system to activate and brake the actuator. For example, when the cell phone detects an incoming call, it generates a driving signal to drive the actuator at its resonant frequency to generate vibration, thereby alerting the user of the cell phone to the incoming call. Then to stop the vibrations, the cell phone generates a braking signal at the resonant frequency and approximately 180 degrees out of phase with the driving signal to brake the actuator and halt the vibrations.

[0017] By activating and braking the actuator in sequence, the cell phone can generate a wide variety of vibrotactile haptic effects. For example, an incoming call may generate three short, strong vibrations in rapid succession. The cell phone can also generate vibrotactile effects synchronized to ring tones such that the vibrotactile haptic effects correspond to the low frequencies, or bass portions, of the ring tone. The vibrotactile haptic effects can be played in time with the ring tone such that the user can feel the bass portions of the ring tone through the vibrations.

[0018] This example is given to introduce the reader to the general subject matter discussed herein. The invention is not limited to this example. The following sections describe various embodiments of systems and methods for controlling a resonant device.

Controlling a Resonant Device

[0019] Embodiments of the invention presented herein is used to decelerate a resonant actuator quickly once actuator motion is no longer desirable. By applying an inverted drive signal to the actuator (a signal that is approximately 180 degrees out of phase with the driving signal), the actuator resists the movement of the oscillating mass, forcing the oscillations to stop faster than they would with no intervention. By actively braking the actuator, the present invention is able to create vibration patterns that feel much "crisper" than would be possible if the actuator were simply allowed to return to rest with no intervention. The active braking, therefore, significantly increases the perceivable haptic bandwidth.

[0020] For example, an audible piece of music augmented with a vibration track in a resonant actuator-driven handheld device in one embodiment of the present invention is better able to produce the rapid pulses needed to augment a snare drum roll. A vibration track to a fast-paced piano solo also feels like distinct notes rather than a constant vibration of varying intensity. Many musical flourishes in several genres occur at cadences that require the high degree of actuator control that can be produced using various embodiments of the invention described herein. Thus, an advantage of embodiments of the present invention is using actuator braking to quickly stop a vibrating actuator in order to generate more compelling and pleasing haptic effects.

[0021] Referring now to the drawings in which like numerals indicate like elements throughout the several Figures, **FIG. 1** is a block diagram illustrating a system **100** for braking an actuator in one embodiment of the present invention. The system **100** comprises a signal generator **101**. There are many types of signal generators that may be used as the signal generator **101** including but not limited to:

[0022] Digital/Analog ("D/A") conversion

[0023] (a) with high sampling rate, or

[0024] (b) with low sampling rate and filtering;

[0025] Pulse Width Modulation ("PWM") with filtering;

[0026] Analog Oscillator;

[0027] PWM with amplitude control and an invert input/output ("I/O") line; and

[0028] PWM with adjustable frequency.

[0029] A D/A converter can be used to drive a resonant device at the resonant frequency of the device. A fundamental drive signal may be a sinusoid at approximately the resonant frequency of the device. If the available sampling rate of the D/A converter is not high enough to ensure a smooth sinusoid, passive filtering can be used to smooth the drive signal in order to reduce audio noise.

[0030] Some resonant devices create significant audio noise when driven with square wave signals. To reduce the noise, sinusoid signals can be used that have less high frequency components. Other resonant devices do not create much audio noise and can be driven by square wave signals. For these devices, the signal generator can be simplified as the drive signal can be a resonant square wave.

[0031] In some embodiments, it may be advantageous to use a band pass filter to extract the component of a square signal at the desired frequency. In such an embodiment, it may be advantageous to extract a sinusoid at approximately the same frequency as the square signal. The filter may be implemented physically with passive or active components in order to avoid sampling frequency issues and quantization problems. Generation of the same sinusoid signal in software may require higher output resolution as well as higher sampling frequencies.

[0032] In other embodiments, a bidirectional PWM signal can be used to drive the resonant device. The amplitude of the signal driving the resonant device may be modulated by controlling the "on" time of the PWM signal while driving at the resonant frequency. Filtering can also be used to smooth out the square nature of this signal if required.

[0033] An alternate way to generate the drive signal is to use an analog oscillator, where the oscillator may be set approximately to the resonant frequency. The amplitude of the drive signal may be controlled with an available D/A converter and an amplifier.

[0034] In one embodiment of the present invention, a circuit using PWM with amplitude control and an I/O invert line can be used to generate a PWM signal to drive a resonant actuator and control amplitude of the signal. The PWM signal is set at the resonant frequency of the resonant actuator. In such an embodiment, the amplitude control is achieved with a second PWM connected to an amplifier, the second PWM generates a modulating signal and controls the amplitude of first and second actuator signals by varying the pulse width of the modulating signal.

[0035] In the embodiment described above, the I/O invert line is used to control signal inversion by transmitting an invert signal. For example, when the invert signal is low, the PWM signal is passed to the resonant actuator. When the invert signal is high, a switch can reverse the leads of the resonant actuator effectively inverting the PWM signal. In other embodiments, the signal may be inverted by other methods including, but not limited to, gating in a different