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(54) **HAPTIC FEEDBACK GENERATION BASED
ON RESONANT FREQUENCY**

(75) Inventors: **Pedro Gregorio**, Verdun (CA); **Danny
A. Grant**, Laval (CA); **Patrice Favreau**,
Mascouche (CA); **Eric Meunier**,
Montreal North (CA)

(73) Assignee: **Immersion Corporation**, San Jose, CA
(US)

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(52) **U.S. Cl.** **331/65**; 331/116 R; 331/154;
715/702; 345/173

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331/35, 116 R, 116 M, 154; 715/702; 310/318,
310/37; 345/156, 173

See application file for complete search history.

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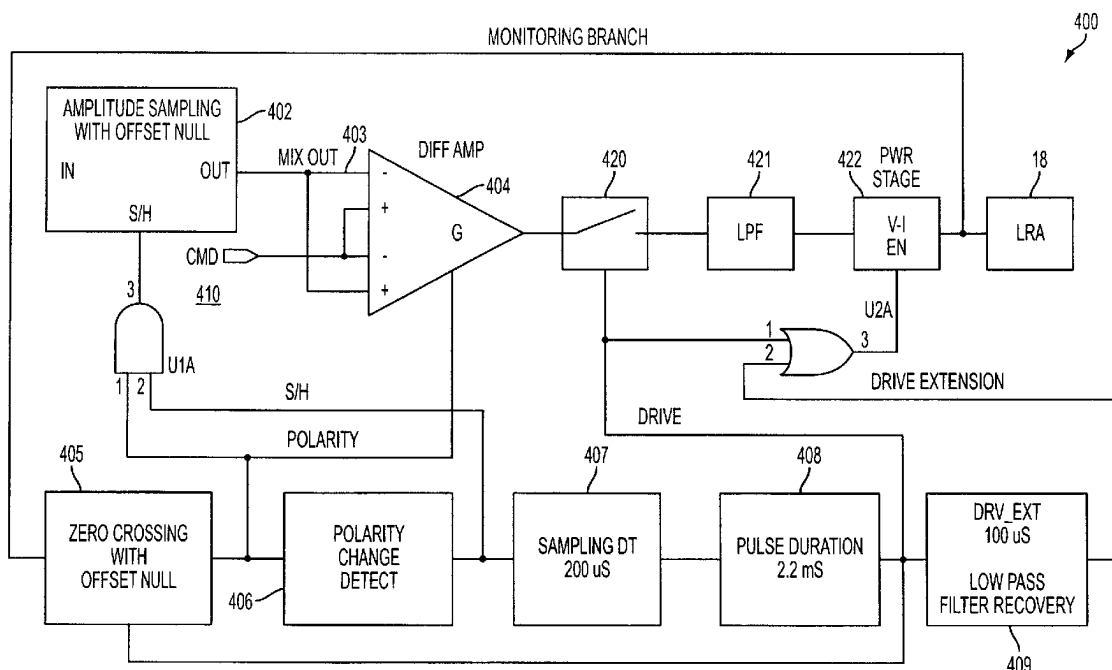
Primary Examiner—Joseph Chang

(74) *Attorney, Agent, or Firm*—Squire, Sanders & Dempsey,
LLP

(57) **ABSTRACT**

A system that generates a haptic effect generates a drive cycle signal that includes a drive period and a monitoring period. The drive period includes a plurality of drive pulses that are based on the haptic effect. The system applies the drive pulses to a resonant actuator during the drive period and receives a signal from the resonant actuator that corresponds to the position of a mass in the actuator during the monitoring period.

25 Claims, 6 Drawing Sheets



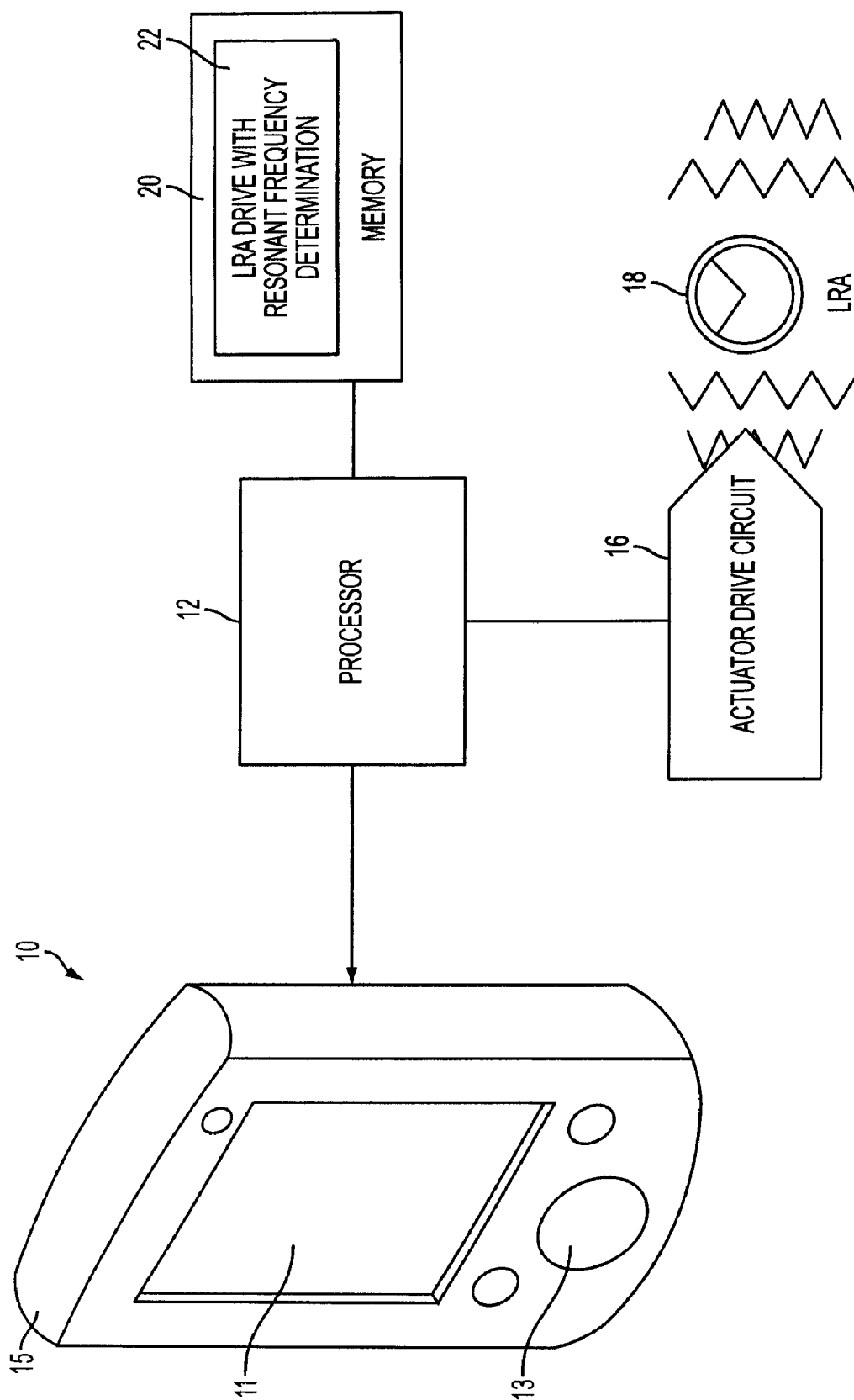


FIG. 1

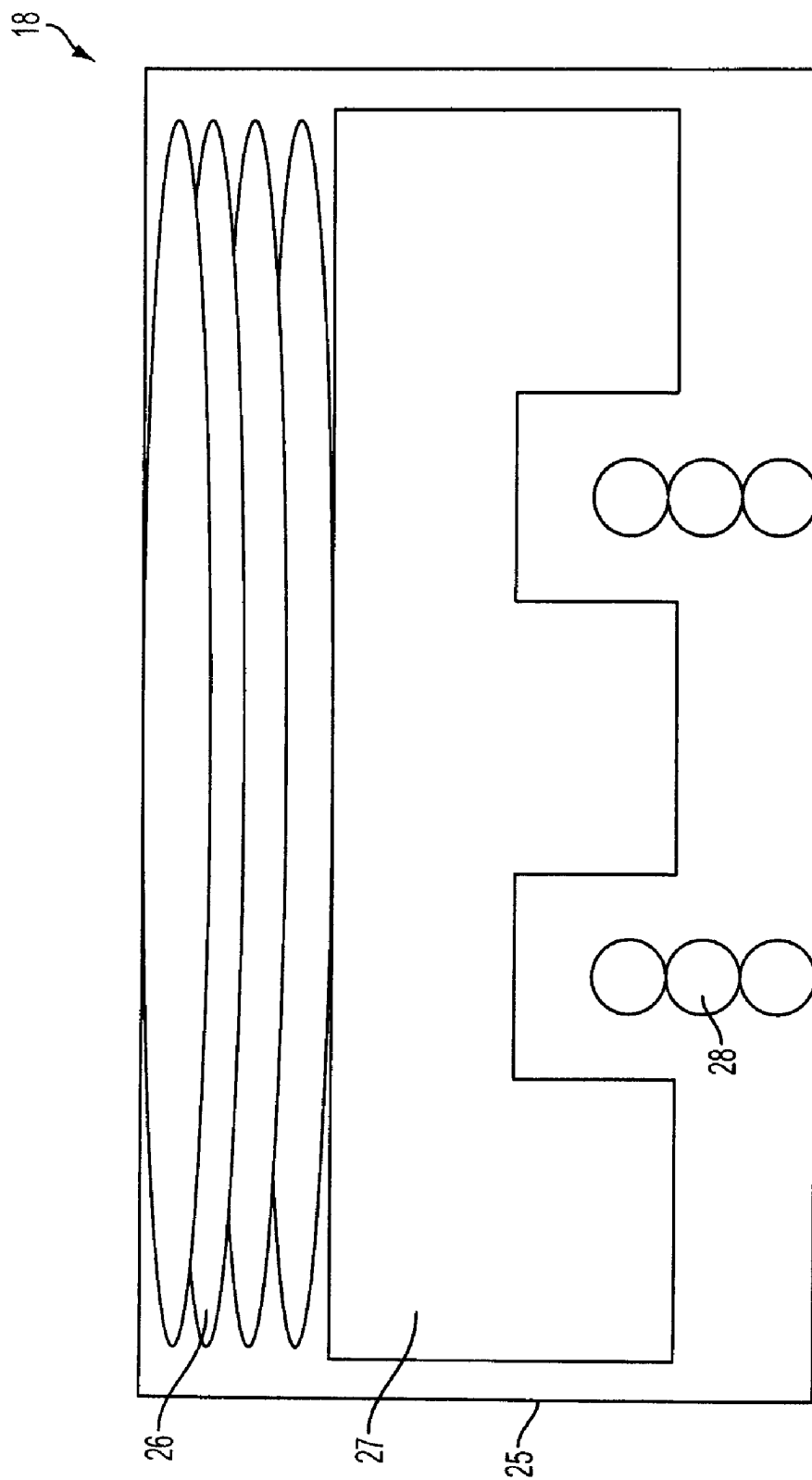


FIG. 2

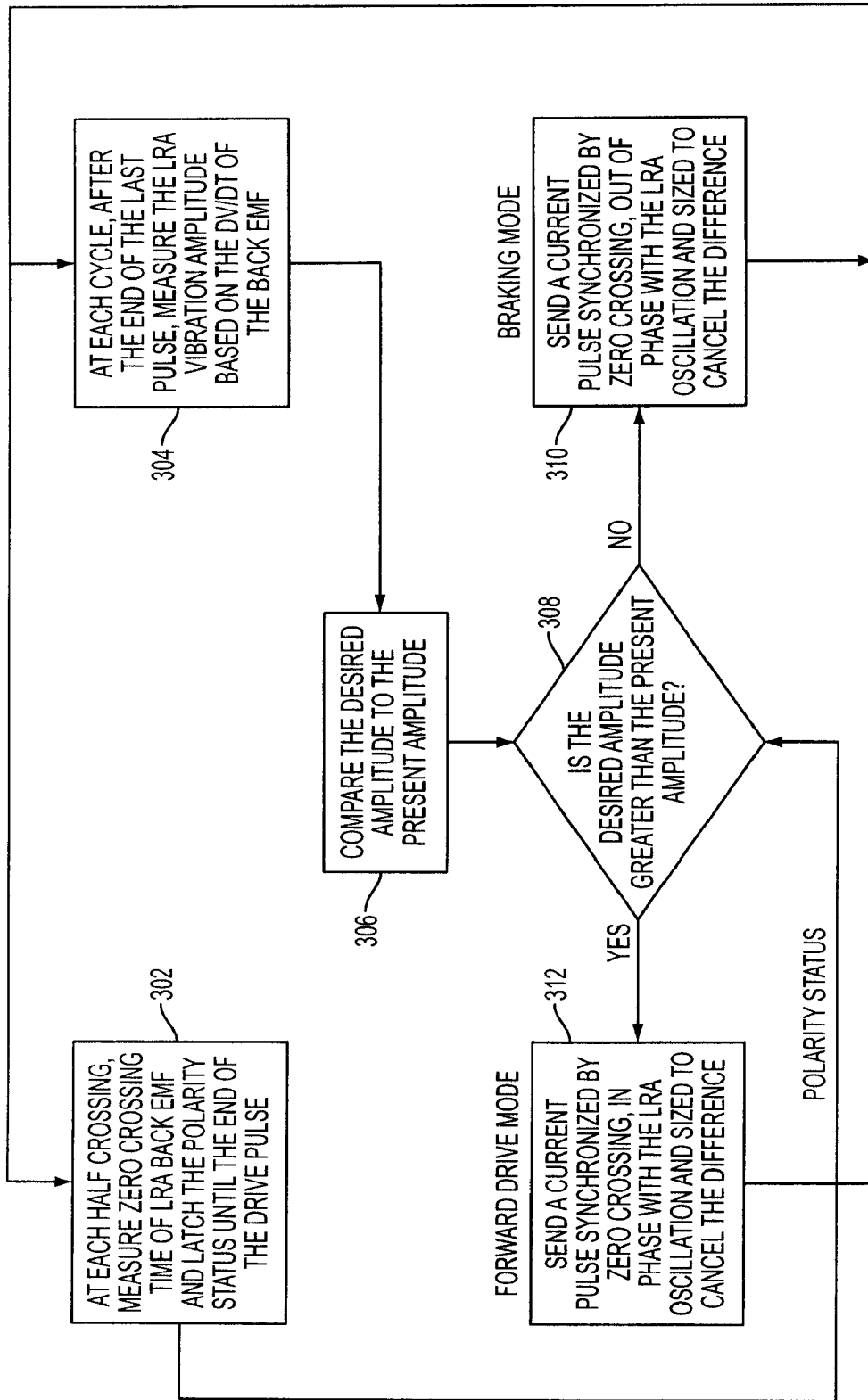


FIG. 3

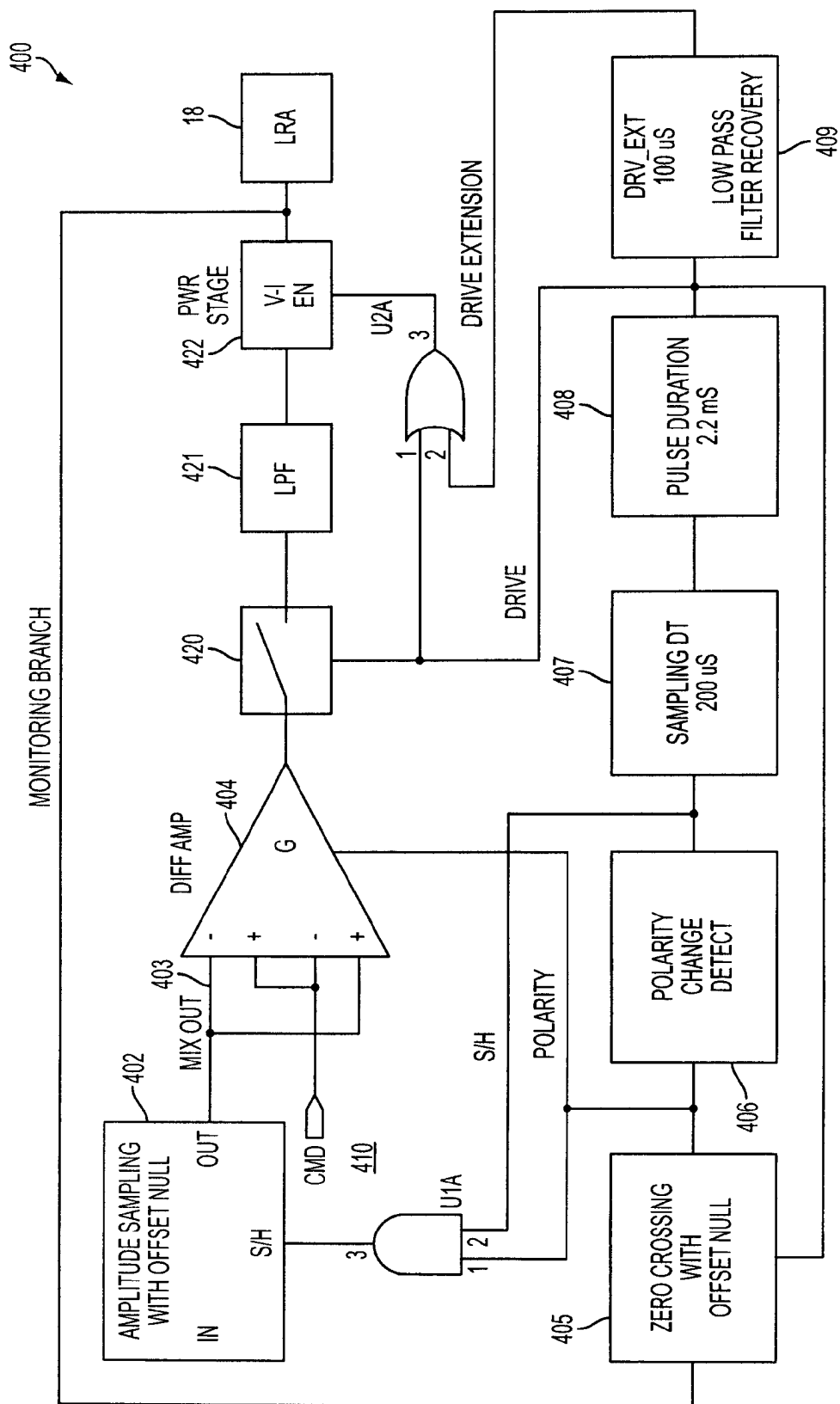


FIG. 4

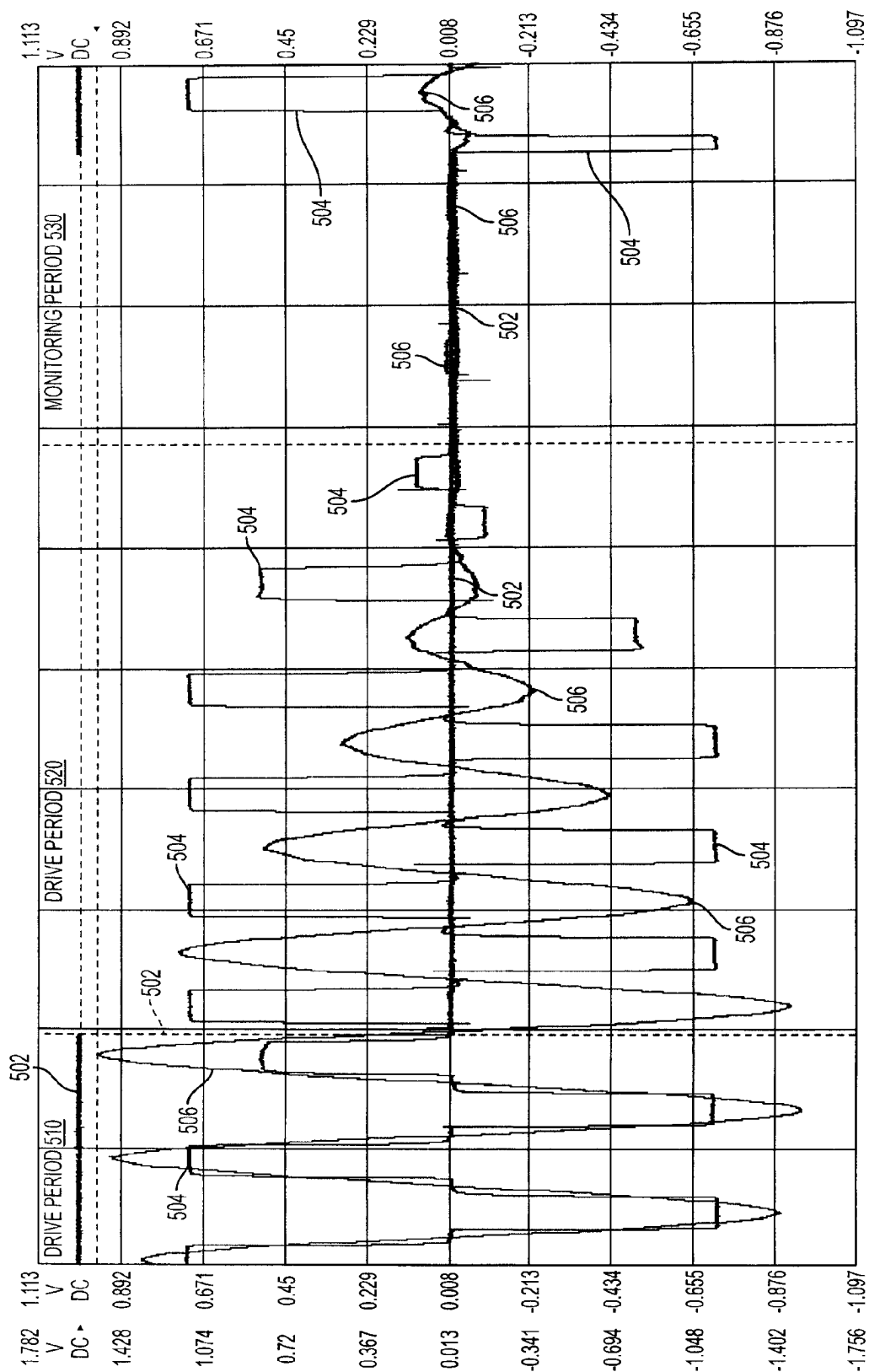


FIG. 5

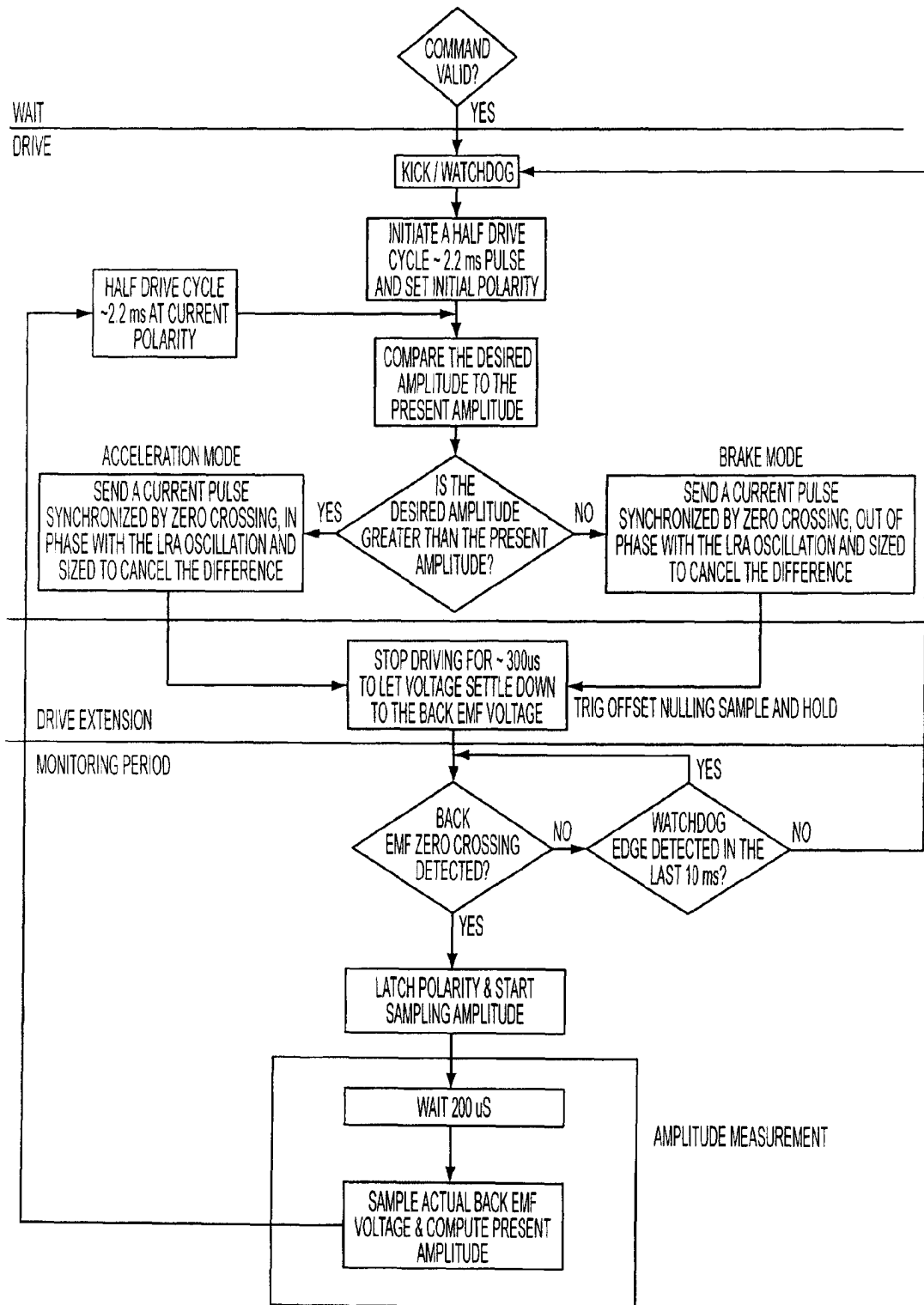


FIG. 6

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HAPTIC FEEDBACK GENERATION BASED ON RESONANT FREQUENCY

FIELD OF THE INVENTION

One embodiment is directed generally to a user interface for a device, and in particular to generating haptic feedback for the user interface.

BACKGROUND INFORMATION

Electronic device manufacturers strive to produce a rich interface for users. Conventional devices use visual and auditory cues to provide feedback to a user. In some interface devices, kinesthetic feedback (such as active and resistive force feedback) and/or tactile feedback (such as vibration, texture, and heat) is also provided to the user, more generally known collectively as “haptic feedback” or “haptic effects”. Haptic feedback can provide cues that enhance and simplify the user interface. Specifically, vibration effects, or vibrotactile haptic effects, may be useful in providing cues to users of electronic devices to alert the user to specific events, or provide realistic feedback to create greater sensory immersion within a simulated or virtual environment.

In order to generate vibration effects, many devices utilize some type of actuator. Known actuators used for this purpose include an electromagnetic actuator such as an Eccentric Rotating Mass (“ERM”) in which an eccentric mass is moved by a motor, a Linear Resonant Actuator (“LRA”) in which a mass attached to a spring is driven back and forth, or a “smart material” such as piezoelectric, electro-active polymers or shape memory alloys. Many of these actuators, and the devices that they interact with, have built-in resonant frequencies that optimally are dynamically determined and controlled so that drive signals that generate the haptic effects can be most effective and efficient.

SUMMARY OF THE INVENTION

One embodiment is a system that generates a haptic effect. The system generates a drive cycle signal that includes a drive period and a monitoring period. The drive period includes a plurality of drive pulses that are based on the haptic effect. The system applies the drive pulses to a resonant actuator during the drive period and receives a signal from the resonant actuator that corresponds to the position of a mass in the actuator during the monitoring period.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a haptically-enabled system in accordance with one embodiment.

FIG. 2 is a cut-away side view of an LRA in accordance to one embodiment.

FIG. 3 is a flow diagram of the functionality of a module in conjunction with a processor and an actuator drive circuit when driving LRA to generate haptic feedback accordance with one embodiment.

FIG. 4 is a block diagram of a circuit for generating the functionality of FIG. 3 for driving the LRA in accordance with one embodiment.

FIG. 5 is a graph that illustrates an example of a portion of a drive cycle that includes a drive period and a monitoring period.

FIG. 6 is a flow diagram of the functionality of a module in conjunction with a processor and an actuator drive circuit when driving LRA to generate haptic feedback accordance with one embodiment.

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DETAILED DESCRIPTION

One embodiment is a system that drives an LRA to generate vibrotactile haptic feedback on a user interface or other area of a device. The system drives the LRA so that the resonant frequency of the LRA can be determined during a drive period and the drive signal can be adjusted to maximize the haptic feedback based on the determined resonant frequency.

FIG. 1 is a block diagram of a haptically-enabled system 10 in accordance with one embodiment. System 10 includes a touch sensitive surface 11 or other type of user interface mounted within a housing 15, and may include mechanical keys/buttons 13. Internal to system 10 is a haptic feedback system that generates vibrations on system 10. In one embodiment, the vibrations are generated on touch surface 11.

The haptic feedback system includes a processor 12. Coupled to processor 12 is a memory 20 and an actuator drive circuit 16, which is coupled to an LRA actuator 18. Processor 12 may be any type of general purpose processor, or could be a processor specifically designed to provide haptic effects, such as an application-specific integrated circuit (“ASIC”). Processor 12 may be the same processor that operates the entire system 10, or may be a separate processor. Processor 12 can decide what haptic effects are to be played and the order in which the effects are played based on high level parameters. In general, the high level parameters that define a particular haptic effect include magnitude, frequency and duration. Low level parameters such as streaming motor commands could also be used to determine a particular haptic effect. A haptic effect may be considered “dynamic” if it includes some variation of these parameters when the haptic effect is generated or a variation of these parameters based on a user’s interaction.

Processor 12 outputs the control signals to drive circuit 16 which includes electronic components and circuitry used to supply LRA 18 with the required electrical current and voltage to cause the desired haptic effects. System 10 may include more than one LRA 18, and each LRA may include a separate drive circuit 16, all coupled to a common processor 12. Memory device 20 can be any type of storage device or computer-readable medium, such as random access memory (“RAM”) or read-only memory (“ROM”). Memory 20 stores instructions executed by processor 12. Among the instructions, memory 20 includes an LRA Drive with Resonant Frequency Determination module 22 which are instructions that, when executed by processor 12, generate drive signals for LRA 18 while also determining the resonant frequency of LRA 18 and adjusting the drive signals accordingly. The functionality of module 22 is discussed in more detail below. Memory 20 may also be located internal to processor 12, or any combination of internal and external memory.

Touch surface 11 recognizes touches, and may also recognize the position and magnitude of touches on the surface. The data corresponding to the touches is sent to processor 12, or another processor within system 10, and processor 12 interprets the touches and in response generates haptic effect signals. Touch surface 11 may sense touches using any sensing technology, including capacitive sensing, resistive sensing, surface acoustic wave sensing, pressure sensing, optical sensing, etc. Touch surface 11 may sense multi-touch contacts and may be capable of distinguishing multiple touches that occur at the same time. Touch surface 11 may be a touchscreen that generates and displays images for the user to interact with, such as keys, dials, etc., or may be a touchpad with minimal or no images.

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System **10** may be a handheld device, such as a cellular telephone, PDA, computer tablet, etc. or may be any other type of device that provides a user interface and includes a haptic effect system that includes one or more LRAs. The user interface may be a touch sensitive surface, or can be any other type of user interface such as a mouse, touchpad, mini-joy-stick, scroll wheel, trackball, game pads or game controllers, etc. In embodiments with more than one LRA, each LRA may have a different resonant frequency in order to create a wide range of haptic effects on the device. Each LRA may be any type of resonant actuator.

FIG. 2 is a cut-away side view of LRA **18** in accordance to one embodiment. LRA **18** includes a casing **25**, a magnet/mass **27**, a linear spring **26**, and an electric coil **28**. Magnet **27** is mounted to casing **25** by spring **26**. Coil **28** is mounted directly on the bottom of casing **25** underneath magnet **27**. LRA **18** is typical of any known LRA. In operation, when current flows thru coil **28** a magnetic field forms around coil **28** which in interaction with the magnetic field of magnet **27** pushes or pulls on magnet **27**. One current flow direction/polarity causes a push action and the other a pull action. Spring **26** controls the up and down movement of magnet **27** and has a deflected up position where it is compressed, a deflected down position where it is expanded, and a neutral or zero-crossing position where it is neither compressed or deflected and which is equal to its resting state when no current is being applied to coil **28** and there is no movement/oscillation of magnet **27**.

For LRA **18**, a mechanical quality factor or “Q factor” can be measured. In general, the mechanical Q factor is a dimensionless parameter that compares a time constant for decay of an oscillating physical system’s amplitude to its oscillation period. The mechanical Q factor is significantly affected by mounting variations. The mechanical Q factor represents the ratio of the energy circulated between the mass and spring over the energy lost at every oscillation cycle. A low Q factor means that a large portion of the energy stored in the mass and spring is lost at every cycle. In general, a minimum Q factor occurs with system **10** is held firmly in a hand due to energy being absorbed by the tissues of the hand. The maximum Q factor generally occurs when system **10** is pressed against a hard and heavy surface that reflects all of the vibration energy back into LRA **18**.

In direct proportionality to the mechanical Q factor, the forces that occur between magnet/mass **27** and spring **26** at resonance are typically 10-100 times larger than the force that coil **28** must produce to maintain the oscillation. Consequently, the resonant frequency of LRA **18** is mostly defined by the mass of magnet **27** and the compliance of spring **26**. However, when an LRA is mounted to a floating device (i.e., system **10** held softly in a hand), the LRA resonant frequency shifts up significantly. Further, significant frequency shifts can occur due to external factors affecting the apparent mounting weight of LRA **18** in system **10**, such as a cell phone flipped open/closed or the phone held tightly. Further, it is difficult using known manufacturing techniques to manufacture an LRA with a known resonant frequency within a tight tolerance. Therefore, known uses of LRA typically must assume a fixed resonant frequency at all times, which does not take into account changing resonant frequency due to different uses of a device or due to manufacturing tolerances. Since the assumption of the resonant frequency is typically inaccurate, the subsequent use of the LRA to generate haptic feedback is typically inefficient and not as effective as possible.

One embodiment of the present invention constantly and dynamically determines the resonant frequency of LRA **18** while during a monitoring period of a drive signal cycle. A

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drive signal cycle includes a drive period where drive signal pulses are applied to LRA **18**, and a monitoring period where the back electromagnetic field (“EMF”) of the moving mass **27** is received and used to determine the resonant frequency of the LRA. The drive signal pulses incorporate the desired haptic effect so that they are translated by LRA **18** into the haptic effect. In one embodiment, LRA **18** includes a sensing coil, Hall sensor, optical sensor or other type of sensing device that is located in proximity to mass **27** for detecting the position of mass **27**. In this embodiment, the sensing device will provide a sensed position signal that can be used as the monitoring signal to provide information about the position of the mass **27** instead of the back EMF signal generated by the mass and drive coil of the LRA itself.

FIG. 3 is a flow diagram of the functionality of module **22** in conjunction with processor **12** and actuator drive circuit **16** when driving LRA **18** to generate haptic feedback. The functionality of FIG. 3, and FIG. 6 below, is executed as a continuous loop during a drive cycle that includes a drive period and a monitoring period. When the functionality of FIG. 3 is initially executed, a resonant frequency for LRA **18** is assumed. During the drive period (approximately 90%) of the drive cycle, a drive pulse in the form of a square wave is applied to LRA **18**, and during the monitoring period (approximately 10%) of the drive cycle, drive circuit **16** “listens” or monitors and receives magnetic back EMF (i.e., the voltage generated by the internal motion inside LRA **18**) from LRA **18**. In one embodiment, the functionality of the flow diagram of FIG. 3 is implemented by software stored in memory or other computer readable or tangible medium, and executed by a processor. In other embodiments, the functionality may be performed by hardware (e.g., through the use of an application specific integrated circuit (“ASIC”), a programmable gate array (“PGA”), a field programmable gate array (“FPGA”), etc.), or any combination of hardware and software.

At **302**, at each half crossing of the drive pulse (i.e., when the square wave pulse goes from positive to negative and vice versa), the zero crossing time of the LRA back EMF is measured and the polarity status is latched until the end of the drive pulse.

At **304**, during each drive cycle, after the end of the last drive pulse (i.e., during the monitoring portion of the drive cycle), the LRA vibration amplitude is measured based on the derivative of the speed of the mass (“dv/dt”), which is based on the back EMF. The derivative of the speed of the mass provides a measurement of how far the mass will rise above the zero crossing.

At **306**, the desired amplitude is compared to the present amplitude as determined at **304**.

At **308**, it is determined if the desired amplitude is greater than the present amplitude. Decision block **308** also is provided as input the polarity status from **302**. Based on the decision at **308**, functionality proceeds to forward drive mode at **312** because the amplitude of the mass needs to be increased, or braking mode at **310** because the amplitude of the mass needs to be decreased.

At **312**, a drive pulse is sent that is synchronized by the zero crossing and in phase with the LRA oscillation. The drive pulse is sized to cancel the difference between the present amplitude and the desired amplitude.

At **310**, a drive pulse is sent that is synchronized by the zero crossing and out of phase with the LRA oscillation. The drive pulse is sized to cancel the difference between the present amplitude and the desired amplitude.

FIG. 4 is a block diagram of a circuit **400** for generating the functionality of FIG. 3 for driving LRA **18** in accordance with

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one embodiment. In the embodiment of FIG. 4, the driving signal is generated primarily in hardware as opposed to FIG. 3 which can be generated by any combination of software (via module 22) or hardware.

Circuit 400 is controlled by a “command” signal 410 that is converted from a Pulse-width modulation (“PWM”). When command 410 exceeds a starting threshold and becomes “valid” it initiates a “kick” pulse that is an initiation of the first drive pulse. If LRA 18 was stopped for any reason while command 410 was valid a kick pulse would be issued every 10 ms.

During a drive cycle, the drive pulse has a duration of approximately 2.2 ms generated by pulse duration 408, and it is then followed by an approximately 100 μ s delay generated by drive extension 409 that allows the drive pulse to go back to zero. During this 100 μ s monitoring period, the LRA back EMF is transmitted along monitoring branch 430 to Zero Crossing with Offset Null circuit 405. Circuit 405 waits for a zero crossing. This edge initiates a 200 μ s sampling amplitude delay 407 that will restart a new pulse. Further, when an edge is detected, the polarity of the transition is latched in latch 406 for the next pulse and sampling logic.

Circuit 405 includes a comparator and two analog switches. When the pulse driven is active via switch 420, the negative input is connected back to the output, thereby nulling the offset of the comparator. Offset nulling is needed in one embodiment because the back EMF amplitude may be generally low, especially after the first pulse. An excessively positive offset would make the detection of the edge too early, thereby increasing the frequency of the system. However, if the offset were excessively negative the edge would never be detected and the pulses would stop.

Amplitude sampling with offset null circuit 402 includes an operational amplifier and three analog switches. Circuit 402 measures the difference of amplitude between the time the zero crossing is detected until the end of the sampling period, which last approximately 200 μ s. Circuit 402 also nulls the amplifier offset. Offsets increase amplitude errors and decrease the performance at braking.

Dual differential amplifier circuit 404 includes an operational amplifier and double pole, double throw (“DPDT”) analog switch. Depending on the polarity, the amplitude of the MIX-OUT signal 403 is subtracted from command 410. The result is sent to a pulse shaping circuit.

The pulse shaping circuit includes an analog switch 420 for shaping the pulse and a filter 421 to smooth the pulse and reduce the high frequency content to avoid excessive audio noise. The filtered pulse is then converted to current by current generator 422.

Driving a current allows for a compensation in a change in impedance variation that would affect the response, in particular at the end of braking. Switch 420 is also used to switch from the drive period (switch is closed) to the monitoring period (switch is open).

FIG. 5 is a graph that illustrates an example of a portion of a drive cycle that includes a drive period and a monitoring period. A command signal 502 (which corresponds to command signal 410 of FIG. 4) transitions between periods 510 and 520. A drive signal 504 is a square wave that is active during drive pulse periods 510 and 520, and inactive during monitoring period 530. Drive signal 504 is applied to LRA 18 of FIG. 4. An output signal 506 gradually is reduced in amplitude but is still active during monitoring period 530 due to the back EMF generated by the moving mass of LRA 18. Output signal 506 is what is transmitted along monitoring branch 430 of FIG. 4.

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FIG. 6 is a flow diagram of the functionality of module 22 in conjunction with processor 12 and actuator drive circuit 16 when driving LRA 18 to generate haptic feedback in accordance with one embodiment.

As disclosed, the drive circuit in accordance with one embodiment generates haptic feedback with an LRA by including a monitoring period where the resonant frequency of the LRA is determined. The subsequent drive pulses are then adjusted to account for the resonant frequency.

Several embodiments are specifically illustrated and/or described herein. However, it will be appreciated that modifications and variations of the disclosed embodiments are covered by the above teachings and within the purview of the appended claims without departing from the spirit and intended scope of the invention.

What is claimed is:

1. A method of generating a haptic effect comprising:
 - generating a drive cycle signal that comprises a drive period and a monitoring period, wherein the drive period comprises a plurality of drive pulses that are based on the haptic effect;
 - applying the drive pulses to a resonant actuator during the drive period, wherein the resonant actuator comprises a mass; and
 - receiving a signal that comprises a position of the mass from the resonant actuator during the monitoring period.
2. The method of claim 1, further comprising:
 - modifying an amplitude of one of the drive pulses in response to the signal.
3. The method of claim 2, wherein the signal is a back electromagnetic field (EMF).
4. The method of claim 3, wherein the amplitude is modified based on a derivative of the back EMF.
5. The method of claim 2, wherein the drive pulse is out of phase with a resonant actuator oscillation.
6. The method of claim 2, wherein the drive pulse is in phase with a resonant actuator oscillation.
7. The method of claim 1, further comprising:
 - determining a resonant frequency of the resonant actuator during the monitoring period.
8. The method of claim 1, wherein the haptic effect is a vibrotactile haptic effect.
9. The method of claim 1, wherein the resonant actuator is a linear resonant actuator.
10. The method of claim 1, wherein the signal is generated by a sense coil in proximity to the mass.
11. A haptic effect enabled system comprising:
 - a resonant actuator that comprises a mass;
 - circuitry coupled to the resonant actuator, wherein the circuitry is adapted to generate a drive cycle signal that comprises a drive period and a monitoring period, wherein the drive period comprises a plurality of drive pulses that are based on a haptic effect;
 - wherein the circuitry is adapted to apply the drive pulses to a resonant actuator during the drive period, and receive a signal that comprises a position of the mass from the resonant actuator during the monitoring period.
12. The system of claim 11, the circuitry further adapted to modify an amplitude of one of the drive pulses in response to the signal.
13. The system of claim 12, wherein the signal is a back electromagnetic field (EMF).
14. The system of claim 13, wherein the amplitude is modified based on a derivative of the back EMF.
15. The system of claim 12, wherein the drive pulse is out of phase with a resonant actuator oscillation.

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16. The system of claim 12, wherein the drive pulse is in phase with a resonant actuator oscillation.

17. The system of claim 11, the circuitry further adapted to determine a resonant frequency of the resonant actuator during the monitoring period.

18. The system of claim 11, wherein the haptic effect is a vibrotactile haptic effect.

19. The system of claim 11, wherein the resonant actuator is a linear resonant actuator.

20. The system of claim 11, wherein the signal is generated by a sense coil in proximity to the mass.

21. The system of claim 11, wherein the circuitry comprises a processor and instructions stored on a computer readable media.

22. A system for generating a haptic effect comprising:
means for generating a drive cycle signal that comprises a drive period and a monitoring period, wherein the drive period comprises a plurality of drive pulses that are based on the haptic effect;

means for applying the drive pulses to a resonant actuator during the drive period, wherein the resonant actuator comprises a mass; and

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means for receiving a signal that comprises a position of the mass from the resonant actuator during the monitoring period.

23. A computer readable media having instructions stored thereon that, when executed by a processor, causes the processor to generate a haptic effect, the instructions comprising: generating a drive cycle signal that comprises a drive period and a monitoring period, wherein the drive period comprises a plurality of drive pulses that are based on the haptic effect;

applying the drive pulses to a resonant actuator during the drive period, wherein the resonant actuator comprises a mass; and

receiving a signal that comprises a position of the mass from the resonant actuator during the monitoring period.

24. The computer readable media of claim 23, the instructions further comprising:
modifying an amplitude of one of the drive pulses in response to the signal.

25. The computer readable media of claim 23, wherein the signal is a back electromagnetic field (EMF).

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