-threshold values, carillonneurs and non-carillonneurs were able to detect differences in clapper dynamics.

The average K_{pc} threshold was $132N/m$ (153% of K_o) for carillonneurs and $144N/m$ (176%of K_o) for non-carillonneurs. The average M_{pc} threshold was $6.4kg$ (43% of M_o) for carillonneurs and $6.3kg$ (45% of M_o)for non-carillonneurs. These results showed that, on average, carillonneurs in this study were slightly more sensitive to the F_{pc} and K_{pc} values than non-carillonneurs, but were less sensitive to M_{pc} values than non-carillonneurs. However, the differences between the two groups for each of the F_{pc}, K_{pc}, and M_{pc} values were not statistically significant ($p >> 0.05$). There was no correlation between years of carillon experience and detection threshold in the carillonneur group.

Three carillonneur subjects were unable to detect the largest M_{pc} step size and so we set their threshold value to the largest size possible.

The sub-thresholds for F_{pc}, K_{pc}, and M_{pc} provide guidance in two respects. First, it is clear that fewer adjustment locations would suffice to adjust F_{pc}, K_{pc}, and M_{pc} to values that are within the player's detection abilities. Second, our passive system provides greater variability than players can detect. As such, it suggests that a passive system is adequate for replicating the appropriate haptics for a practice carillon. However, further testing is needed to compare the haptics of the practice carillon to a real carillon in case there are unmodelled dynamics to consider.

It is unclear if the thresholds for F_{pc}, K_{pc}, and M_{pc} measured in this experiment represent the upper bound on detection. Playing the batons faster, slower, with more flick or throwing, or during a well-rehearsed performance may lead to different results. Further testing is necessary to determine how technique and repetition affect the F_{pc}, K_{pc}, and M_{pc} thresholds.

8 Conclusion

In this paper, we have described a design for a passive dynamics haptic practice carillon. This purely mechanical system can achieve the haptic feel of many real carillons in New England and costs much less than haptic practice carillons that utilize electric motors for haptic rendering. We evaluated the design of our clappers by conducting a 3-alternative forced-choice (3AFC) threshold test to determine players' sensitivities to the clapper dynamics – the F, K, and M variables.

We compared the haptic sensitivities of carillonneurs and non-carillonneurs and found that carillonneurs were more sensitive to the F_{pc} and M_{pc} values than non-carillonneurs but less sensitive to K_{pc} values than non-carillonneurs. However these differences between the groups were not statistically significant. The average thresholds for F_{pc}, K_{pc}, and M_{pc} were 26%/34%, 153%/177%, and 43%/45%, respectively, for carillonneurs/non-carillonneurs. These threshold values indicate that players were relatively insensitive to moderate changes in F_{pc}, K_{pc}, and M_{pc}. This knowledge will allow us to optimize the clapper design by decreasing the resolution of clapper adjustments as well as consolidating the present set of 4 clappers into a set of 3.

As a final note, it is encouraging that a passive system with thoughtful kinematics and dynamics can be adjusted to create a high fidelity, high dynamic range haptic device. Creating an equivalent system with electromechanical actuators would be significantly more complex and expensive.

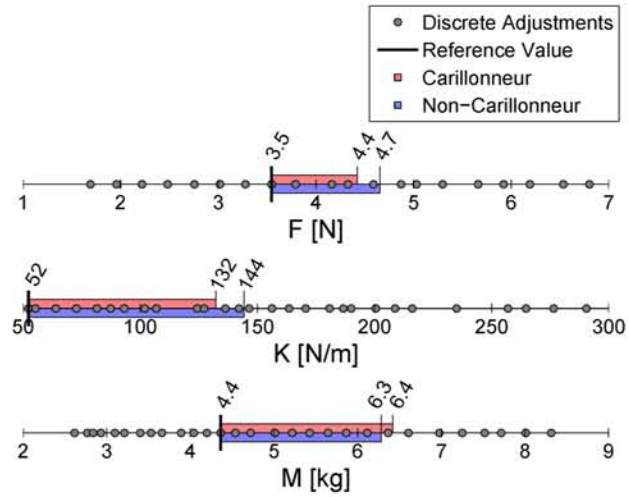

Figure 10: Results of sensitivity testing for F_{pc}, K_{pc}, and M_{pc} . The figures here show the reference value and sub-threshold regions for F_{pc}, K_{pc}, and M_{pc} . When varying F_{pc}, $K_{pc} = 75N/m$ and $M_{pc} = 4.6kg$. When varying K_{pc}, $F_{pc} = 4.6N$ and $M_{pc} = 4.1kg$. When varying M_{pc}, $F_{pc} = 4.4N$ and $K_{pc} = 136N/m$.

9 Future Work

The results of this study motivate our future work in several areas. First, we aim to perform more extensive threshold sensitivity tests around several F_o, K_o, and M_o values that span several orders of magnitude. In this study we tested subjects' sensitivities to clapper dynamics around one specific set of F_o, K_o, and M_o. However, real carillons span a wide range of F, K, and M and it is unclear whether the sensitivities to F, K, and M will remain a relatively constant percentage of the parameter of interest or not. Gathering threshold data about multiple reference values would allow us to investigate this trend and formulate clapper design recommendations for practice carillons across the full range of real carillon clapper dynamics.

Second, we would like to redesign our current haptic practice carillon clappers to reduce their mass and simplify their geometries. Consolidating the clapper sizes from 4 to 3 would also reduce manufacturing complexity for the haptic practice carillon. In the clapper redesign, we also hope to constrain their volume to fit inside existing practice carillons in order to augment the practice carillons with a more accurate haptic feel.

Finally, we wish to investigate how closely the feel of our haptic practice carillon matches with real carillons across New England. We hope to recruit carillon players of all levels to conduct just-noticeable difference (JND) threshold tests to evaluate our design.

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References

[1] Association pour la Creation et la Recherche sur les Outils d'Expression. Instrumentarium. http://www-acroe.imag.fr/produits/instrumentarium/instrumentarium_en.html.

[2] B. Bongers, G. van der Veer, and M. Simon. Improving gestural articulation through active tactual feedback in musical instruments. *ConGAS Symposium on Gesture Interfaces for Multimedia Systems*, March 2004.

[3] Chimemaster. Millennium Carillon by Chime Master. http://www.chimemaster.com/millennium/, September 2011.

[4] J.-M. Dessirier, J.-M. Sieffermann, and M. O'Mahony. Taste discrimination by the 3-AFC method: Testing sensitivity predictions regarding particular tasting sequences based on the sequential sensitivity analysis model. *Journal of Sensory Studies*, 14(3):271–287, 1999.

[5] B. Gillespie. The Touchback Keyboard. *Internaional Computer Music Conference*, 1992.

[6] M. Havryliv, F. Geiger, M. Guertler, F. Naghdy, and G. Schiemer. The carillon and its haptic signature: Modeling the changing force-feedback constraints of a musical instrument for haptic display. In *Proceedings of the 4th International Conference on Haptic and Audio Interaction Design*, pages 91–99. Springer-Verlag, 2009.

[7] M. Havryliv, F. Naghdy, and G. Schiemer. Synthesising touch: haptic-rendered practice carillon. In A. Riddell, A & Thorogood, editor, *Proceedings of the Australasian Computer Music Conference 2007: TRANS Boundaries / Permeability / Reification*, pages 66–73, 2007.

[8] M. Havryliv, F. Naghdy, G. Schiemer, and T. Hurd. Haptic carillon: A computationally enhanced mechanical performing instrument. In *Cultural Computing*, volume 333, pages 75–86. Springer Boston, 2010.

[9] M. Havryliv, G. Schiemer, and F. Naghdy. Haptic carillon: Sensing and control in musical instruments. In *Proceedings of the Australian Computer Music Conference*, 2006.

[10] F. Jen, P. Gururaja, R. Middleton, and S. Shea. True Force Keyboard: Force-reflecting electronic musical instrument interface. University of Michigan Capstone Design and Manufacturing Experience, Department of Mechanical Engineering, April 18, 2006.

[11] S. Kemp, T. Hollowood, and J. Hort. *Sensory Evaluation: A Practical Handbook*. Wiley & Sons, 2009.

[12] F. A. A. Kingdom and N. Prins. *Psychophysics: A Practical Introduction*. Elsevier, 2010.

[13] B. Kollmeier, R. H. G. Gilkey, and U. K. Sieben. Adaptive staircase techniques in psychoacoustics: A comparison of human data and a mathematical model. *Journal of the Acoustical Society of America*, 83(5):1852–1862, 1988.

[14] S. O'Modhrain and C. Chafe. Incorporating haptic feedback into interfaces for music applications. In *8th International Symposium on Robotics with Applications, ISORA*, 2000.

[15] C. Ramstein. US Patent 7659473, system and method for providing haptic feedback to a musical instrument, February 2010.

[16] M. B. Wolf. *Sensory testing methods*. American Society for Testing and Materials, 1996.

[17] Yamaha. DGX630P. http://usa.yamaha.com/.

[18] Yamaha. Portable Grand Piano DGX630. http://usa.yamaha.com/.

Appendix

Table 1: Variables used to model dynamics of a carillon bell

Name	Description
F_{player}	The impedance felt by the player
F	Static impedance parameter
K	Resistive impedance parameter
M	Inertial impedance parameter
θ_0	Resting angle of clapper offset to verticle
θ_d	Angle swept out by clapper in deflected position
θ	Instantaneous position of clapper relative to θ_0
y	Instantaneous baton deflection, measured at wire
y_d	Baton deflection in deflected position, measured at wire
L_{CM}	Distance from clapper fulcrum to center of mass
L_1	Distance from clapper fulcrum to wire connecting to bell crank
L_2	Distance from baton fulcrum to wire connecting to bell crank
L_{baton}	Distance from baton fulcrum to end
W_c	Weight of clapper
F_a	Force from an assist spring
F_{a_0}	Static force from an assist spring
k_a	Spring constant of an assist spring
x_a	Instantaneous deflection of an assist spring
F_r	Force from a return spring
F_{r_0}	Static force from a return spring
k_r	Spring constant of a return spring
x_r	Instantaneous deflection of a return spring
I_c	Rotational inertia of clapper

Table 2: Variables used to model dynamics of Passive Dynamics Practice Carillon

Name	Description
F_{pc}	Force term of practice carillon impedance
K_{pc}	Stiffness term of practice carillon impedance
M_{pc}	inertial term of practice carillon impedance
B_1	Adjustable block 1
B_2	Adjustable block 2
S	Adjustable Spring
D_1	x component of clapper center of rotation to center of mass of B_1
D_2	y component of clapper center of rotation to center of mass of B_2
D_3	y component of clapper center of rotation to spring S attachment
$D_{1_{min}}$	Smallest possible value of D_1
$D_{2_{min}}$	Smallest possible value of D_2
W_{B_1}	Weight of B_1
W_{B_2}	Weight of B_2
R	Clapper pulley radius
y_d	Baton deflection in deflected position, measured at wire
L_2	Distance from baton fulcrum to wire connecting to bell crank
L_{baton}	Distance from baton fulcrum to end
$F^*_{pc}(D_3)$	F_{pc} as a function of D_3 when $D_1 = D_{1_{min}}$, $D_2 = D_{2_{min}}$
$K^*_{pc}(D_3)$	K_{pc} as a function of D_3 when $D_1 = D_{1_{min}}$, $D_2 = D_{2_{min}}$
$I_{pc}(D_1, D_2)$	Rotational inertia of practice carillon clapper as a function of D_1 and D_2