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(54) **Title:** THERMAL MODEL OF TRANSDUCER FOR THERMAL PROTECTION AND RESISTANCE ESTIMATION

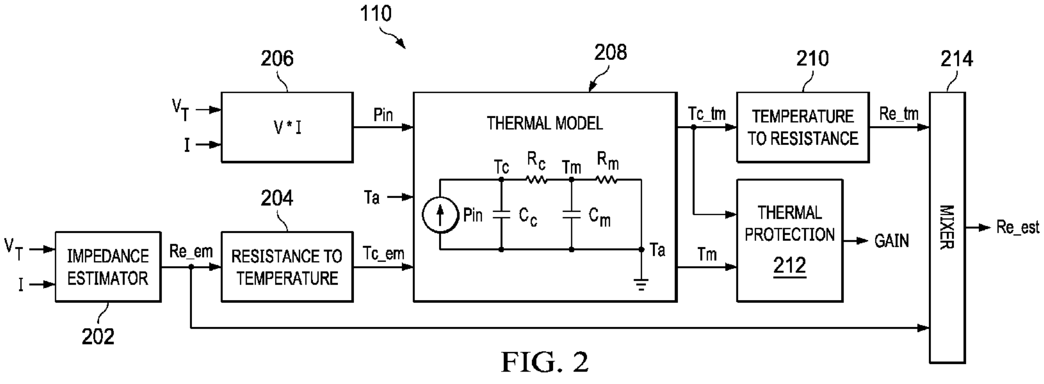

FIG. 2

(57) **Abstract:** A method for determining a direct current impedance of a transducer may include receiving an input signal indicative of an electrical power consumed by the transducer and calculating, by a thermal model of the transducer, the direct current impedance based on the electrical power.

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THERMAL MODEL OF TRANSDUCER FOR THERMAL PROTECTION AND RESISTANCE ESTIMATION

FIELD OF DISCLOSURE

The present disclosure relates in general to estimating parameters of an electromagnetic load, for example, a haptic transducer.

BACKGROUND

Mobile platforms are continually demanding better performance from their transducers, such as louder audio and better sound quality from their sound systems and better haptics performance.

For haptic transducers and other transducers, it may be desirable to determine a precise estimated resistance of the transducer, for purposes of accounting for such resistance when generating a transducer driving signal, so as to improve dynamic operation and control of the transducer. For example, it may be desirable to apply negative impedance to a transducer driving signal, which may reduce an effective quality factor of the transducer, which may in turn minimize ringing occurring in the transducer after the transducer driving signal has ended. As another example, some control systems for haptic transducers may operate effectively when a precise estimate of direct-current resistance of the haptic transducer is available. For instance, a filter or controller may be used to regulate a back-electromotive force of a transducer, and such back-electromotive force may be estimated by subtracting a voltage drop across the estimated direct-current resistance a load voltage of the haptic transducer.

Further, transducers may be damaged when they are pushed to their limits. One common failure mode for over-driven transducers (e.g., speakers/haptics) is thermal damage. As an example, for speakers, if the voice coil exceeds a maximum temperature, the glues that hold the voice coil together and connect it to the diaphragm can melt and cause irreparable damage. As another example, at higher temperatures, magnets in a haptic transducer may become demagnetized and/or a coil of the haptic transducer may fuse, causing an electrical short. Speaker protection algorithms are commonly used to drive the speaker to its maximum volume while ensuring it does not exceed its rated limits, and similar protection algorithms may be used in connection with haptic transducers.

SUMMARY

In accordance with the teachings of the present disclosure, the disadvantages and problems associated with undesirable dynamics and thermal protection of an electromagnetic load may be reduced or eliminated.

In accordance with embodiments of the present disclosure, a method for determining a direct current impedance of a transducer may include receiving an input signal indicative of an electrical power consumed by the transducer and calculating, by a thermal model of the transducer, the direct current impedance based on the electrical power.

In accordance with these and other embodiments of the present disclosure, a system may include a transducer and a control system for monitoring operation of the transducer and configured to determine a direct current impedance of a transducer by receiving an input signal indicative of an electrical power consumed by the transducer, and calculating, by a thermal model of the transducer implemented by the control system, the direct current impedance based on the electrical power.

Technical advantages of the present disclosure may be readily apparent to one having ordinary skill in the art from the figures, description and claims included herein. The objects and advantages of the embodiments will be realized and achieved at least by the elements, features, and combinations particularly pointed out in the claims.

It is to be understood that both the foregoing general description and the following detailed description are examples and explanatory and are not restrictive of the claims set forth in this disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present embodiments and advantages thereof may be acquired by referring to the following description taken in conjunction with the accompanying drawings, in which like reference numbers indicate like features, and wherein:

FIGURE 1 illustrates an example control system for use with a transducer, in accordance with embodiments of the present disclosure;

FIGURE 2 illustrates an example thermal protection and resistance estimation block, in accordance with embodiments of the present disclosure;

FIGURE 3 illustrates example waveforms for estimated input power to a haptic transducer and thermally-modeled series resistance of the haptic transducer over a plurality of haptic events, in accordance with the present disclosure; and

FIGURE 4 illustrates a flowchart for an example method for thermal protection and resistance estimation, in accordance with embodiments of the present disclosure.

DETAILED DESCRIPTION

The description below sets forth example embodiments according to this disclosure. Further example embodiments and implementations will be apparent to those having ordinary skill in the art. Further, those having ordinary skill in the art will recognize that various equivalent techniques may be applied in lieu of, or in conjunction with, the embodiment discussed below, and all such equivalents should be deemed as being encompassed by the present disclosure.

Various electronic devices or smart devices may have transducers, speakers, and acoustic output transducers, for example any transducer for converting a suitable electrical driving signal into an acoustic output such as a sonic pressure wave or mechanical vibration. For example, many electronic devices may include one or more speakers or loudspeakers for sound generation, for example, for playback of audio content, voice communications and/or for providing audible notifications.

Such speakers or loudspeakers may comprise an electromagnetic actuator, for example a voice coil motor, which is mechanically coupled to a flexible diaphragm, for example a conventional loudspeaker cone, or which is mechanically coupled to a surface of a device, for example the glass screen of a mobile device. Some electronic devices may also include acoustic output transducers capable of generating ultrasonic waves, for example for use in proximity detection type applications and/or machine-to-machine communication.

Many electronic devices may additionally or alternatively include more specialized acoustic output transducers, for example, haptic transducers, tailored for generating vibrations for haptic control feedback or notifications to a user. Additionally or alternatively, an electronic device may have a connector, e.g., a socket, for making a removable mating connection with a corresponding connector of an accessory apparatus and may be arranged to provide a driving signal to the connector so as to drive a transducer, of one or more of the types mentioned above, of the accessory apparatus when connected. Such an electronic device will thus comprise driving circuitry for driving the transducer of the host device or connected accessory with a suitable driving signal. For acoustic or haptic transducers, the driving signal will generally be an analog time varying voltage signal, for example, a time varying waveform.

FIGURE 1 illustrates an example control system 100 for use with a transducer 101, in accordance with embodiments of the present disclosure. In some embodiments, system 100 may be integral to a host device comprising system 100 and haptic transducer 101. Such device may include, without limitation, a mobile device, home appliance, a vehicle, and/or any other system, device, or apparatus that includes a human-machine interface. As described in greater detail below, a system 100 may implement negative impedance block 124 to apply to the raw transducer driving signal, which may reduce an effective quality factor q of the transducer, which may in turn minimize ringing occurring after the raw transducer driving signal has ended.

Accordingly, one way system 100 may minimize quality factor q is to effectively decrease DC resistance Re of the transducer. In some embodiments, system 100 may ideally decrease the effective DC resistance Re to a point in which critical damping occurs in haptic transducer 101. To lower effective DC resistance *Re*, system 100 may, via negative impedance block 124, apply a negative impedance *Re_neg* in series with DC resistance *Re*. Negative impedance *Re_neg* may sum with resistance *Re* in series to produce a lower effective series resistance. As described in greater detail below, system 100 may implement negative impedance *Re_neg* as a feedback loop around haptic transducer 101.

For example, where a measure of a current $I(t)$ and terminal voltage $V_T(t)$ resulting from applying a waveform signal $x(t)$ through haptic transducer 101 is readily accessible, then system 100 may implement a negative feedback loop in the form of adding the mathematical product Re x R_{e_cancel} x $I(t)$ to a raw waveform signal $x'(t)$ at negative impedance block 124 to generate waveform signal $x(t)$ for driving haptic transducer 101. Multiplicative factor R_{e_cancel} may be a value between 0 and 1 (e.g., 0.97) that sets a fraction of DC resistance *Re* to be cancelled at negative impedance block 124 (e.g., by multiplying an estimate of DC resistance *Re* (R_{e_est}) by multiplicative factor R_{e_cancel} at multiplier 116). Resistance estimate R_{e_est} may be an estimate of true series resistance *Re*. As shown in FIGURE 1, a thermal protection and resistance estimation block 110 may generate resistance estimate R_{e_est} as described in greater detail below. In addition, as described in greater detail below, thermal protection and resistance estimation block 110 may generate a gain GAIN that may be applied to raw waveform signal $x'(t)$ (e.g., by multiplying raw waveform signal $x'(t)$ by gain GAIN at multiplier 120).

In operation, a pulse generator 122 may generate raw waveform signal $x'(t)$. Raw waveform signal $x'(t)$ may comprise any suitable signal for driving haptic transducer 101 (e.g., having characteristics to generate a desired haptic effect at haptic transducer 101). For example, raw waveform signal $x'(t)$ may have characteristics based on a resonant frequency, quality factor, and/or other parameter of haptic transducer 101. Multiplier 120 may apply gain GAIN to raw waveform signal $x'(t)$ and negative impedance block 124 of system 100 may generate waveform signal $x(t)$

from the gained raw waveform signal $x'(t)$. Waveform signal $x(t)$ may in turn be amplified by amplifier 106 to generate the driving signal $V(t)$ for driving haptic transducer 101. Although FIGURE 1 depicts haptic transducer 101, in some embodiments, another electromagnetic load (e.g., a loudspeaker, a microspeaker, a piezoelectric transducer) may be present in lieu of haptic transducer 101.

Responsive to driving signal $V(t)$, a sensed terminal voltage $V_T(t)$ of haptic transducer 101 may be converted to a digital representation V_T by a first analog-to-digital converter (ADC) 103. Similarly, sensed current $I(t)$ may be converted to a digital representation I by a second ADC 104. Current $I(t)$ may be sensed across a shunt resistor 102 having resistance R_s coupled to a terminal of haptic transducer 101. The terminal voltage $V_T(t)$ may be sensed by a terminal voltage sensing block 107, for example a volt meter.

These real-time digital estimates of sensed terminal voltage $V_T(t)$ and sensed current $I(t)$ may be made available to system 100, which may be implemented in whole or in part by a central processing unit, digital signal processor, or other digital circuit. System 100 may in turn perform thermal protection and resistance estimation for haptic transducer 101, as described in greater detail elsewhere in this disclosure.

FIGURE 2 illustrates an example thermal protection and resistance estimation block 110, in accordance with embodiments of the present disclosure. As shown in FIGURE 2, thermal protection and resistance estimation block 110 may include an impedance estimator 202, a resistance-to-temperature converter 204, an input power estimator 206, a thermal model 208, a temperature-to-resistance converter 210, a thermal protection subblock 212, and a mixer 214.

Impedance estimator 202 may comprise any suitable system, device, or apparatus configured to generate an electrically-measured series resistance Re_em for actual series resistance Re of haptic transducer 101. For example, in some embodiments, impedance estimator 202 may simply calculate electrically-measured series resistance Re_em as a quantity equal to an amplitude of terminal voltage V_T

divided by amplitude of current *I*. In other embodiments, impedance estimator 202 may more accurately estimate electrically-measured impedance by a least-squares fitting a voltage and current sequence (e.g., having a sequence length between 5 and 100 milliseconds) to a series resistive and inductive impedance.

Resistance-to-temperature converter 204 may comprise any suitable system, device, or apparatus configured to calculate a measured coil temperature *Tc_em* of haptic transducer 101. For example, in some embodiments, resistance-to-temperature converter 204 may calculate measured coil temperature *Tc_em* by translating resistance to temperature based on a temperature coefficient of series resistance *Re*.

Input power estimator 206 may comprise any suitable system, device, or apparatus configured to calculate an estimated input power P_{in} driven to haptic transducer 101. For example, in some embodiments, an input power estimator 206 may calculate estimated input power P_{in} as the product of an amplitude of terminal voltage V_T and an amplitude of current *I*. In other embodiments, input power estimator 206 may estimate power input in another manner, such as calculating estimated input power P_{in} as the square of an amplitude of current *I* multiplied by electrically-measured series resistance *Re_em* or as the square of an amplitude terminal voltage V_T divided by electrically-measured series resistance *Re_em*.

Thermal model 208 may comprise any suitable system, device, or apparatus configured to receive estimated input power P_{in}, which represents an amount of heat generated by haptic transducer 101 in response to driving signal $V(t)$, and based thereon, calculate an estimated coil temperature *Tc_tm* and estimated magnetic temperature *Tm*. As shown in FIGURE 2, thermal model 208 may include a modeled coil temperature *Tc*, modeled magnetic temperature *Tm*, and modeled ambient temperature *Ta* as state variables of the model, wherein such variables are modeled as voltage nodes of an equivalent circuit model as resistances and capacitances (e.g., representing thermal mass and other thermal parameters) driven by estimated input power P_{in} modeled as a power source. For example, thermal parameters of a coil of haptic transducer 101 may be modeled as an equivalent resistance *Rc* and capacitance

Cc, and magnetic parameters of the load may be modeled as an equivalent resistance *Rm* and capacitance *Cm*. However, thermal model 208 may include a model different than that depicted in FIGURE 2. For instance, in some embodiments, thermal model 208 may be modeled as a third-order or higher-order model as opposed to the second order model shown in FIGURE 2.

As shown in FIGURE 2, thermal model 208 may receive measured coil temperature *Tc_em* such that modeled coil temperature *Tc* may from time to time be updated with an actual measured temperature represented by measured coil temperature *Tc_em* in order to improve modeling accuracy. Also as shown in FIGURE 2, thermal model 208 may receive an actual ambient temperature *Ta* such that modeled ambient temperature *Ta* may from time to time be updated with an actual ambient temperature *Ta* in order to improve modeling accuracy. In the event that an actual ambient temperature *Ta* is not provided, in some instances thermal model 208 may assume that modeled ambient temperature *Ta* is equal to modeled coil temperature *Tc*, as would be the case if haptic transducer 101 has not been in operation long enough to heat up from being driven by driving signal $V(t)$. In other instances, thermal model 208 may assume that modeled ambient temperature *Ta* represents a nominal environmental temperature that does not require updating. In yet other instances, modeled ambient temperature *Ta* may be an output of thermal model 208.

In some embodiments, thermal model 208 may be implemented by or form an integral part of an infinite impulse response filter. On other embodiments, thermal model 208 may be implemented by or form an integral part of a Kalman filter.

Temperature-to-resistance converter 210 may comprise any suitable system, device, or apparatus configured to, based on estimated coil temperature *Tc_tm*, calculate a thermally-modeled series resistance *Re_tm* for actual series resistance *Re* of haptic transducer 101. For example, in some embodiments, temperature-to-resistance converter 210 may calculate thermally-modeled series resistance *Re_tm* by translating temperature to resistance based on a temperature coefficient of series resistance *Re*.

In some embodiments, resistance-to-temperature converter 204, thermal model 208, and temperature-to-resistance converter 210 may be combined into a single model that receives as inputs estimated input power P_{in}, electrically-measured series resistance *Re_em*, and an ambient-temperature resistance *Ra* that represents a resistance of the coil when it has settled to ambient temperature *Ta*. Such combined model may generate thermally-modeled series resistance *Re_tm* and a thermally-modeled magnetic resistance *Rm_tm* as outputs. In such combined model, state variables of thermal model 208 may represent the resistance values the coil and magnet would have when the coil and magnet temperatures reach estimated coil temperature *Tc_tm* and modeled magnetic temperature *Tm*, respectively. Such combined model may have the benefit that no temperature is estimated by the combined model, wherein such temperature estimation may otherwise require a calibration step to accurately map at least one resistance value to a temperature value and wherein a thermal protection circuit tests its inputs of thermally-modeled series resistance *Re_tm* and thermally-modeled magnetic resistance *Rm_tm* against worst-case resistance thresholds to decide on engaging thermal protection. The combined method may be less accurate than comparing to actual threshold temperatures but may be adequate for particular applications.

Inputs to and outputs from thermal model 208 may change over time as controlled by a sequencing state-machine, and such inputs and outputs may be adapted to best determine all the quantities modeled: modeled coil temperature *Tc*, modeled magnetic temperature *Tm*, and modeled ambient temperature *Ta*, based on availability of external information, including without limitation estimated input power P_{in}, measured coil temperature *Tc_em*, and externally-measured ambient temperature *Ta_ext*. It is noted that modeled ambient temperature *Ta* may be different than externally-measured ambient temperature *Ta_ext* (e.g., which may be determined by an external temperature sensor or some other means). When thermal model 208 receives estimated input power P_{in} and measured coil temperature *Tc_em* as inputs, it may estimate and output modeled magnetic temperature *Tm* and/or estimated coil temperature *Tc_tm* (and also modeled ambient temperature *Ta* if modeled ambient temperature *Ta* is assumed non-constant). When thermal model 208 receives estimated input power P_{in} and modeled ambient temperature *Ta* as inputs, it may estimate and output modeled magnetic temperature *Tm* and/or estimated coil temperature *Tc_tm*.

Thermal protection subblock 212 may comprise any suitable system, device, or apparatus configured to, based on one or more temperatures associated with haptic transducer 101 (e.g., estimated coil temperature *Tc_tm* and/or modeled magnetic temperature *Tm*) determine if such one or more temperatures exceed thermal limits for haptic transducer 101 and reduce gain GAIN if such one or more temperatures exceed thermal limits for haptic transducer 101. In some embodiments, thermal protection subblock 212 may use other approaches for reducing thermal power to haptic transducer 101 (e.g., request clipping to the output of amplifier 106).

Mixer 214 may comprise any suitable system, device, or apparatus configured to mix a selected portion of thermally-modeled series resistance *Re_tm* and a portion of electrically-measured series resistance *Re_em* to be mixed together to generate estimated DC resistance R_{e_est}. In some embodiments, mixer 214 may operate as a multiplexer passing either thermally-modeled series resistance *Re_tm* or electrically-measured series resistance *Re_em* as estimated DC resistance R_{e_est}.

In operation, and as described in greater detail below, during a first haptic event (e.g., during an actual haptic event for providing haptic feedback to a user or a pilot tone generated by pulse generator 122 for characterizing estimated DC resistance R_{e_est}), thermal protection and resistance estimation block 110 may determine estimated DC resistance R_{e_est} based on electrically-measured series resistance *Re_em* and set state variables for modeled coil temperature *Tc*, modeled magnetic temperature *Tm*, and/or modeled ambient temperature *Ta* of thermal model 208 based on measured coil temperature *Tc_em* converted from electrically-measured series resistance *Re_em*. For a later-occurring second haptic event, thermal protection and resistance estimation block 110 may determine estimated DC resistance R_{e_est} to be equal to thermally-modeled series resistance *Re_tm* calculated by thermal model 208 based on estimated input power P_{in}, thus permitting an estimate of DC resistance *Re* without generating a measurement by impedance estimator 202. To further illustrate this operation, FIGURE 3 illustrates example waveforms for estimated input power P_{in} and thermally-modeled series resistance *Re_tm* over a plurality of haptic events, in accordance with the present disclosure. As shown in FIGURE 3, during a first haptic event, thermal model 208 may estimate thermal states (including modeled ambient temperature *Ta*) for the coil and magnet of haptic transducer 101 increasing modeled series resistance *Re_tm* in a transient fashion, which should track an actual increase in actual DC resistance *Re*. A hibernation period may occur after the first haptic event, in which actual DC resistance *Re* may decrease (and in which modeled series resistance *Re_tm* may decrease). At the start of the second haptic event, thermal model 208 may predict thermal states for the coil and magnet of haptic transducer 101 based on the last known states prior to hibernation and the duration between events (including an assumption that modeled ambient temperature *Ta* determined during the first haptic event remains constant during the hibernation period). For example, such thermal states may be predicted based on an estimate of transient electrical and/or thermal effects, such as an estimated decrease of modeled series resistance *Re_tm* in a transient fashion during the hibernation period. These states may be mapped to modeled series resistance *Re_tm* for the second haptic event and any subsequent haptic event unless and until an actual DC resistance *Re* may be determined.

FIGURE 4 illustrates a flowchart for an example method 400 for thermal protection and resistance estimation, in accordance with embodiments of the present disclosure. According to one embodiment, method 400 may begin at step 402. As noted above, teachings of the present disclosure may be implemented in a variety of configurations of system 100 and thermal protection and resistance estimation block 110. As such, the preferred initialization point for method 400 and the order of the steps comprising method 400 may depend on the implementation chosen.

At step 402, a device comprising system 100, haptic transducer 101, and amplifier 106 may power on. At step 404, pulse generator 122 may drive a pilot tone (e.g., at 10Hz) for raw waveform signal $x'(t)$ for a period of time long enough to measure terminal voltage $V_T(t)$ and current I.

At step 406, based on measured terminal voltage $V_T(t)$ and current I, impedance estimator 202 may calculate electrically-measured series resistance *Re_em*. At step 408, resistance-to-temperature converter 204 may calculate measured coil temperature *Tc_em* based on electrically-measured series resistance *Re_em*.

At step 410, thermal protection and resistance estimation block 110 may initialize state variables of thermal model 208. For example, modeled ambient temperature *Ta* may be set to a user setting, default setting, or other setting indicative of an ambient temperature for haptic transducer 101, modeled magnetic temperature *Tm* may be set to the modeled ambient temperature *Ta*, and modeled coil temperature *Tc* may be set to measured coil temperature *Tc_em*. At step 412, after state variables are initialized, thermal protection and resistance estimation block 110 may enable thermal model 208 to generate thermally-modeled estimates for coil temperature *Tc_tm* and estimated magnetic temperature *Tm* based on estimated input power P_{in}.

At step 414, thermal protection and resistance estimation block 110 may initiate a watchdog timer. At step 416, thermal protection and resistance estimation block 110 may monitor for a haptic playback request and expiration of the watchdog timer, and method 400 may proceed to step 418 upon occurrence of a haptic playback request or expiration of the watchdog timer. Accordingly, the watchdog timer may trigger estimation events for estimating DC resistance *Re*, and in such cases, a pilot tone below resonance frequency of haptic transducer 101 may be generated, wherein such pilot tone may not produce a user-perceptible haptic response. The generation of such pilot tone may assist in tracking variation of modeled ambient temperature *Ta* (e.g., predicted from electrically-measured series resistance *Re_em* and ambient-temperature resistance *Ra* when no external ambient temperature input (e.g. *Ta_ext*) is provided).

At step 418, responsive to expiration of the watchdog timer or the haptic playback request, temperature-to-resistance converter 210 may calculate thermally-modeled series resistance *Re_tm* based on estimated coil temperature *Tc_tm* generated from modeled coil temperature *Tc*, and thermal protection subblock 212 may determine a gain GAIN based on estimated coil temperature *Tc_tm* and/or modeled magnetic temperature *Tm*. Mixer 214 may pass thermally-modeled series resistance *Re_tm* as an estimated DC resistance R_{e_est}, which may be used by negative impedance block 124 to apply a negative resistance to raw waveform signal $x'(t)$.

At step 420, system 100 may play back waveform signal $x(t)$ (e.g., either a pilot tone or haptic playback signal). At step 422, concurrent with the playback of waveform signal $x(t)$, impedance estimator 202 may calculate electrically-measured series resistance *Re_em* and resistance-to-temperature converter 204 may calculate measured coil temperature *Tc_em* based on electrically-measured series resistance *Re-_em*. At step 424, thermal protection and resistance estimation block 110 may update modeled coil temperature *Tc*, modeled ambient temperature *Ta*, and/or other thermal parameters based on the newly-calculated measured coil temperature *Tc_em*. Until a subsequent haptic event (or a pilot tone triggered based on expiration of the watchdog timer) updates modeled ambient temperature *Ta*, modeled ambient temperature *Ta* may be assumed to remain constant. Thus, parameters of thermal model 208 may be estimated based on a time since the prior haptic event (which may be indicated by a status of the watchdog timer) based on principles of transient operation of electrical signals and temperatures. After completion of step 424, method 400 may proceed again to step 414.

Although FIGURE 4 discloses a particular number of steps to be taken with respect to method 400, method 400 may be executed with greater or lesser steps than those depicted in FIGURE 4. In addition, although FIGURE 4 discloses a certain order of steps to be taken with respect to method 400, the steps comprising method 400 may be completed in any suitable order.

Method 400 may be implemented using system 100, thermal protection and resistance estimation block 110, or any other system operable to implement method 400. In certain embodiments, method 400 may be implemented partially or fully in software and/or firmware embodied in computer-readable media.

As used herein, when two or more elements are referred to as “coupled” to one another, such term indicates that such two or more elements are in electronic communication or mechanical communication, as applicable, whether connected indirectly or directly, with or without intervening elements.

This disclosure encompasses all changes, substitutions, variations, alterations, and modifications to the example embodiments herein that a person having ordinary skill in the art would comprehend. Similarly, where appropriate, the appended claims encompass all changes, substitutions, variations, alterations, and modifications to the example embodiments herein that a person having ordinary skill in the art would comprehend. Moreover, reference in the appended claims to an apparatus or system or a component of an apparatus or system being adapted to, arranged to, capable of, configured to, enabled to, operable to, or operative to perform a particular function encompasses that apparatus, system, or component, whether or not it or that particular function is activated, turned on, or unlocked, as long as that apparatus, system, or component is so adapted, arranged, capable, configured, enabled, operable, or operative. Accordingly, modifications, additions, or omissions may be made to the systems, apparatuses, and methods described herein without departing from the scope of the disclosure. For example, the components of the systems and apparatuses may be integrated or separated. Moreover, the operations of the systems and apparatuses disclosed herein may be performed by more, fewer, or other components and the methods described may include more, fewer, or other steps. Additionally, steps may be performed in any suitable order. As used in this document, “each” refers to each member of a set or each member of a subset of a set.

Although exemplary embodiments are illustrated in the figures and described below, the principles of the present disclosure may be implemented using any number of techniques, whether currently known or not. The present disclosure should in no way be limited to the exemplary implementations and techniques illustrated in the drawings and described above.

Unless otherwise specifically noted, articles depicted in the drawings are not necessarily drawn to scale.

All examples and conditional language recited herein are intended for pedagogical objects to aid the reader in understanding the disclosure and the concepts contributed by the inventor to furthering the art, and are construed as being without limitation to such specifically recited examples and conditions. Although embodiments of the present disclosure have been described in detail, it should be understood that various changes, substitutions, and alterations could be made hereto without departing from the spirit and scope of the disclosure.

Although specific advantages have been enumerated above, various embodiments may include some, none, or all of the enumerated advantages. Additionally, other technical advantages may become readily apparent to one of ordinary skill in the art after review of the foregoing figures and description.

To aid the Patent Office and any readers of any patent issued on this application in interpreting the claims appended hereto, applicants wish to note that they do not intend any of the appended claims or claim elements to invoke 35 U.S.C. § 112(f) unless the words “means for” or “step for” are explicitly used in the particular claim.

WHAT IS CLAIMED IS:

1. A method for determining a direct current impedance of a transducer, comprising:

receiving an input signal indicative of an electrical power consumed by the transducer; and

calculating, by a thermal model of the transducer, the direct current impedance based on the electrical power.

2. The method of Claim 1, wherein calculating the direct current impedance comprises:

generating, by the thermal model of the transducer, a coil temperature associated with the transducer; and

calculating the direct current impedance based on the coil temperature.

3. The method of Claim 1, wherein calculating the direct current impedance comprises calculating the direct current impedance directly from the electrical power, without an intermediate calculation of a coil temperature associated with the transducer.

4. The method of Claim 1, further comprising mixing the direct current impedance with an estimated impedance value derived from an electrical model of the direct current impedance.

5. The method of Claim 1, further comprising controlling a load power delivered to the transducer based on at least one of the coil temperature and another temperature generated by the thermal model.

6. The method of Claim 5, wherein controlling the load power comprises determining a gain to be applied to a driving signal for driving the transducer based on at least one of the coil temperature and another temperature generated by the thermal model.

7. The method of Claim 5, wherein controlling the load power comprises clipping to a driving signal for driving the transducer.

8. The method of Claim 1, wherein the thermal model is implemented with a Kalman filter.

9. The method of Claim 1, wherein the thermal model is implemented with an infinite impulse response filter.

10. The method of Claim 1, wherein the transducer is a haptic transducer.

11. The method of Claim 1, wherein the transducer is an audio speaker.

12. The method of Claim 1, further comprising:

driving the transducer with a driving signal;

estimating an electrically-measured direct current impedance based on an electrical model of the transducer;

estimating an electrically-measured coil temperature based on the electrically-measured direct current impedance; and

setting one or more state variables of the thermal model based on the electrically-measured coil temperature.

13. The method of Claim 12, further comprising in the absence of the driving signal including a haptic event, driving a pilot tone to the transducer at regular intervals to set an ambient temperature as one of the one or more state variables.

14. The method of Claim 12, further comprising:

halting updates to the one or more state variables between haptic events within the driving signal; and

prior to driving the transducer with the driving signal comprising a haptic event, updating the one or more state variables based on a time elapsed since a previous haptic event.

15. A system comprising:

a transducer; and

a control system for monitoring operation of the transducer and configured to determine a direct current impedance of a transducer by:

receiving an input signal indicative of an electrical power consumed by the transducer; and

calculating, by a thermal model of the transducer implemented by the control system, the direct current impedance based on the electrical power.

16. The system of Claim 15, wherein calculating the direct current impedance comprises:

generating, by the thermal model of the transducer, a coil temperature associated with the transducer; and

calculating the direct current impedance based on the coil temperature.

17. The system of Claim 15, wherein calculating the direct current impedance comprises calculating the direct current impedance directly from the

electrical power, without an intermediate calculation of a coil temperature associated with the transducer.

18. The system of Claim 15, further wherein the thermal model is configured to mix the direct current impedance with an estimated impedance value derived from an electrical model of the direct current impedance.

19. The system of Claim 15, further wherein the control system is further configured to control a load power delivered to the transducer based on at least one of the coil temperature and another temperature generated by the thermal model.

20. The system of Claim 19, wherein controlling the load power comprises determining a gain to be applied to a driving signal for driving the transducer based on at least one of the coil temperature and another temperature generated by the thermal model.

21. The system of Claim 19, wherein controlling the load power comprises clipping to a driving signal for driving the transducer.

22. The system of Claim 15, wherein the thermal model is implemented with a Kalman filter.

23. The system of Claim 15, wherein the thermal model is implemented with an infinite impulse response filter.

24. The system of Claim 15, wherein the transducer is a haptic transducer.

25. The system of Claim 15, wherein the transducer is an audio speaker.

26. The system of Claim 15, further comprising:

a driver configured to drive the transducer with a driving signal;

wherein the thermal model is further configured to:

estimate an electrically-measured direct current impedance based on an electrical model of the transducer;

estimate an electrically-measured coil temperature based on the electrically-measured direct current impedance; and

set one or more state variables of the thermal model based on the electrically-measured coil temperature.

27. The system of Claim 26, wherein the control system is further configured to, in the absence of the driving signal including a haptic event, cause the driver to drive a pilot tone to the transducer at regular intervals to set an ambient temperature as one of the one or more state variables.

28. The system of Claim 26, wherein the control system is further configured to:

halt updates to the one or more state variables between haptic events within the driving signal; and

prior to driving the transducer with the driving signal comprising a haptic event, update the one or more state variables based on a time elapsed since a previous haptic event.

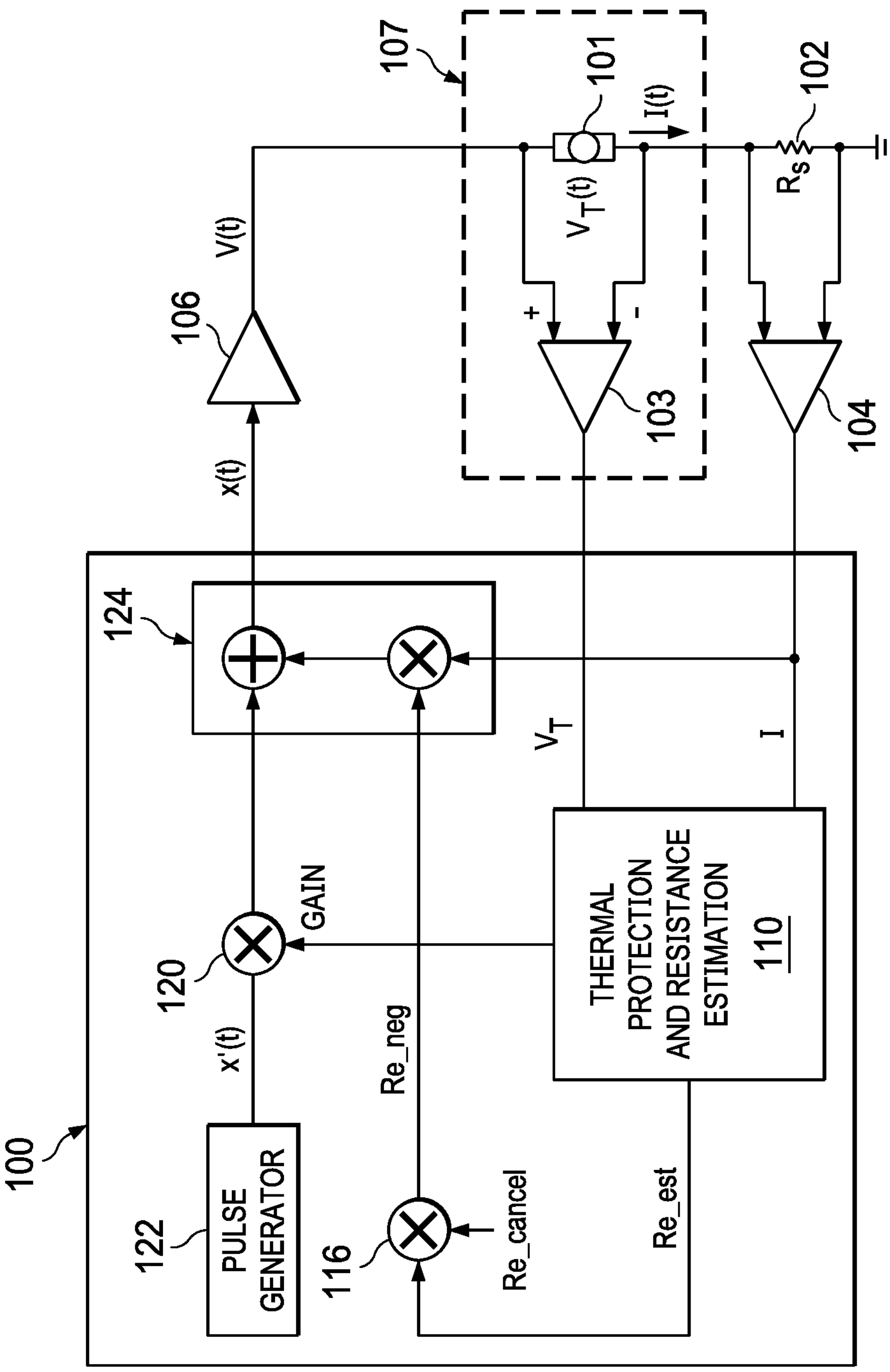
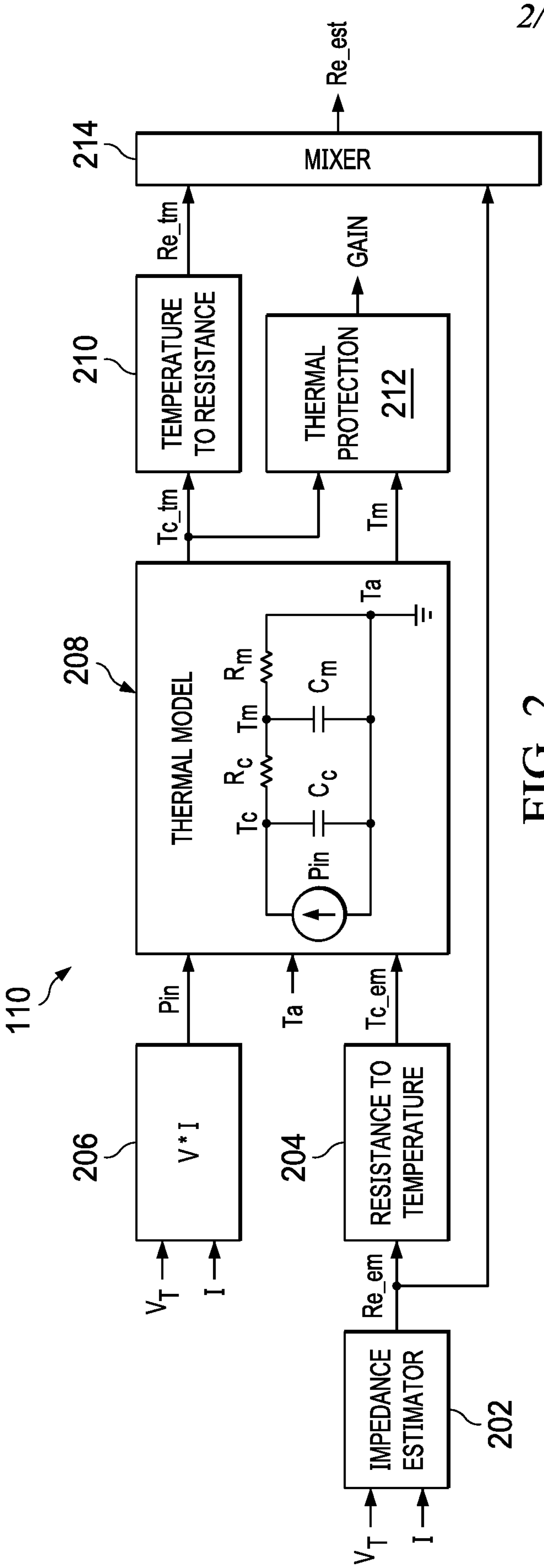
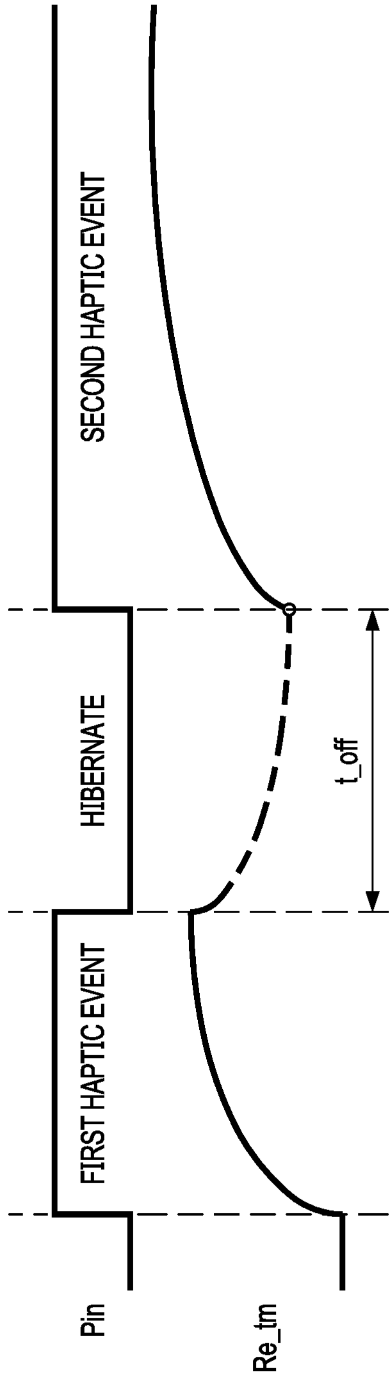

107
101
I(t)
102
V(t)
$V_T(t)$
R_S
106
+
-
103
104
x(t)
124
V_T
I
THERMAL PROTECTION AND RESISTANCE ESTIMATION
110
GAIN
120
x'(t)
Re_neg
100
122
PULSE GENERATOR
116
Re_cancel
Re_est

FIG. 1



110
V_T
I
206
V*I
Pin
202
IMPEDANCE ESTIMATOR
Re_em
204
RESISTANCE TO TEMPERATURE
Tc_em
Ta
208
THERMAL MODEL
Pin
Tc
Cc
Rc
Tm
Cm
Rm
Ta
Tc_tm
Tm
210
TEMPERATURE TO RESISTANCE
Re_tm
THERMAL PROTECTION
212
GAIN
214
MIXER
Re_est

FIG. 2



Pin
Re_tm
FIRST HAPTIC EVENT
HIBERNATE
SECOND HAPTIC EVENT
t_off

FIG. 3

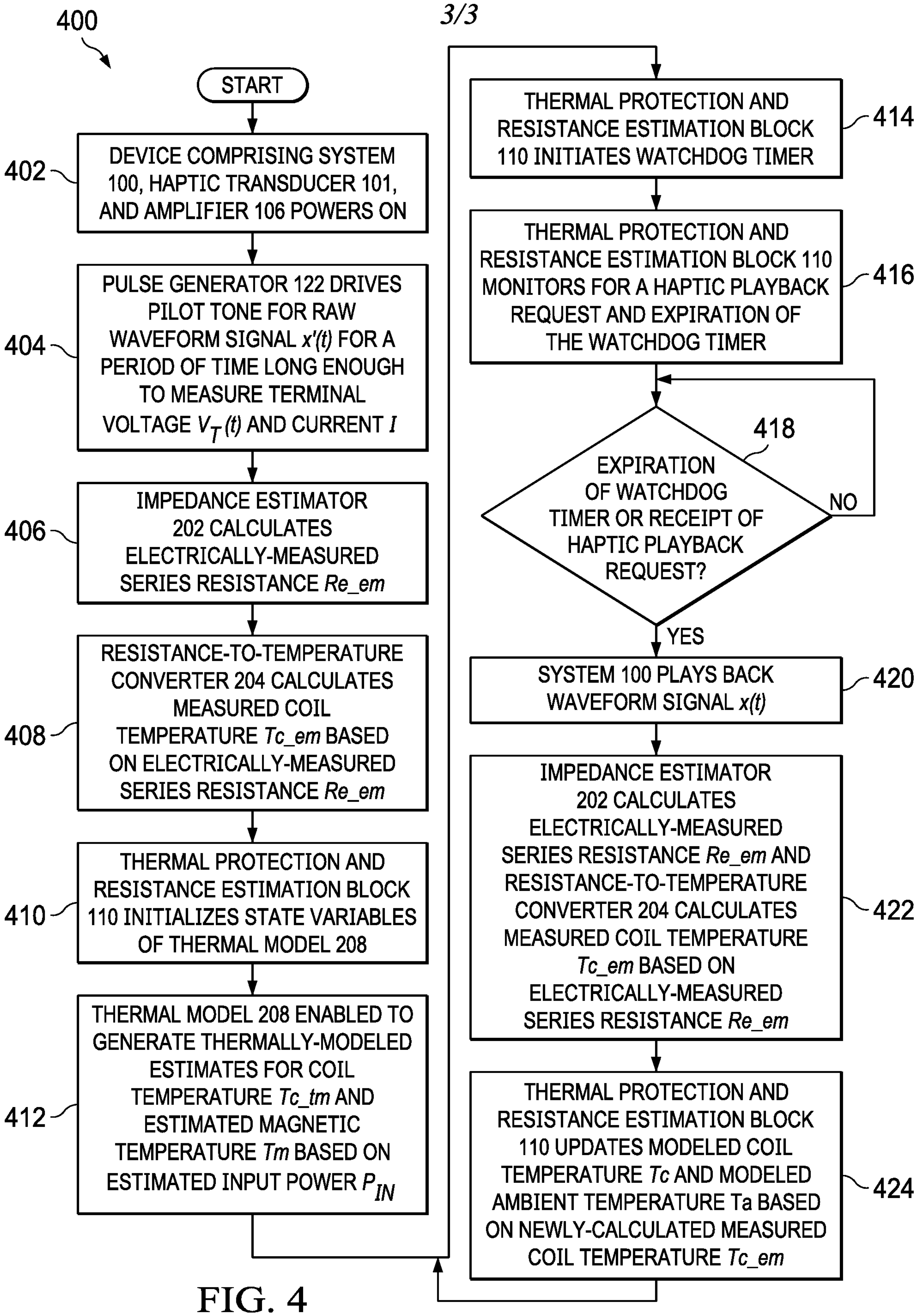

400
START
402
DEVICE COMPRISING SYSTEM 100, HAPTIC TRANSDUCER 101, AND AMPLIFIER 106 POWERS ON
404
PULSE GENERATOR 122 DRIVES PILOT TONE FOR RAW WAVEFORM SIGNAL x'(t) FOR A PERIOD OF TIME LONG ENOUGH TO MEASURE TERMINAL VOLTAGE V_T(t) AND CURRENT I
406
IMPEDANCE ESTIMATOR 202 CALCULATES ELECTRICALLY-MEASURED SERIES RESISTANCE Re_em
408
RESISTANCE-TO-TEMPERATURE CONVERTER 204 CALCULATES MEASURED COIL TEMPERATURE Tc_em BASED ON ELECTRICALLY-MEASURED SERIES RESISTANCE Re_em
410
THERMAL PROTECTION AND RESISTANCE ESTIMATION BLOCK 110 INITIALIZES STATE VARIABLES OF THERMAL MODEL 208
412
THERMAL MODEL 208 ENABLED TO GENERATE THERMALLY-MODELED ESTIMATES FOR COIL TEMPERATURE Tc_tm AND ESTIMATED MAGNETIC TEMPERATURE Tm BASED ON ESTIMATED INPUT POWER P_IN
414
THERMAL PROTECTION AND RESISTANCE ESTIMATION BLOCK 110 INITIATES WATCHDOG TIMER
416
THERMAL PROTECTION AND RESISTANCE ESTIMATION BLOCK 110 MONITORS FOR A HAPTIC PLAYBACK REQUEST AND EXPIRATION OF THE WATCHDOG TIMER
418
EXPIRATION OF WATCHDOG TIMER OR RECEIPT OF HAPTIC PLAYBACK REQUEST?
NO
YES
420
SYSTEM 100 PLAYS BACK WAVEFORM SIGNAL x(t)
422
IMPEDANCE ESTIMATOR 202 CALCULATES ELECTRICALLY-MEASURED SERIES RESISTANCE Re_em AND RESISTANCE-TO-TEMPERATURE CONVERTER 204 CALCULATES MEASURED COIL TEMPERATURE Tc_em BASED ON ELECTRICALLY-MEASURED SERIES RESISTANCE Re_em
424
THERMAL PROTECTION AND RESISTANCE ESTIMATION BLOCK 110 UPDATES MODELED COIL TEMPERATURE Tc AND MODELED AMBIENT TEMPERATURE Ta BASED ON NEWLY-CALCULATED MEASURED COIL TEMPERATURE Tc_em

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2020/027971

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04R3/00 H04R29/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	KLIPPEL ET AL: "Nonlinear Modeling of the Heat Transfer in Loudspeakers", JAES, AES, 60 EAST 42ND STREET, ROOM 2520 NEW YORK 10165-2520, USA, vol. 52, no. 1/2, 1 February 2004 (2004-02-01), pages 3-25, XP040507072,	1-3,5,9, 11, 15-17, 19,23,25
Y	title, sections 0, 2, 4.1, 7 figures 1, 2, 17, 18, 19 -----	8,22
X	WO 02/21879 A2 (HARMAN INT IND [US]; BUTTON DOUGLAS J [US]; WILLIAMS PAUL ROBERT [GB]) 14 March 2002 (2002-03-14) paragraphs [0024] - [0046]; figures 1, 2 -----	1,2,5,9, 11,15, 16,19, 23,25
	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 June 2020	04/09/2020

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Lörch, Dominik

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 2 806 656 A1 (ST ERICSSON SA [CH]) 26 November 2014 (2014-11-26) paragraphs [0054], [0055] -----	8,22
A	US 2019/110145 A1 (LAWRENCE JASON WILLIAM [US] ET AL) 11 April 2019 (2019-04-11) paragraphs [0002], [0010], [0030], [0041], [0042], [0056] -----	8,22

1

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2020/027971

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-3, 5, 8, 9, 11, 15-17, 19, 22, 23, 25

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-3, 5, 8, 9, 11, 15-17, 19, 22, 23, 25

   determination of direct current impedance from input power and thermal model without intermediate step of determining voice coil temperature
   thermal model is based on infinite impulse response (IIR) filter
   thermal model is based on Kalman filter
   controlling load power based on coil temperature and another temperature generated by the thermal model

1.1. claims: 8, 22

   thermal model is based on Kalman filter

1.2. claims: 9, 23

   thermal model is based on infinite impulse response (IIR) filter

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2. claims: 4, 18

   mixing estimates of direct current resistance obtained from thermal model and from electrical model

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3. claims: 6, 7, 20, 21

   Controlling the load power comprises determining a gain to be applied to a driving signal for driving the transducer

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4. claims: 10, 24

   transducer is a haptic transducer

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5. claims: 12-14, 26-28

   estimation of voice coil temperature from electrical model and setting state variables of thermal model based on voice coil temperature

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2020/027971

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 0221879 A2	14-03-2002	AU 8713201 A	22-03-2002
		US 2002118841 A1	29-08-2002
		WO 0221879 A2	14-03-2002
EP 2806656 A1	26-11-2014	NONE	
US 2019110145 A1	11-04-2019	NONE	