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Shaping Event-Based Haptic Transients Via an Improved Understanding of Real Contact Dynamics

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Shaping Event-Based Haptic Transients Via an Improved Understanding of Real Contact Dynamics

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Abstract

Haptic interactions with stiff virtual surfaces feel more realistic when a short-duration transient is added to the spring force at contact. But how should this event-based transient be shaped? To answer this question, we present a targeted user study on virtual surface realism that demonstrates the importance of scaling transients correctly and hints at the complexity of this dynamic relationship. We then present a detailed examination of the dynamics of tapping on a rigid surface with a hand-held probe; theoretical modeling is combined with empirical data to determine the influence of impact velocity, impact acceleration, and user grip force on the resulting transient surface force. The derived mathematical relationships provide a formula for generating open-loop, event-based force transients upon impact with a virtual surface. By incorporating an understanding of the dynamics of real interactions into the re-creation of virtual contact, these findings promise to improve the performance and realism of a wide range of haptic simulations.

1 Introduction

Realistic excitation of the user's sense of touch during virtual interactions has been shown to decrease task completion time, error incidence, and cognitive load [2, 14]. Numerous applications exist wherein realistic virtual simulations could have significant potential, ranging from medical training to mechanical design. For instance, a sufficiently realistic simulator could be used to immerse surgeons in complex operative tasks without endangering live patients, thereby providing a safe, repeatable environment for learning and practicing new procedures. Such simulators can be used for both traditional and minimally-invasive surgery (MIS), with particular application in the emergent field of robotic MIS. To be a viable alternative to traditional training, systems must faithfully reproduce the haptic cues that surgeons experience during live procedures, a design goal that requires careful attention to the dynamics of the corresponding real interactions.

While today's impedance-type haptic simulators can adeptly portray interactions with soft environments, rendering realistic rigid contact has been a significantly more challenging objective. A large body of research over the past decade has sought to improve the feel of virtual hard contact, and one of the most promising advances has been recognizing the value of transient contact forces. An overview of this field is presented in Section 2, and Section 3 presents a human subject study that examines how transient amplitude affects surface realism. In Section 4, we introduce a set of dynamic models based on first principles to reveal the relationship between the mechanical parameters of the contacting objects (stylus and hand mass, surface stiffness, and surface damping), the user-controlled impact parameters (incoming velocity, incoming acceleration, and grip force), and the shape of the resulting force transient. Understanding the dynamics of contact between a hand-held stylus and a physical hard object will facilitate the process of virtual transient selection and enable more realistic virtual environments.

2 Background

While both slow pressing and discrete taps yield useful information about an unknown material touched through a stylus, LaMotte showed that active tapping best enables humans to make accurate material property judgments, as the quickly changing contact force provides salient cues about surface compliance [10]. During interactions with rigid surfaces, haptic feedback necessarily becomes the primary sensory channel because the tool's penetration into the surface is too small to be detected via vision or proprioception. As shown in Fig. 1, tapping a stylus on a firm surface produces a high-frequency transient acceleration, which is known to excite the Pacinian corpuscles that lay deep within the glabrous skin of the hand [1, 17]. The central nervous

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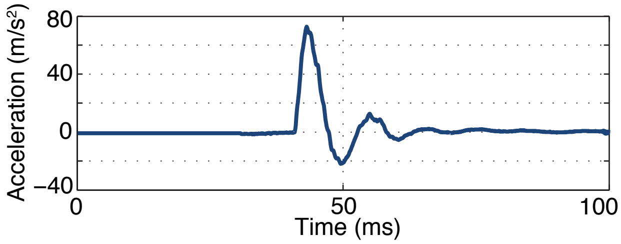

Figure 1: The acceleration of a hand-held probe when tapped on a firm surface.

system processes this sensory response and generates a haptic impression of the event, which depends primarily on the material and geometry of the object and is naturally controlled for changes in contact velocity and grip force [10].

Contact acceleration transients like the one shown in Fig. 1 are often modeled with an exponentially decaying sinusoid, where the amplitude is linearly proportional to the impact velocity and the frequency and duration depend empirically on the material properties of the surface and tool [12, 16]. Unfortunately, the low closed-loop bandwidth of most existing impedance-type haptic interfaces restricts the maximum virtual stiffness to that of soft foam [3, 8]. Simulations that attempt to portray hard materials with closed-loop position feedback thus feel far too soft and lack the high-frequency accelerations that users expect when interacting with hard objects. While efforts have been made to overcome these limitations, the required 1000-fold improvement in renderable stiffness remains elusive.

One promising alternative for rendering stiff contact is the paradigm of event-based haptics, wherein traditional position-based feedback is augmented with the open-loop display of high-frequency force transients. Wellman and Howe first implemented such an algorithm on a haptic device, providing vibratory feedback via a secondary actuator mounted near the user's fingertips [16]. Shortly thereafter, Salcudean and Vlaar showed that an open-loop pulse at contact improved the perceived stiffness of virtual walls without causing instability [13], and Okamura et al. demonstrated that overlaying proportional feedback with psychophysically-tuned decaying sinusoids improved material discrimination [11]. Hwang et al. continued this line of research through the use of short-duration force pulses to bring the stylus to rest with minimal penetration [7].

Kuchenbecker et al. then developed a deterministic approach to transform real recorded accelerations into open-loop motor current transients to be played at contact, using a full dynamic model of the haptic system to ensure accurate matching of the virtual and real accelerations [8]. A complementary user study of blind tapping on real and virtual surfaces showed that the inclusion of fixed-width pulse, decaying sinusoid, or acceleration matched transients significantly improved the perceived realism of virtual surfaces over proportional feedback. Further work by Fiene et al. demonstrated that a grip-force sensor could be used to estimate changing hand dynamics, which could then be accounted for in real time by adjusting the system's dynamic model [4]. Such a system was shown to be capable of producing event-based virtual surfaces that accurately recreated recorded transient accelerations over a wide range of grip force values and incoming velocities.

3 Perception of Transient Amplitude

Prior work has shown that event-based transients generally improve the realism of virtual hard contact, but little is known about the relationship between transient shape and surface feel. We hypothesize that the perceived realism of a virtually rendered surface is strongly dependent on how the amplitude of the acceleration transient compares to that produced during interactions with the corresponding real surface. A brief user study was conducted to test this hypothesis, as presented below.

3.1 Experimental Design

For direct user comparison between real and virtual surfaces, the workspace of a desktop Phantom was divided laterally between a virtual rendering and a real object (a layer of wood on a foam substrate, similar to that used in [8]). A stylus was attached to the distal link of the Phantom to allow the user to tap on both surfaces. An Analog Devices ADXL321 $\pm$18 g accelerometer was affixed near the tip of the stylus, and a Flexi-force A201-1 force-sensitive resistor was located under the user's index finger to measure grip force. A PC running RTAI Linux was used to render the virtual surface and sample the sensors at 5 kHz using a National Instruments PCI-1200 card, providing resolutions of 0.172 m/s^2 and 0.009 N respectively. The user's haptic sense was isolated through the use of a visual barrier and headphones playing cacophonous noise.

The virtual surface consisted of a 50 ms long, 50 Hz decaying-sinusoid transient overlaid on a 900 N/m spring. For each tap on the virtual surface, the 32 Ns/m transient amplitude was scaled by the incoming velocity and multiplied by a random value between 0 and 2 to introduce wide variations in contact response. Users were instructed to alternate tap on the real and virtual surfaces. After each pair of taps, users were asked to rate the feel of the virtual surface on a seven-point bipolar rating scale, where a rating of 0 corresponds to a realistic virtual rendering, +3 is far too strong and -3 is far too weak.

3.2 Results

Three users participated in the study, each rating 62 virtual surfaces. To understand the significance of these rat-

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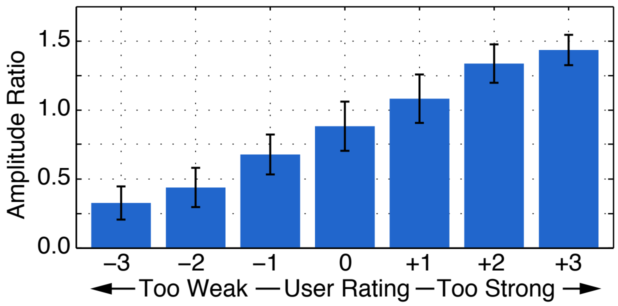

Figure 2: Relationship between realism ratings and the virtual-to-real transient amplitude ratio.

ings, we quantitatively compared each virtual contact to the response of the real surface, as follows. First, a linear fit between incoming velocity and peak contact acceleration for taps on the real surface was determined for each user. Then the amplitude ratio of each virtual tap was calculated by dividing the measured peak acceleration by that predicted using the linear scaling model. Figure 2 shows the mean and standard deviation of these ratios for each realism rating averaged across subjects; as hypothesized, amplitude ratio correlates well with rated realism. Interestingly, the best realism rating (0) corresponds to a mean amplitude ratio of approximately 0.86, echoing the anecdotal observation of [8] that users prefer virtual transients that are slightly less powerful than real surfaces. Additionally, the wide standard deviations of Fig. 2 show that an amplitude ratio that is corrected for velocity alone does not fully characterize the intricacies of user perception, though it captures a strong trend. As such, the remainder of this work will examine the dynamics of real interactions to more thoroughly understand the factors controlling transient amplitude.

4 Modeling and Analysis of Real Tapping

Event-based haptic algorithms commonly scale or index the amplitude of the contact transient by the velocity with which the user impacts the virtual surface [8, 11, 16]. While this relationship significantly improves the feel of hard virtual surfaces, it does not provide an obvious way to incorporate the effects of other varying parameters such as incoming acceleration and changes in hand dynamics. To understand how these other parameters affect the resulting surface force, an ATI Mini-40 force sensor was placed beneath a sample object, and the Phantom setup described above was used to measure position, acceleration, grip force, and surface force for a series of 300 real taps spanning a range of incoming velocities, incoming accelerations, and grip force levels.

To elucidate the relationships between the user-controlled parameters and the resulting surface force, this section introduces three successive dynamic models of the stylus/hand system at contact and tests them against this recorded tap data. In all models, hand motion (position, velocity, and acceleration) and surface force are defined positive away from the surface, such that negative incoming velocities cause positive surface forces.

4.1 Momentum Approach

The first explored model treats the stylus/hand system as a lumped mass, m, with a constant pre-impact velocity of v_{in}. Under conservation of momentum, perfectly plastic impact with a stationary surface will produce zero velocity after time t_1, and the change in linear momentum, L, of the mass must equal the integral of the surface force, as follows

$$L_1 - L_0 = 0 - m\, v_{in} = \int_0^{t_1} F_s(t)\, dt \qquad (1)$$

Assuming that the contact acceleration follows an exponentially decaying sinusoid, the surface force will take the form

$$F_s(t) = \beta \sin(\omega t)\, e^{-\alpha t} \qquad (2)$$

where the frequency, ω, and decay rate, α, are empirically determined from sample contacts. Substituting (2) into (1), solving for β, and rewriting (2) yields

$$F_s(t) = -\frac{m(\alpha^2+\omega^2)}{\omega}\, v_{in} \sin(\omega t) e^{-\alpha t} \qquad (3)$$

which provides the previously observed linear correlation between incoming velocity and transient force amplitude. The peak of the decaying sinusoid surface force,

$$F_s^* = -m\, v_{in} \sqrt{\alpha^2+\omega^2}\, e^{-(\alpha/\omega)\tan^{-1}(\omega/\alpha)} \qquad (4)$$

is therefore also proportional to the incoming velocity.

Least squares regression between the incoming velocity and the peak of the surface force for the recorded data yields the linear fit shown in Fig. 3, which has an RMS error of 0.205 N. While this model captures the primary trend, the scatter suggests that other factors contribute to the dynamics of a tap, echoing the results of the user study in Sec. 3.

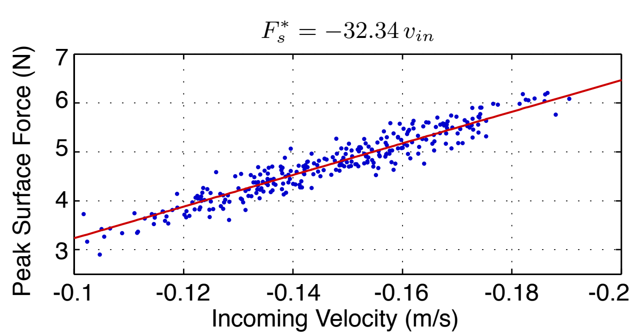

Figure 3: Linear fit between stylus incoming velocity and peak surface force.

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4.2 Adding a Constant Force

Recognizing that the user's hand velocity may not be constant before contact, we can use a measurement of the pre-impact acceleration, a_{in}, to augment the model derived from the momentum approach. This acceleration stems from the user applying a force, $F_{in} = m\,a_{in}$, which we can treat as constant over the short duration of the impact. The surface force after contact must oppose this additional hand force, resulting in

$$F_s(t) = -\frac{m(\alpha^2+\omega^2)}{\omega}\,v_{in}\sin(\omega t)\,e^{-\alpha t} - F_{in} \qquad (5)$$

$$F_s^* = -m\,v_{in}\sqrt{\alpha^2+\omega^2}\,e^{-(\alpha/\omega)\tan^{-1}(\omega/\alpha)} - m\,a_{in} \quad (6)$$

Introducing an acceleration-dependent term into the least-squares fitting process reduces the RMS error to 0.148 N. Figure 4 presents these results graphically, wherein each parameter is isolated by subtracting off the estimated contribution of the other parameters. The empirical data shows the predicted linear effect of incoming acceleration, though quantization of the acceleration signal produces significant striping. The resulting vertical spread in the data would collapse somewhat with a higher-resolution acceleration measurement.

Analyzing the result of the linear fit in connection with (6), we see that the acceleration scaling term should provide a direct estimate of the impacting system mass. Considering the addition of the stylus and device, the least-squares result of 0.335 kg is reasonable when compared with other hand mass estimates [15].

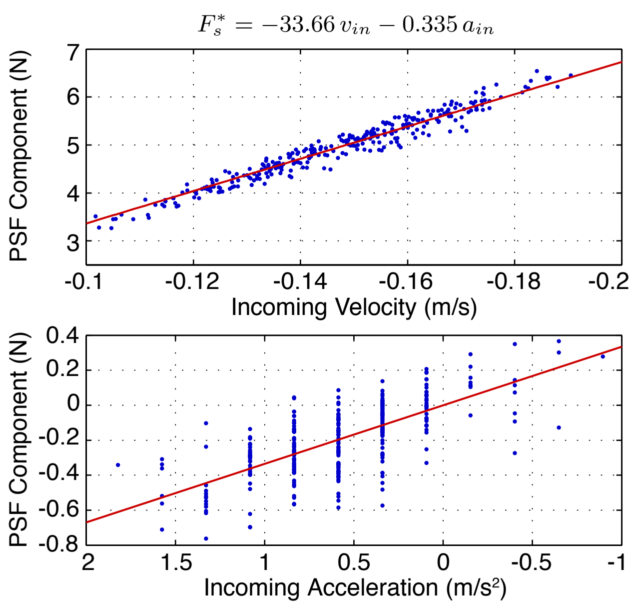

Figure 4: Linear fits between incoming velocity, incoming acceleration, and peak surface force.

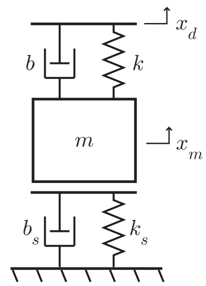

Figure 5: Dynamic Impact Model.

4.3 Hand and Surface Dynamics

It is widely recognized that the dynamics of the hand change with configuration and muscle contraction. By analyzing the surface force recorded from real taps with a stylus held in a two-finger grasp, Fiene et al. found an approximately linear relationship between grip force and the effective stiffness, k, and damping, b, of the user's hand [4], a result that matches well with other research [5, 6, 9].

To account for changes in user impedance, we introduce the model shown in Fig. 5, which combines a second-order user model with a spring-damper representation of the surface. We define the state vector, $\mathbf{x} = [x_m\ \dot{x}_m\ x_d]^\top$, the input vector $\mathbf{u} = [\dot{x}_d]$, and the full state-space dynamics

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \qquad \mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} \qquad (7)$$

$$\dot{\mathbf{x}} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{-(k+k_s)}{m} & \frac{-(b+b_s)}{m} & \frac{k}{m} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_m \\ \dot{x}_m \\ x_d \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{b}{m} \\ 1 \end{bmatrix} [\dot{x}_d] \qquad (8)$$

$$\mathbf{y} = \begin{bmatrix} -k_s & -b_s & 0 \end{bmatrix} \begin{bmatrix} x_m \\ \dot{x}_m \\ x_d \end{bmatrix} + [0]\,[\dot{x}_d] \qquad (9)$$

where the output $\mathbf{y}$ is the surface force, F_s. Assuming the user has a constant desired acceleration, we know the input $\dot{x}_d(t) = v_{in} + a_{in}t$, and we can include an initial user force, applied via the spring k, by choosing the following initial state vector

$$\mathbf{x}_0 = \begin{bmatrix} x_{m,0} \\ \dot{x}_{m,0} \\ x_{d,0} \end{bmatrix} = \begin{bmatrix} 0 \\ v_{in} \\ m\,a_{in}/k \end{bmatrix} \qquad (10)$$

The Laplace transform of the system output can then be derived with the equation

$$\mathbf{Y}(s) = \mathbf{C}(s\mathbf{I}-\mathbf{A})^{-1}\mathbf{B}\mathbf{U}(s) + \mathbf{C}(s\mathbf{I}-\mathbf{A})^{-1}\mathbf{x}_0 \quad (11)$$

where $\mathbf{U}(s) = [v_{in}/s + a_{in}/s^2]$, providing

$$F_s(s) = -\frac{(v_{in}s + a_{in})(b_s s + k_s)(ms^2 + bs + k)}{s^3(ms^2 + (b+b_s)s + (k+k_s))} \quad (12)$$

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Solving for the inverse Laplace transform of $F_s(s)$ results in a time-domain solution of the form

$$F_s(t) = -\beta \sin(\omega t + \phi) e^{-\alpha t} - c_2 t^2 - c_1 t - c_0 \quad (13)$$

supporting the use of a decaying sinusoid transient in the previous two models. After comparing the terms in (12) and (13), we can determine that the parameters governing the decaying sinusoid are

$$\omega = \sqrt{\frac{k + k_s}{m} - \left(\frac{b + b_s}{m}\right)^2} \qquad \alpha = \frac{b + b_s}{m} \quad (14)$$

$$\beta = \sqrt{c_3 \left(v_{in}^2 - \frac{b + b_s}{k + k_s} v_{in} a_{in} + \frac{m}{k + k_s} a_{in}^2\right)} \quad (15)$$

where

$$c_3 = \frac{4(b b_s k_s - m k_s^2 - k b_s^2)^2}{(k + k_s)^2((b + b_s)^2 - 4m(k + k_s))} \quad (16)$$

and the phase shift, ϕ, which stems from the addition of a decaying cosinusoid term, has the form

$$\tan \phi = p_1 \frac{p_2 a_{in} - p_3 v_{in}}{p_4 a_{in} + p_5 v_{in}} \quad (17)$$

where the p_n terms are various combinations of the system's mechanical parameters. Simulation has shown minimal effect from the phase shift, which is on the order of 0.02 radians for the parameters of our system. The remaining three terms in (13) are

$$c_2 = k_e a_{in} \qquad c_1 = k_e v_{in} + k_e^2 \, d \, a_{in} \quad (18)$$

$$c_0 = k_e^2 \, d \, v_{in} + \frac{m k_s^2 + k_e(2 b b_s - d(k + k_s))}{(k + k_s)^2} a_{in} \quad (19)$$

where the series spring stiffness, k_e, and the d term are:

$$k_e = \frac{k k_s}{k + k_s} \quad \text{and} \quad d = \frac{b}{k^2} + \frac{b_s}{k_s^2} \quad (20)$$

Examining the system for the simplified case of zero incoming acceleration, the time-domain response reduces to

$$F_s(t) = v_{in} \sqrt{c_3} \sin(\omega t + \phi) e^{-\alpha t} + k_e v_{in}(t + k_e d) \quad (21)$$

which combines a velocity-scaled decaying sinusoid with ramp and step functions resulting from movement of the desired position within the surface.

To visualize how changes in hand parameters affect the peak surface force, a simulation of the system was created using nominal values for the surface parameters and the hand mass. Fig. 6(a) shows the resulting change in peak surface force as a function of hand stiffness and damping for zero incoming acceleration. The solid line, which is also

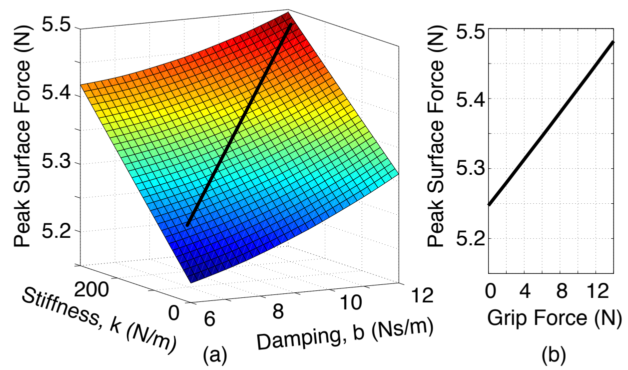

Figure 6: Simulation of the change in peak surface force as a function of (a) the hand stiffness and damping, and (b) the user-specific grip-force.

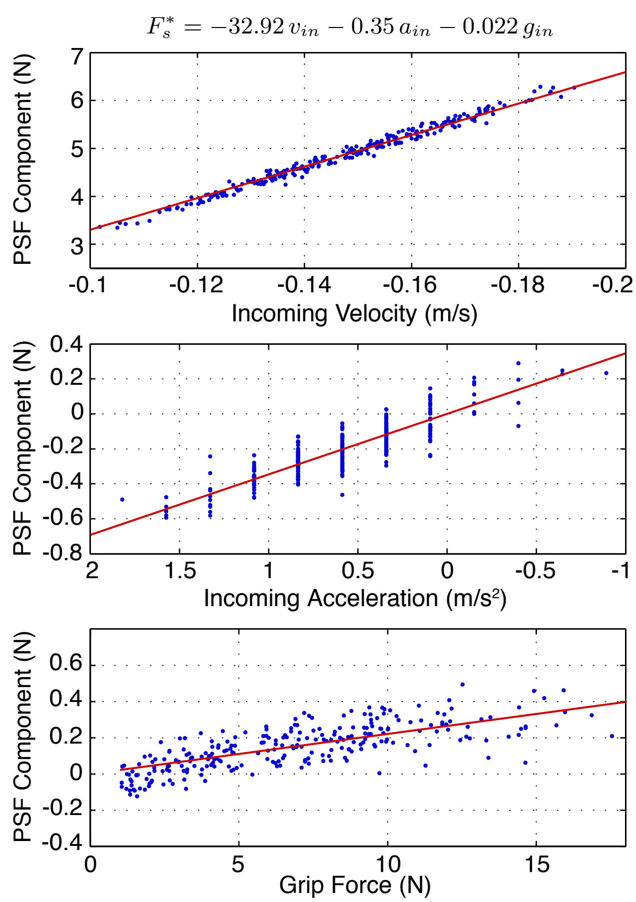

Figure 7: Linear fits between incoming velocity, incoming acceleration, grip force, and peak surface force.

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shown in Fig. 6(b), represents the user-dependent relationship between hand parameters and grip force from [4]. The flatness of the surface in Fig. 6(a) suggests that user-to-user differences in the grip-force-to-hand-parameter relationship should not significantly affect the overall correlation to peak surface force.

Introducing a linear dependence on grip force into the least-squares parameter fitting routine reduces the RMS error to 0.081 N, suggesting that the inclusion of both incoming acceleration and grip force most accurately accounts for the amplitude of the transient response. The components of the peak surface force can be visualized along with the least-squares results in Fig. 7.

5 Conclusion

This work provides an improved understanding of the dynamics of real contact and will enable more realistic virtual rendering of hard objects. The user study presented in Section 3 shows that user realism ratings correlate with the amplitude of event-based virtual surface transients. Interpreting the results of Section 4, we see that momentum analysis provides a justification for the commonly observed approximate linear relationship between incoming velocity and transient force amplitude. The addition of a constant user-applied force accounts for the more subtle effect of incoming acceleration. The state-space model, which includes both hand and surface dynamics, provides a theoretical basis for the commonly assumed decaying sinusoid response. It also yields parametric relationships for the sinusoid frequency and exponential decay rate based on measurable mechanical properties of the surface and the user. Finally, this treatment provides a formula for the surface force as a function of time after contact.

Future work will continue to explore the structure and implications of these models to understand how they can best be employed in the real-time rendering of virtual hard contact, including extension to more complex interactions such as three-dimensional contact and multi-body impacts. To ensure smooth transitions after event-based output, we will develop methods for combining the calculated open-loop transients, which do not necessarily decay to zero, with traditional proportional feedback. We will also perform more extensive user testing to determine the full effect of transient shape on perception.

Acknowledgments

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