Reality-Based Models for Vibration Feedback in Virtual Environments

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***Abstract*—Reality-based modeling of vibrations has been used to enhance the haptic display of virtual environments for impact events such as tapping, although the bandwidths of many haptic displays make it difficult to accurately replicate the measured vibrations. We propose modifying reality-based vibration parameters through a series of perceptual experiments with a haptic display. We created a vibration feedback model, a decaying sinusoidal waveform, by measuring the acceleration of the stylus of a three degree-of-freedom haptic display as a human user tapped it on several real materials. For some materials, the measured parameters (amplitude, frequency, and decay rate) were greater than the bandwidth of the haptic display; therefore, the haptic device was not capable of actively displaying all the vibration models. A series of perceptual experiments, where human users rated the realism of various parameter combinations, were performed to further enhance the realism of the vibration display for impact events given these limitations. The results provided different parameters than those derived strictly from acceleration data. Additional experiments verified the effectiveness of these modified model parameters by showing that users could differentiate between materials in a virtual environment.**

***Index Terms*—Force feedback, haptic interface, haptics, perceptual experiments, reality-based modeling, vibrations, virtual environments.**

I. INTRODUCTION

CONVENTIONAL approaches to haptic display usually consist of designing a virtual model with simple geometry and analytical equations, then using a first-order stiffness control law to emulate a hard surface. However, such first-order models often lack the realism of higher order effects, such as impact. With common haptic rendering algorithms, surfaces feel "squishy" or unrealistically smooth.

When humans touch an environment, fast-acting sensors embedded in the skin record the minute vibrations occurring from this interaction. When tapping on a table top, the presence of the table is detected not only by kinesthetic sensors in the muscles and tactile sense due to skin deformation, but also from vibrations resulting from the contact of two surfaces (the finger and the table) that can be both heard and felt [8]. Haptic displays are often good at providing kinesthetic sensations, but the amount of force is limited in comparison to the elastic forces provided by many real materials.

Hard surfaces are difficult to display with conventional non-passive haptic (or force-feedback) devices. Due to limited actuator power, system delays, and possible instabilities, the display of hard surfaces is always limited in stiffness, and therefore, in realism. One solution to improving the realism of such environments is to add higher order effects such as vibrations. These effects can use surface models based on physical measurements. Empirical data can be used to model textures, surface geometry, and the vibrations resulting from performing various tasks. Vibration feedback is an enhancement to virtual environments that can be accomplished without additional hardware for most haptic displays.

This study of models for vibration feedback fits into a larger class of research on reality-based modeling. In reality-based modeling systems, models and virtual environments are created using data acquired from real environments using various sensing methods. While shape acquisition is already an essential part of applications such as reverse engineering and computer graphics, new technologies for rapid acquisition of other physical properties are emerging, with the potential to acquire rich, multimodal models. There are recent examples in force [3], vision [15], [19], and audition [16]. In addition, telerobotic data acquisition systems such as the Active Measurement Facility of the University of British Columbia [13] are being developed to provide "one-stop-shopping" for a variety of registered measurements.

Tactile and auditory impact vibration models and feedback have been studied by various groups. Durst and Krotkov [5] studied the impact acoustics resulting from object collisions and were able to develop an object classification system from the data. For the application of haptic display, Howe and colleagues [4], [9], [12], [21] have studied the vibrations resulting from several different tasks in both virtual and teleoperated environments. Kontarinis and Howe [9] investigated the use of tactile displays for conveying task-related vibrations in both types of environments, using a haptic display augmented with a voice coil motor, which shook a small mass, the motor magnet, to provide high-frequency vibrations. For their two-fingered master–slave teleoperation system, users successfully identified damaged ball bearings, punctured membranes, and assembled a peg in a slot. In these experiments, an accelerometer measured the vibrations at the slave fingertip. This signal was directly fed back to the user through the inertial load of a voice coil motor. Using a similar feedback mechanism, teleoperation

Manuscript received April 15, 2000; revised February 28, 2001. This work was supported by the U.S. Army under STRICOM Grant M67004-97-C-0026, through Immersion Corporation, San Jose, CA. Recommended by Guest Editor N. Xi.

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Publisher Item Identifier S 1083-4435(01)08142-X.

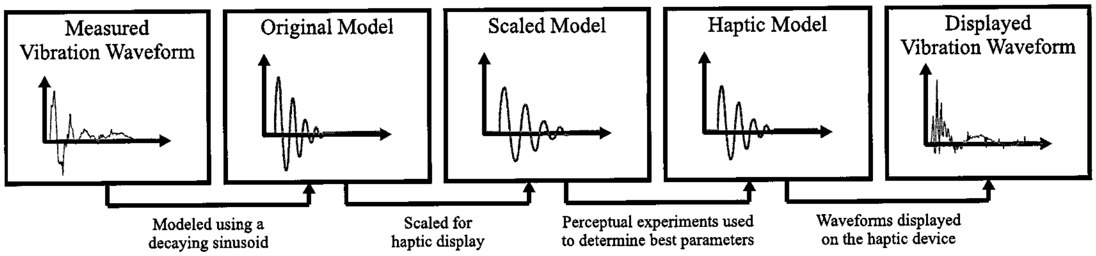

Fig. 1. Measured and modeled vibration waveforms. Starting with the data collected from tapping on real surfaces, an original decaying sinusoid model is created. Taking into consideration the bandwidths of the haptic display and human tactile sensitivity, the scaled model is determined. Psychophysical experiments identify the parameters for the haptic model, and the final displayed vibration waveform is measured.

experiments were performed by Dennerlein and Howe [4]. Piezoelectric sensors embedded in the grippers of a six degree-of-freedom Schilling (Davis, CA) underwater assembly robot sensed vibrations, which were fed directly back to the user.

For vibration feedback in virtual environments, there is no simultaneous vibration measurement, thus, a model is used in order to determine the forces to display. Wellman and Howe modeled the vibrations resulting from tapping on surfaces of different stiffness, and played them back to observers through a force feedback device augmented with a voice coil motor [21]. They also compared the ability of humans to distinguish between surfaces of different stiffness in real and virtual environments, finding that the virtual environments worked almost as well as the real ones. Okamura, *et al.* expanded this work in surface stiffness and also considered the tasks of puncture and patterned texture stroking with a stylus [12]. Vibration models were obtained for these tasks and assembled into a vibration waveform library. Unlike Wellman and Howe and Kontarinis and Howe, Okamura, *et al.* displayed the vibrations through the actuators of the haptic display itself, rather than an augmenting the haptic display with an additional voice coil-type shaker.

We seek to improve realism without additional or modified haptic display hardware. As a result, several primary questions are addressed in order to create realistic vibration feedback algorithms for virtual environments. First, what type of model is appropriate for vibrations in the virtual environment? Wellman and Howe [21] provide a good framework, on which we expand. Second, since we are not modifying the haptic device, what are the required performance criteria for the device to display vibration feedback models? For models which cannot be displayed with the limited capabilities of the haptic device, the model parameters can be scaled. Third, given the probable limitations of a haptic display, how can vibration feedback be made to feel as realistic as possible? Since we are seeking a feeling of realism for the user, a set of perceptual experiments are used to improve the scaled reality-based models. Finally, does this modified vibration model for virtual models work? When different materials and their vibration models are displayed in a virtual environment, can subjects correctly identify the material?

These questions provide the specific aims for this study.

1) Create a virtual library of vibrations and display algorithms;

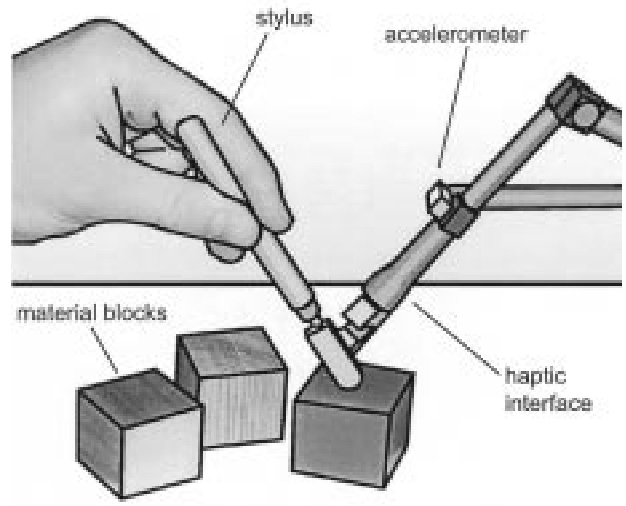

Fig. 2. Tapping on material samples (rubber, wood, and aluminum) with a stylus. The stylus is attached to the end-effector of the 3GM haptic interface, which is instrumented with an accelerometer for impact vibration measurement. The accelerometer is placed to measure the vibrations experienced by the haptic display.

2) Evaluate the haptic display and modify the models to display the vibrations by first scaling the parameters and then using psychophysical methods;
3) Evaluate the effectiveness of the vibration display in a virtual environment.

The following three sections of this paper are each devoted to one of these aims, and each includes subsections for experiments, results, and discussion. The concluding section summarizes the results of each experiment and discusses avenues for future work.

II. Building Reality-Based Vibration Feedback Models

Building the vibration models involved several steps. Fig. 1 shows the various vibration waveforms and models examined in this work. The first step is the measurement of vibration waveforms resulting from tapping on real surfaces and modeling them using a decaying sinusoid.

In this set of experiments, we considered three materials with disparate stiffness: Urethane RTV rubber, wood, and aluminum. The samples used were solid 3.5 cm cubes of the materials, as shown in Fig. 2. Previous research in using vibration feedback to distinguish between surfaces has shown that unless materials differ significantly in hardness or stiffness, humans cannot tell them apart even when tapping on real materials [21].

The experimental apparatus used to measure the vibration parameters in the real environment, and then to later display the vibrations in a virtual environment, was a six degree-of-freedom desktop haptic device with three degrees of freedom of force feedback and position/velocity sensing. The stylus end-effector of the device, the 3GM from Immersion Corporation (San Jose, CA) [7], is shown in Fig. 2.

A. Experiment

A tri-axial Kistler 8694M1 500-g accelerometer mounted on the haptic device measured impact vibrations. The choice of this placement was carefully considered. One potential location was the tip of the stylus, in order to record the "pure" acceleration profile of the tapping. This acceleration profile could then potentially be used to model the interactions between a finger and the surface. However, our intent was to build a vibration model of stylus-material interaction, to be displayed on a haptic interface. A stylus interface is quite reasonable for many tasks, and is supported by the design of three degree-of-freedom haptic interfaces such as the 3GM and SensAble's PHANToM [10]. Thus, the accelerometer was positioned to record the vibrations felt by the haptic interface during tapping, at a place where the vibrations can be controlled during haptic display. The sensor must also be placed on the device rather than the stylus because the swivel joint attaching the stylus to the haptic interface is unactuated. Due to space considerations, the accelerometer was attached near the center of the end-effector link of the haptic display. While some higher frequency vibrations may be attenuated at this location, this higher order information is impossible to display with the haptic interface and does not represent a loss in achievable realism of the haptic display.

An aluminum extension attached to the end of the stylus provided a good contact surface with a blunt point approximately 1 mm in diameter. The contact diameter was measured by inking the tip, pressing it onto a piece of paper, and taking the diameter of the resulting mark. Position, velocity, and acceleration data were taken using Pentium 166-MHz personal computer at approximately 25 kHz.

Tapping was done manually, with the stylus held at a 45° angle to the surface and tapped at different velocities as shown in Fig. 2. In previous work (Okamura *et al.* [12]), separate position-sensing and haptic devices were used for recording and playing vibrations; in the current work the same device is used for both tasks. This is important for haptic display because it allows direct comparison between the acceleration data from tapping on real and virtual surfaces.

B. Results and Vibration Model

When determining how to model the vibrations resulting from tapping, there are several issues to consider. One is that the vibrations will be displayed using real-time algorithms. Thus, the model should be simple enough to meet throughput requirements. Alternatively, table look-up or other means can be used to display complicated waveforms with minimal computation time. Another consideration is the necessary accuracy of the models. Vibration frequencies much higher than 1 kHz are not

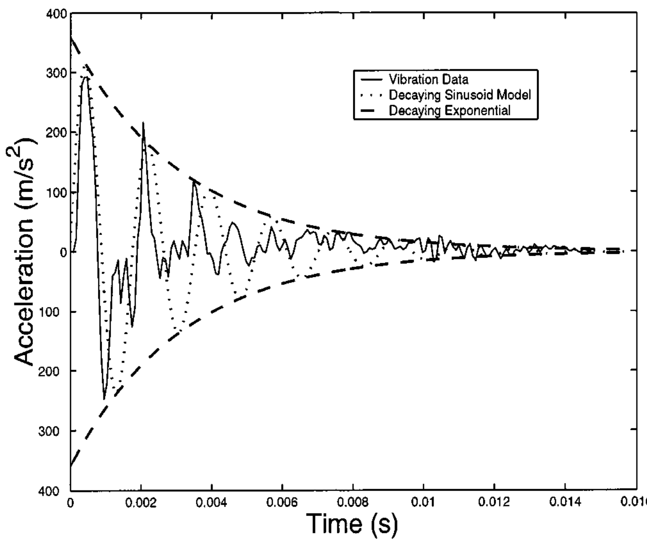

Fig. 3. The decaying sinusoid model fit to experimental data for tapping on wood.

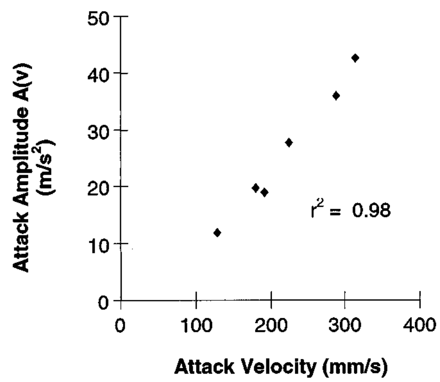

Fig. 4. The plot of initial amplitude of the vibration waveform versus the impact velocity exhibits linearity. The linear fit for rubber has an r^2 value of 0.98.

easily sensed by humans [14], so it may be unnecessary to display vibrations with such detail.

The vibration feedback model developed from the tapping data is a decaying sinusoidal waveform

$$Q(t) = A(v)e^{-Bt}\sin(2\pi\omega t). \quad (1)$$

The estimated model parameters are $A(v)$, the amplitude as a function of impact velocity, B, the decay rate of the sinusoid, and ω, the sinusoid frequency. Fig. 3 shows the decaying sinusoid model fit to experimental data for tapping on wood. These parameters were assumed to be constant for each material. The decaying sinusoid model was chosen because it is the free response of a second-order mass-spring-damper system, a fundamental vibration system having few components and satisfactory simplicity. Adding more components will not likely increase the realism due to limitations in human haptic sensing and haptic device bandwidth, and would it require more computational power for both the system and the user.

The three model parameters were determined separately for each material. The attack amplitude parameter $A(v)$ was measured by plotting acceleration amplitude versus impact velocity. The relationship was approximately linear (Fig. 4), so the amplitude parameter is the product $A{\cdot}v$, where v is the impact velocity

TABLE I
VIBRATION PARAMETERS FOR ORIGINAL DECAYING SINUSOID MODEL

Material	A (s^{-1})	B (s^{-1})	ω (Hz)
Rubber	-116.7	40,000	18
Wood	-1500	600,000	592
Aluminum	-100,000	1,500,000	1153

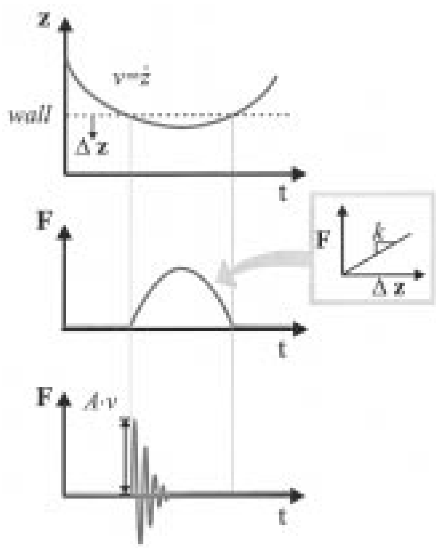

Fig. 5. Algorithm for vibration and force feedback of the tapping task. As the user approaches a virtual surface, the velocity is measured. Spatial feedback is provided as a stiffness control law where the force applied to the user is proportional to and in the opposite direction of penetration into the wall. Temporal feedback is provided by a vibration waveform played at the moment of impact. These two types of feedback are superimposed and displayed simultaneously.

of the stylus tip and A is an empirically determined scaler, called the amplitude slope parameter. The decay parameter, B, was found by a least squares fit to the positive and negative peaks of the vibration waveform. The frequency parameter, ω, is the fundamental frequency identified using a Fast Fourier Transform (FFT). The frequency remained constant despite moderate differences in tapping speed. Table I lists the parameter values for the three materials tested.

Using this vibration feedback model and measured parameters, an algorithm for displaying the impact vibrations was developed (Fig. 5). The first plot shows the position of the end-effector of the haptic display as it approaches, penetrates, and leaves the virtual surface with respect to time. The velocity at the moment of impact is measured. The stiffness of the wall is displayed by measuring the surface penetration (Δz) and displaying a proportional force. For all the materials, the same stiffness k was used. The vibration waveforms were then superimposed on this stiffness force. The amplitude of the vibration waveform was determined by the impact velocity and the amplitude–velocity slope for the material. The appropriate decay rate and frequency parameters were also selected for the particular material being displayed.

Stability is not a large concern with this algorithm. The stability of the force-feedback portion (a virtual wall) has been analyzed in [6]. The vibration feedback portion is performed open-loop. While the the addition of vibration feedback certainly adds energy to the system, it is quickly damped out due to the exponentially decaying nature of the model.

C. Discussion

At the end of this parameter identification process, we obtain vibration waveform models that describe the experimental conditions. The models cannot necessarily be abstracted or extended to other sizes and shapes or new materials. For example, no consistent relationship between modulus of elasticity and vibration frequency has been found. While attack frequency generally increased with increasing material stiffness, parameterization did not yield a good enough fit $(r^2 = 0.61)$ to use stiffness as a predictor of vibration frequency. The experimental conditions for taking tapping data, including the type of stylus (material and shape) and the geometry of the material being tapped, have an effect on the shape of the vibration waveforms. Preliminary experiments showed that when a stylus is tapped in a cantilever position, the vibration waveforms are significantly affected. By tapping with the stylus perpendicular to the surface, the resonant frequency of the stylus is higher and has less effect on the resulting vibrations. The higher frequency vibrations evident in Fig. 3 are due in part to stylus vibration. It is also apparent that the mechanics due to the geometry of the material being tapped will also result in different vibrations. For example, tapping on the hollow thin metal sheet of the hood of a car creates different vibrations than tapping on a solid cube of steel.

While the frequencies identified were generally consistent for the materials tested, we found that at very high-speed taps, the fundamental frequency shifted. (For example, rubber shifted from 18 to 25 Hz). This can be explained by unmodeled nonlinearities in the system. With linear systems, a change in input amplitude will only cause a change in output amplitude, not output frequency. However, when a nonlinear system is excited with different amplitudes of input, the frequency of the output may change. One example of such a case is the analysis of musical instrument tones, where playing "harder" can change the tone [17].

D. Haptic Device Capabilities

Using the physically measured parameters to display vibrations, the model did not feel as realistic as possible, in part due to the inability of the haptic device to accurately display the desired waveform. An analysis of the haptic device using frequency methods was used in order to determine the physical basis of this phenomenon.

Sinusoidal waveforms from a signal generator were input to the 3GM haptic device while the output of the accelerometer on the oscilloscope was monitored. Fig. 6 shows the normalized magnitude response, the ratio of the accelerometer output to the signal generator input signal, of the motor primarily responsible for displaying vibrations during tapping in the virtual environment. From this figure, it is apparent that the ability of the haptic display to display desired magnitude forces falls off as frequency increases.

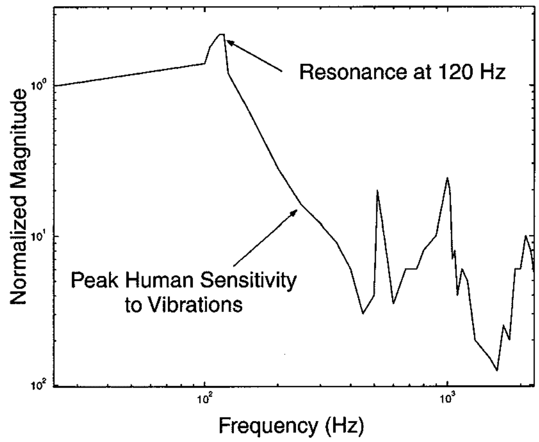

Fig. 6. Normalized magnitude response of the 3GM haptic device to various input frequencies. Data was collected by providing a sinusoidal input to a single motor and measuring the acceleration at the endpoint of the haptic interface. The stylus was lightly grasped by the experimenter to hold the endpoint at the nominal tapping position. The peak sensitivity of humans to vibration is approximately 250 Hz.

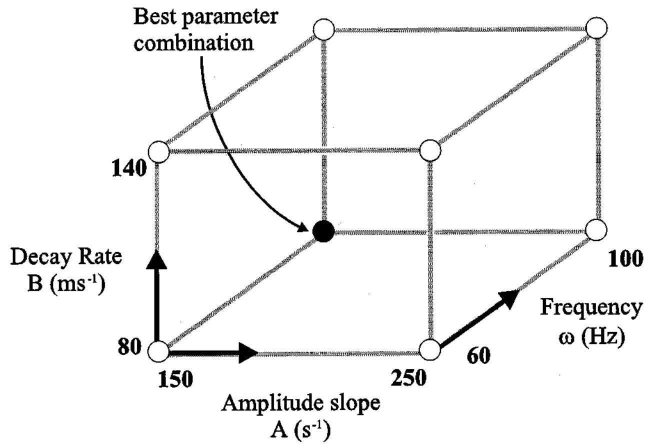

Fig. 7. Factorial experiment design for wood. Maximum and minimum values for each parameter (amplitude, decay rate, and frequency) are chosen around a nominal value determined from the scaled vibration model. Each corner of the cube represents a combination of parameters that was tested in the perceptual experiments, and the black circle shows the experimentally selected best combination.

III. Improving Models with Psychophysical Experiments

Since it was not viable to exactly replicate the original vibration models obtained from experimental data, to was necessary to obtain modified model parameters. Using the original vibration parameters as initial guidelines, the parameters were scaled and then further modified based on subjective evaluations.

The sensitivity for human vibration sensing ranges from dc to over 1 kHz, with peak sensitivity around 250 Hz [1]. As the haptic display is not able to correctly implement high frequencies, and they are also beyond the peak sensitivity of the human haptic sensory system, the haptic model does not need to include frequencies much higher than 250 Hz. The frequency parameter of the model was therefore decreased proportionally so that the scaled models included frequencies that could be easily felt by human haptic sensing. For example, aluminum was scaled from 1153 to 300 Hz. The frequencies for the different materials were not scaled equally; the scale factors were determined by informal perceptual tests with expert users. The goal in scaling was to bring each frequency into the desired range while maintaining a difference between materials that was significant enough to be felt by the expert users.

Once the frequency parameters were chosen, the decay rate and slope parameters were also scaled. By evaluating the simulated models as displayed by the haptic device, new values for decay rate and slope parameters were obtained. The steps in this process were to: 1) begin with the parameter values obtained experimentally; 2) scale the values down using expert user feedback; and 3) use subjective evaluations to determine the final haptic model. Fig. 1 depicts each of these steps, and the following section describes the perceptual experiments performed in step 3).

A. Experiments

In order to ascertain which simulated vibration model parameters were best, perceptual experiments were performed to compare the realism of different parameter combinations. Again, the experimental equipment consisted of the 3GM haptic device, blocks of material for simulated model comparison (rubber, wood, and aluminum), and a control computer. A factorial design, as described by Box and Bisgaard [2], was used to determine parameter combinations. This method entailed choosing two values for each of the three parameters to be examined: frequency, decay rate, and amplitude slope (multiplied by impact velocity in the model). A high and a low value were chosen for each parameter bounding the nominal value from the scaled parameter. These high and low values were chosen so that the difference between the models with the different parameter sets was above the Just Noticeable Difference (JND) of the experimenter. In order to test all combinations of the above parameters, $8(2^3)$ different sets of parameters were displayed for each material. Fig. 7 shows the parameter combinations tested for wood. The parameter combinations selected as most realistic by the users is highlighted.

Nine users were asked to evaluate the eight different simulated vibration models for each of the three materials. They used the 3GM to control a cursor on the computer monitor, which included a virtual surface simulating the appropriate material. The users were encouraged to compare the simulated vibration models with vibrations felt from tapping on the real blocks of materials, in order to better evaluate the realism of the simulated model. The users then rated each of the eight models for a material on a scale of 1–10 (least to most realistic). Each user was presented with a random order of virtual materials and parameter combinations for each material.

B. Results

The experimental data consisted of ratings for each of the eight different simulated models for each material. In order to reduce the data to a meaningful form, each of the users' rating sets (different parameter combinations for a given material) were normalized to have an average of 0 and a standard deviation of 1. This was necessary in order to compare the data

TABLE II
MOST REALISTIC VIBRATION PARAMETERS AS DETERMINED BY PERCEPTUAL EXPERIMENTS

Material	A (s^{-1})	B (s^{-1})	ω (Hz)
Rubber	-240	60,000	30
Wood	-150	80,000	100
Aluminum	-300	90,000	300

of different users, who all had different means and variances. The results of the experiment (Table II) show which parameter values were most realistic for the three materials. These parameters were used to create the haptic model shown in Fig. 1.

The factorial experiment design also allowed calculation of the most sensitive parameter for each material. By comparing pairs of parameter combinations where only one parameter is varying, the main effects, or single factors, can be found. Using Analysis of Variance (ANOVA), it was found that decay rate was most sensitive for displaying rubber, frequency for wood, and slope for aluminum. Different parameters, then, affect the display of different materials with varying levels of sensitivity. The interaction effects were also calculated by taking the differences between pairs of main effects. While interactions were present between pairs of all three parameters, there was no particular interaction that dominated across all three materials simulated.

Qualitative user responses revealed that rating the realism of the models was a difficult task. Several of the users commented that they did not feel any difference between some of the models. A larger difference between the low and high values for each parameter can be used to resolve this problem. Furthermore, these values were obtained using the JND of the experimenter. Also, the number of models rated by each user (a total of 24) was high and resulted in users becoming fatigued toward the end of the experiment.

C. Discussion

Typical haptic display systems cannot display the stiffness of real surfaces, nor can they exactly display the desired vibration waveforms. Since some of the desired vibrations were out of the frequency and acceleration limits of the haptic device, the haptic models were scaled down from the original models. Despite the fact that parameters obtained from the original model are not used, it is important to perform this initial modeling to verify the shape of the waveform and get nominal values for frequency, amplitude, and decay rate. Comparing the original parameters from different materials also provides information about the differences between the responses of various materials.

It is also notable that the sensitivity of different effects is a function of the choice of maximum and minimum parameter values used in the factorial experiment design. The sensitivity results described above can be explained when the properties of different materials are considered. Decay rate was the most sensitive factor for rubber because the damping is relatively low and the differences between the maximum and minimum decay rate values were easily sensed by the users. For wood, the frequency was the most sensitive parameter. This is best explained by a process of elimination. The decay rate is fast enough so that difference between the maximum and minimum values is not easy to detect. The parameter values for amplitude may not have been spread as far apart as for decay rate, resulting in a higher sensitivity to frequency. For aluminum, the frequencies and decay rate were fast and high enough that they are difficult to discriminate using human tactile sensors. Thus, amplitude was the most sensitive factor.

IV. TESTING VIBRATION FEEDBACK MODELS

Based on the last set of experiments, the most realistic model for each of the three materials (rubber, wood, and aluminum) was determined. To verify that these models were effective in a virtual environment, an additional perceptual test was performed.

A. Experiment

Users were shown a single virtual environment with three different surfaces, each using the vibration feedback model for rubber, wood or aluminum, in random order. Each material was displayed using the same stiffness, so they only varied in vibration. The virtual environment was displayed visually on the computer monitor and haptically with the Immersion 3GM, using the algorithm shown in Fig. 5. The most realistic values from Table II were used for the vibration waveforms. The users were informed that there was only one virtual model for each material and were told to tap on the surfaces in order to distinguish between them. They were also provided with real samples of each material to tap on for comparison. Each user did this identification experiment three times. The 14 users, a different set from the previous experiment, ranged in age from 11–35 and in experience level from novice to expert.

B. Results

As shown in Table III, most of the experiments resulted in correct identification of the three materials (83.3%). A “correct” answer occurred when a user correctly identified all three of the materials. Correct identification of one material but switching the other two resulted in an incorrect answer. Each of the 14 users performed the experiment 3 times, resulting in a total of 42 observations. In the post-experiment questionnaire, many of the users revealed that they felt they were learning as they progressed through the three trials. One can see that when only the third trial for each user is considered, the success rate is slightly higher (85.5%). It is also notable that the difference in performance between novice and expert users was not large (88.9% success for experts and 79.2% for novices).

C. Discussion

The most common error in surface identification was mistaking wood and rubber. Many of the users felt that the high frequency “ringing” of the aluminum model was a clear indication of a metallic material. In contrast to the realism rating experiment, many of the users for this test felt that it was straightforward. This is expected, as the task of distinguishing between different materials is much easier than rating very similar models of the same material. When asked to comment on the realism

TABLE III
EXPERIMENTAL RESULTS FOR USER IDENTIFICATION OF MATERIALS

Data type	Number of Experiments	Correct	Incorrect	Percent Correct
All Experiments	42	35	7	83.3%
Third Test Only	14	12	2	85.7 %
Experts Only	18	16	2	88.9%
Novices Only	24	19	5	79.2%

of the surfaces, a few users noted that the vibrating surfaces felt “active” and thus unrealistic. However, many users felt that, while the virtual materials did not exactly feel “realistic”, they did feel more so in comparison with a virtual surface without vibrations.

Subject suggested that they used both tactile feedback and auditory feedback from the motors of the haptic interface in discerning the materials. In previous experiments [12], auditory information was eliminated by playing white noise to the users, and it was shown that vibrations were distinguishable only using the sense of touch. Here, we have allowed the sounds to be part of the system, as users will typically not be listening to white noise in a virtual environment. The auditory signals provide further immersion into the system.

V. CONCLUSIONS

These results indicate that reality-based models of vibrations can be used to enhance virtual environments. The following points address the primary questions posed in Section I.

First, an impact vibration is similar in shape to a decaying sinusoid. Model parameters can be determined by analyzing the FFT, ratio of maximum amplitude to impact velocity, and the envelope of the measured waveform.

Second, the haptic device should have a significant response for frequencies at which humans have peak vibration sensitivity. The vibration waveforms for some materials, such as aluminum, have higher frequencies and cannot be accurately displayed or sensed. High waveform amplitudes are also impossible to display with conventional haptic devices. Thus, when waveform parameters are out of the range for practical display, the waveform must be scaled down for haptic rendering.

Third, vibration feedback models can be made to feel more realistic through perceptual experiments. When the vibration waveforms were modified from the original model to the scaled model, initial testing showed that the selected vibration parameters were not necessarily the best for making the virtual surfaces feel real. Thus, perceptual experiments were used, allowing users to rate various parameter combinations for realism.

Finally, vibration feedback with the new parameter values was effective. In the final experiment, users successfully identified three different virtual materials that differed by vibration feedback alone. Many of the users felt that the vibrations enhanced the realism in comparison with surfaces without vibration feedback.

A. Future Work

During this study of vibration feedback, many interesting issues arose which merit further discussion and also bring possibilities for future work.

Two fundamental questions are whether the model used is optimal, and whether the model will change under different experimental conditions. There are many other possible models for vibration waveforms, including multiple sinusoids and wavelets. An important consideration is that the model used should be simple enough to be calculated in a servo loop running at 1 kHz or greater (a common servo rate for haptic displays). Look-up tables and other means may also be incorporated if a complex model is to be used.

Even with the scaled down haptic model, the accelerations resulting from tapping on a virtual surface do not perfectly match the original model (as is apparent from a comparison of the last two blocks in Fig. 1). Despite the fact that the haptic display cannot display the exact vibrations that were modeled, there is evidence that the technique is effective (Section IV). The vibration feedback presented in this work provides cues that may be “good enough” for most applications. In the future, the level of haptic fidelity required for realistic vibration display could be tested using psychophysical experiments.

One limitation of this approach is that it assumes that the same haptic interface will be used for recording vibration and data and for vibration feedback in a virtual environment. Ideally, we would use a device-independent approach. One method to accomplish this is to characterize each haptic interface and create “device drivers” that account for the dynamics of each one. With this information, vibrations due to a particular material and geometry alone could be characterized and replayed on any haptic interface.

The goal of this work was to increase realism using only algorithmic modifications, so that current haptic displays do not have to be augmented or redesigned. However, another approach to improving the realism of virtual environments is to design haptic devices with the ability to display harder surfaces (for example, using brakes).

There are certainly more tests that can be done to verify the effectiveness of vibration feedback. For example, experiments should be performed to compare the vibration feedback algorithms presented in this work against other algorithms for making surfaces appear hard. For example, Salcudean and Vlaar [18] use an impact energy dissipation method to make surfaces quickly damp out motion and thus appear stiffer. High damping upon impact provides a sudden spike of force similar to that which occurs in real environments. Pai, *et al.* [20] modeled the mechanics that create vibrations when two surfaces collide. However, computation of such models require many parameters, making it difficult to extrapolate a vibration feedback algorithm. Much work has also been done in the design of haptic displays to make them stiffer and thus able to display harder surfaces; this is a mechanical solution. In order to evaluate the capability of haptic displays to provide vibration feedback, one can consider several methods of characterization. Hannaford, *et al.* [11] created a metric called the Shape Deformation ratio that may be used to compare the bandwidth and stiffness of different haptic devices.

Vibration feedback is also useful in many other tasks. Although preliminary studies of texture stroking and puncture tasks have been performed [9], [12], these tasks and others warrant a more thorough investigation.

ACKNOWLEDGMENT

M. Hage contributed to the experiments, and the paper was inspired by collaborations with Prof. R. Howe of Harvard University.

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