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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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G06F 3/01 (2006.01)

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

(58) **Field of Classification Search** ..... 331/65, 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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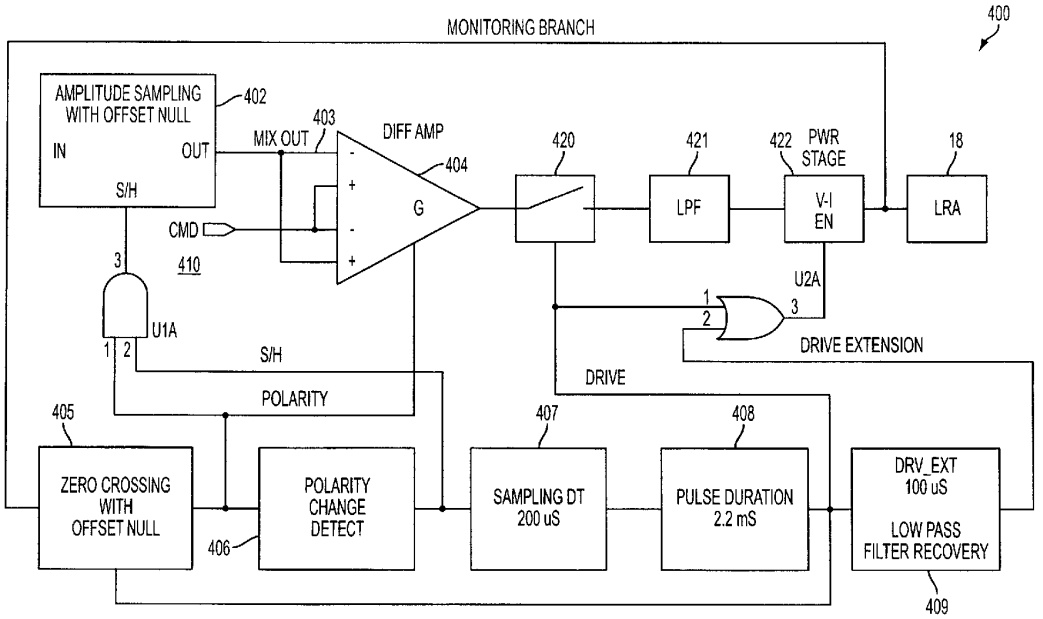
Primary Examiner—Joseph Chang
(74) *Attorney, Agent, or Firm*—Squire, Sanders & Dempsey, LLP

(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



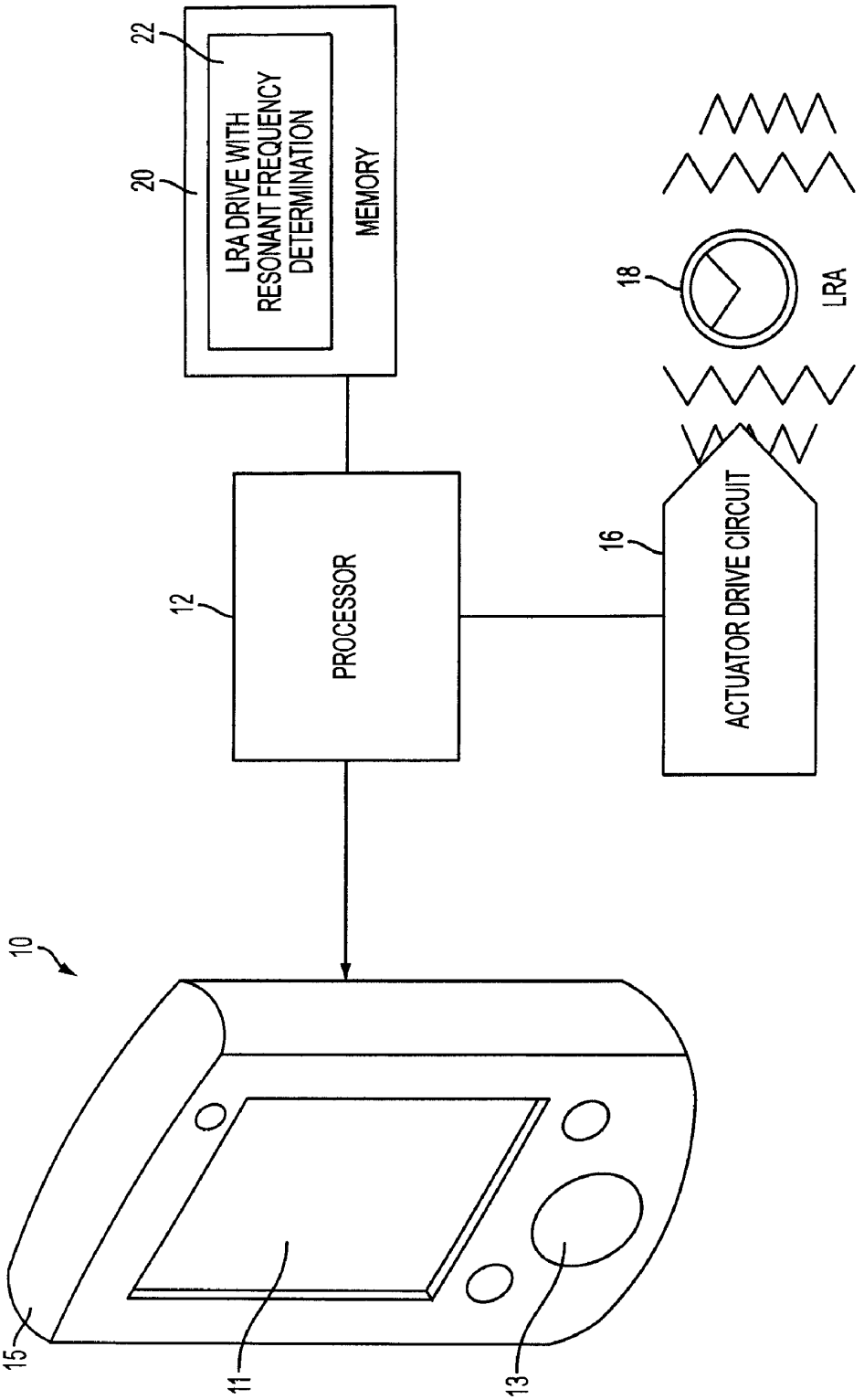

22
20
LRA DRIVE WITH RESONANT FREQUENCY DETERMINATION
MEMORY
12
PROCESSOR
16
ACTUATOR DRIVE CIRCUIT
18
LRA
10
15
11
13

FIG. 1

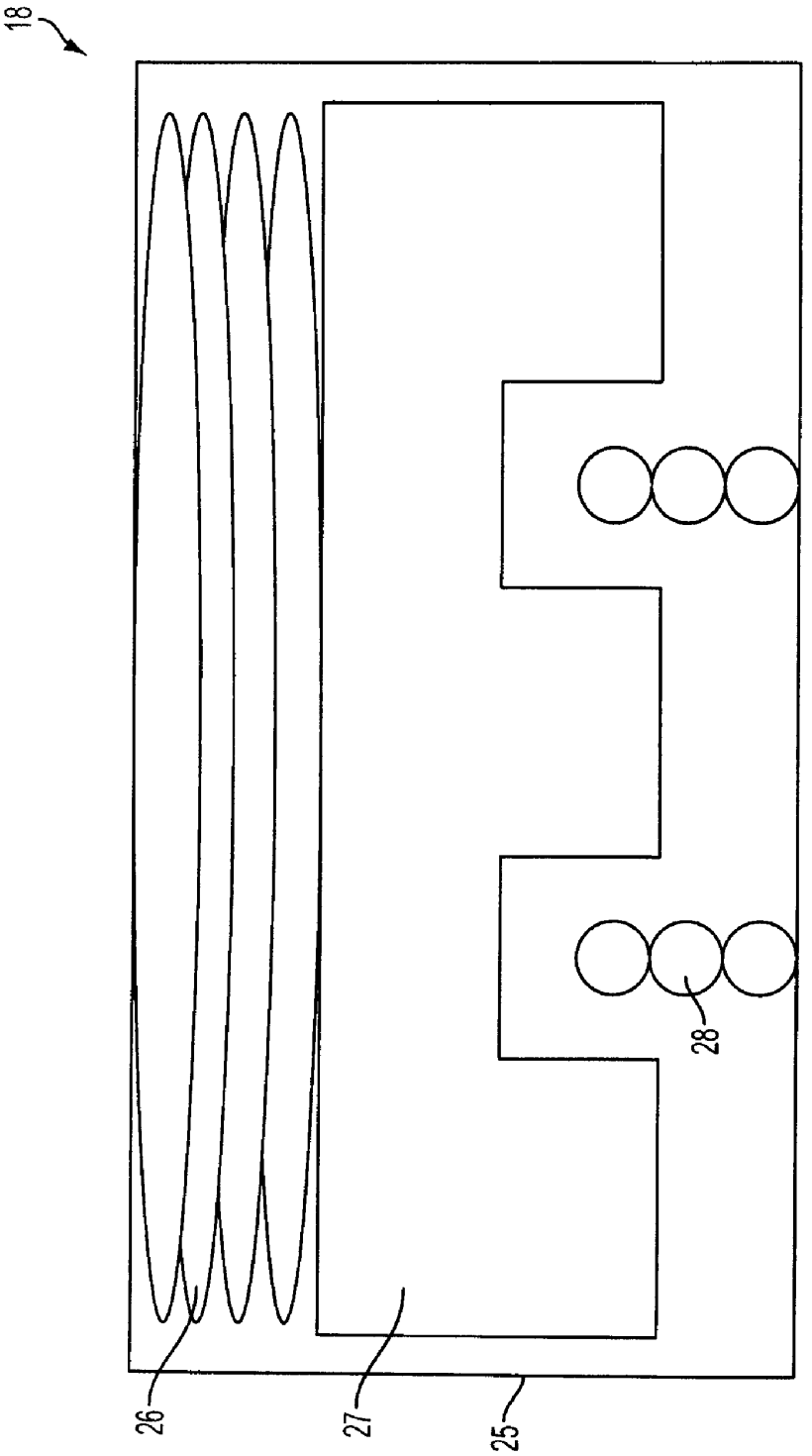


FIG. 2

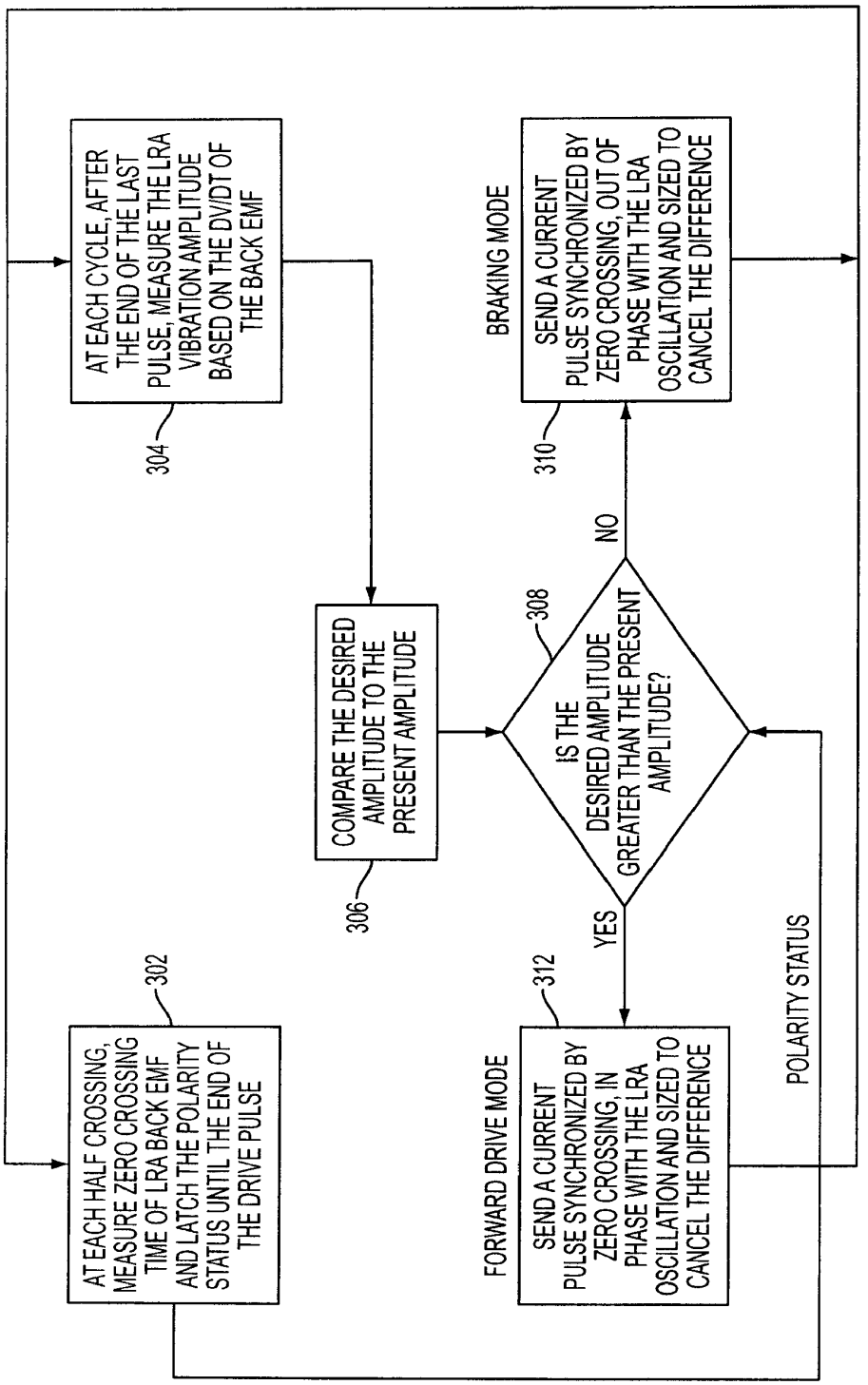

AT EACH HALF CROSSING, MEASURE ZERO CROSSING TIME OF LRA BACK EMF AND LATCH THE POLARITY STATUS UNTIL THE END OF THE DRIVE PULSE
302
AT EACH CYCLE, AFTER THE END OF THE LAST PULSE, MEASURE THE LRA VIBRATION AMPLITUDE BASED ON THE DV/DT OF THE BACK EMF
304
COMPARE THE DESIRED AMPLITUDE TO THE PRESENT AMPLITUDE
306
IS THE DESIRED AMPLITUDE GREATER THAN THE PRESENT AMPLITUDE?
308
YES
NO
FORWARD DRIVE MODE
SEND A CURRENT PULSE SYNCHRONIZED BY ZERO CROSSING, IN PHASE WITH THE LRA OSCILLATION AND SIZED TO CANCEL THE DIFFERENCE
312
BRAKING MODE
SEND A CURRENT PULSE SYNCHRONIZED BY ZERO CROSSING, OUT OF PHASE WITH THE LRA OSCILLATION AND SIZED TO CANCEL THE DIFFERENCE
310
POLARITY STATUS

FIG. 3

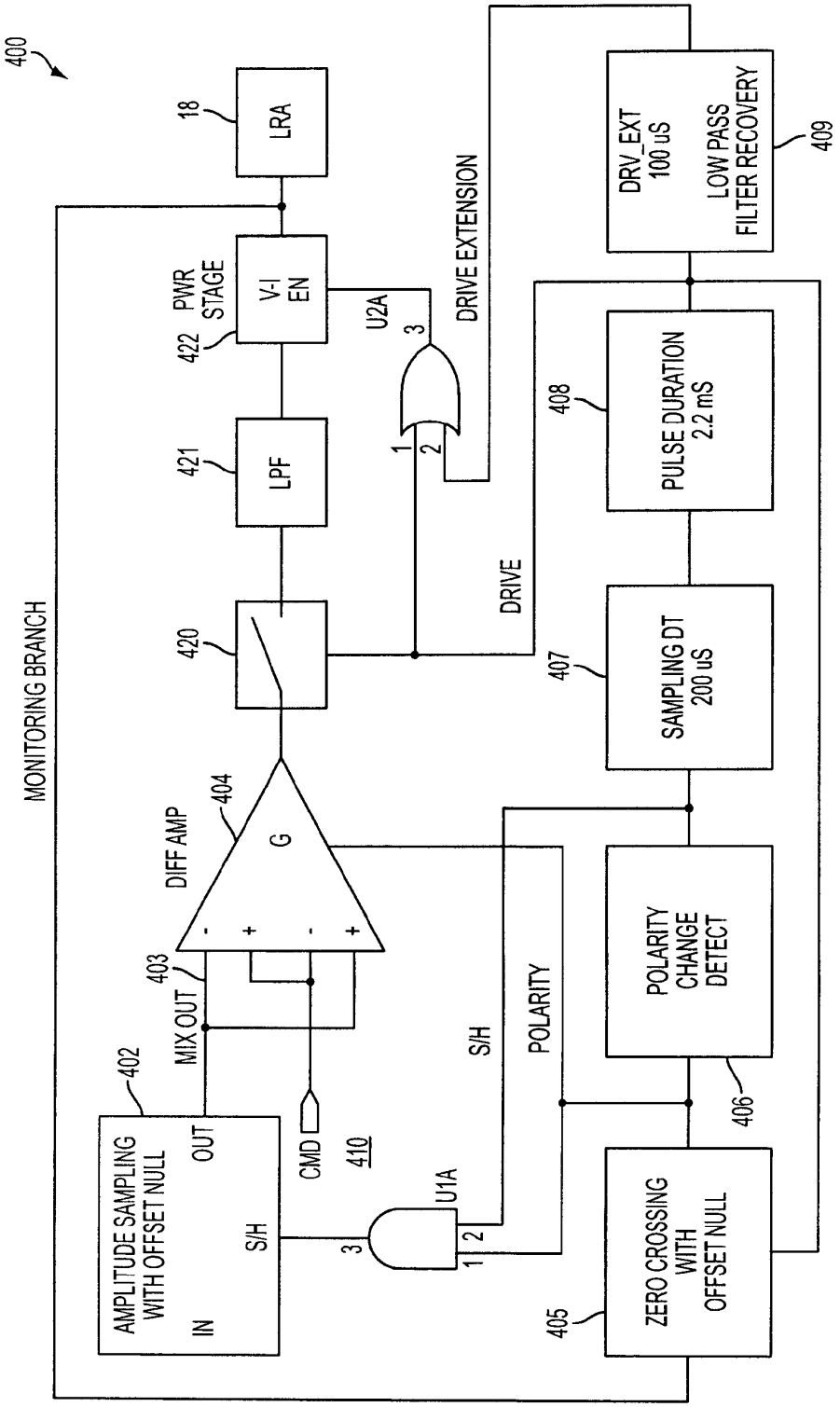

400
MONITORING BRANCH
18
LRA
PWR STAGE
422
V-I EN
421
LPF
420
DIFF AMP
404
G
403
MIX OUT
402
AMPLITUDE SAMPLING WITH OFFSET NULL
IN
S/H
OUT
CMD
410
U1A
U2A
DRIVE EXTENSION
DRIVE
S/H
POLARITY
DRV_EXT 100 uS
LOW PASS FILTER RECOVERY
409
PULSE DURATION 2.2 mS
408
SAMPLING DT 200 uS
407
POLARITY CHANGE DETECT
406
ZERO CROSSING WITH OFFSET NULL
405

FIG. 4

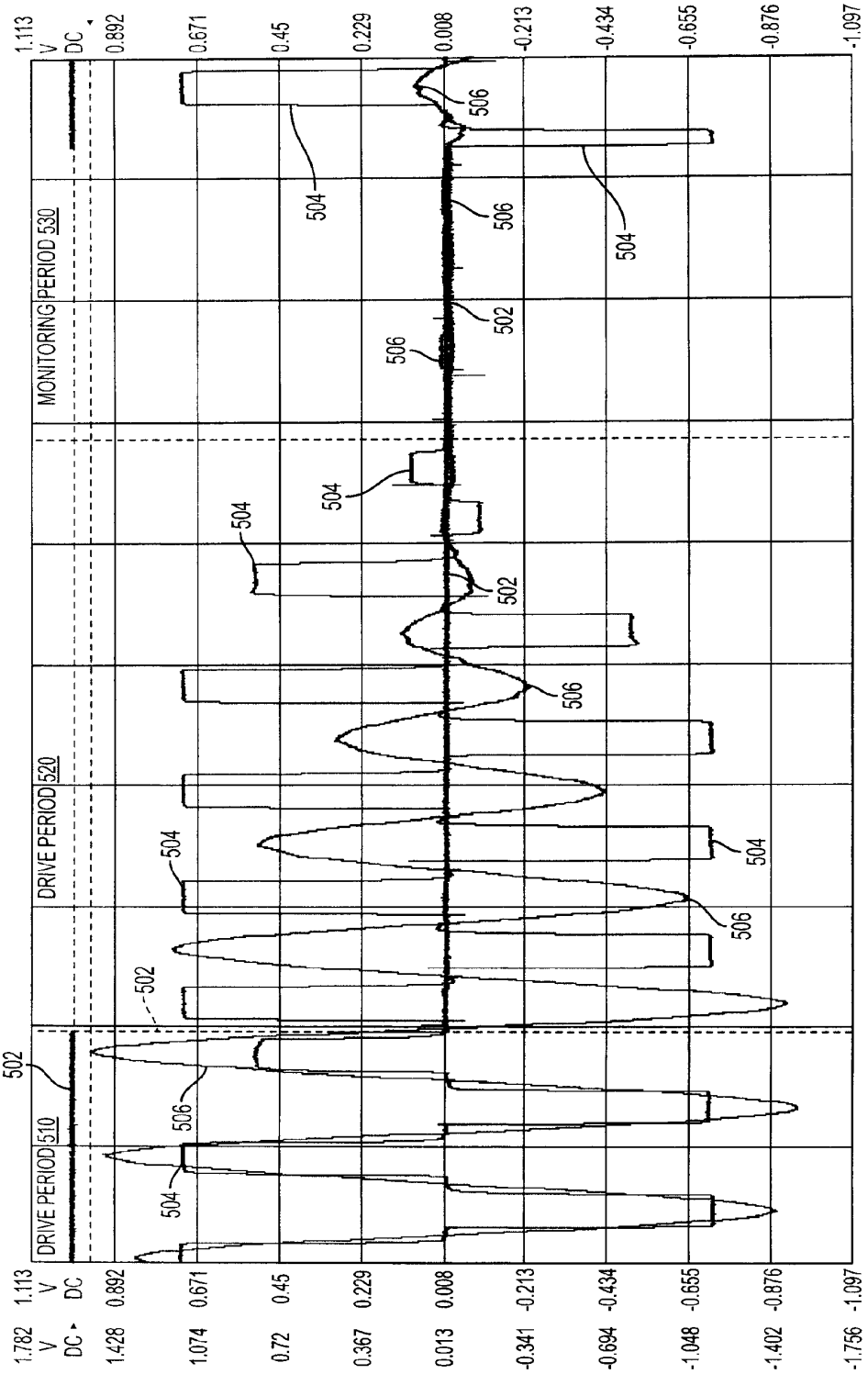

DRIVE PERIOD 510
DRIVE PERIOD 520
MONITORING PERIOD 530
502
504
506
1.782 V DC
1.428
1.074
0.72
0.367
0.013
-0.341
-0.694
-1.048
-1.402
-1.756
1.113 V DC
0.892
0.671
0.45
0.229
0.008
-0.213
-0.434
-0.655
-0.876
-1.097

FIG. 5

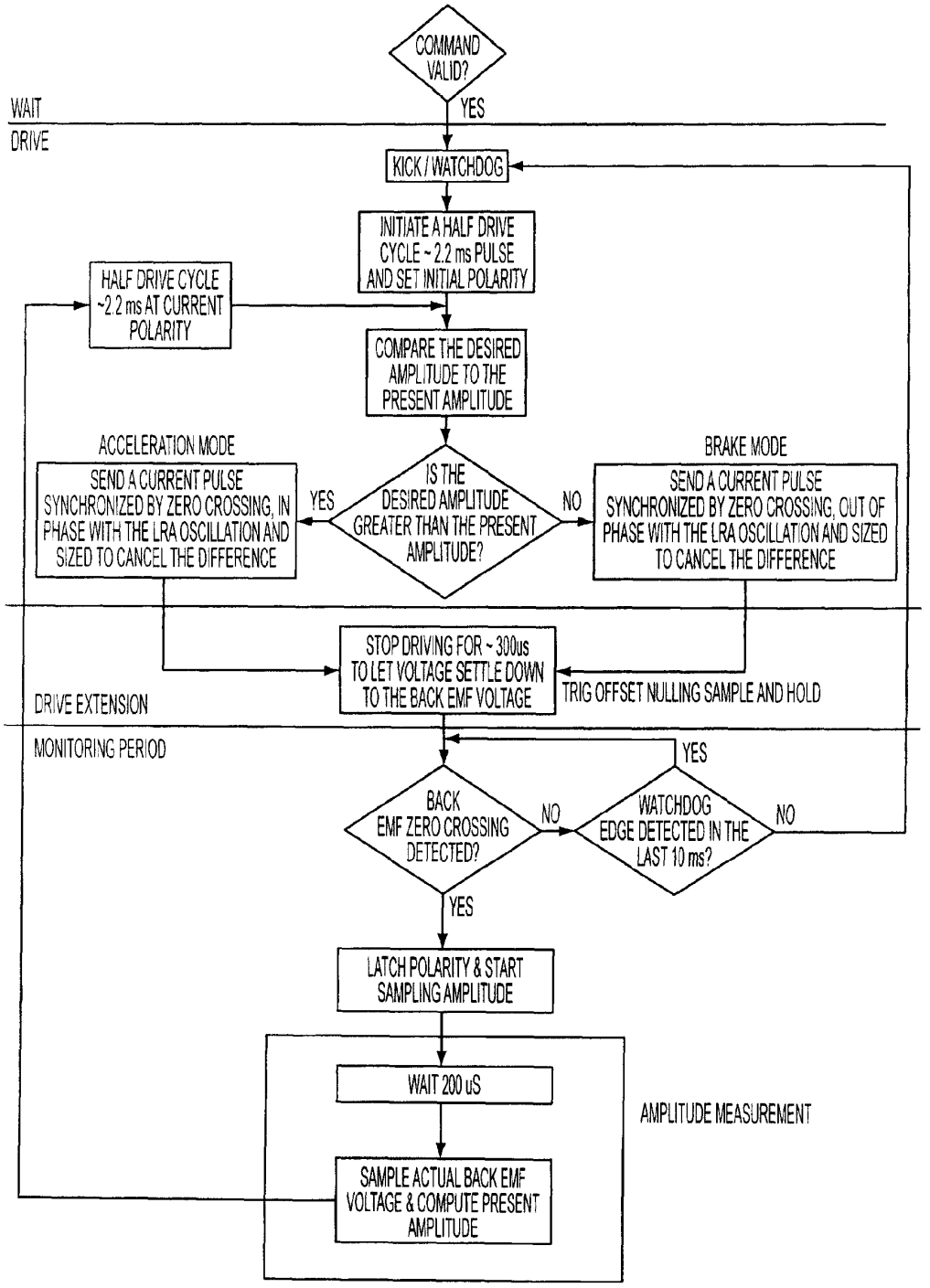

COMMAND VALID?
YES
WAIT
DRIVE
KICK / WATCHDOG
INITIATE A HALF DRIVE CYCLE ~ 2.2 ms PULSE AND SET INITIAL POLARITY
HALF DRIVE CYCLE ~2.2 ms AT CURRENT POLARITY
COMPARE THE DESIRED AMPLITUDE TO THE PRESENT AMPLITUDE
ACCELERATION MODE
SEND A CURRENT PULSE SYNCHRONIZED BY ZERO CROSSING, IN PHASE WITH THE LRA OSCILLATION AND SIZED TO CANCEL THE DIFFERENCE
YES
IS THE DESIRED AMPLITUDE GREATER THAN THE PRESENT AMPLITUDE?
NO
BRAKE MODE
SEND A CURRENT PULSE SYNCHRONIZED BY ZERO CROSSING, OUT OF PHASE WITH THE LRA OSCILLATION AND SIZED TO CANCEL THE DIFFERENCE
STOP DRIVING FOR ~ 300us TO LET VOLTAGE SETTLE DOWN TO THE BACK EMF VOLTAGE
TRIG OFFSET NULLING SAMPLE AND HOLD
DRIVE EXTENSION
MONITORING PERIOD
YES
BACK EMF ZERO CROSSING DETECTED?
NO
WATCHDOG EDGE DETECTED IN THE LAST 10 ms?
NO
YES
LATCH POLARITY & START SAMPLING AMPLITUDE
WAIT 200 uS
AMPLITUDE MEASUREMENT
SAMPLE ACTUAL BACK EMF VOLTAGE & COMPUTE PRESENT AMPLITUDE

FIG. 6

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.

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.

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-joystick, 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 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

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 μs delay generated by drive extension **409** that allows the drive pulse to go back to zero. During this 100 μs 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 μs 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 μs. 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**.

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.

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

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).

* * * * *