Texas Instruments

Application Report
SLAA857–August 2018

SmartPA Speaker Protection Algorithm

Susan Xue, Supriyo Palit, Peter Wei, Andrew Du *China HUAWEI Sales Team*

ABSTRACT

SmartPA has seen increased usage in personal electronic in recent years. SmartPA is used often in smart phones to make full use of the relatively smaller speaker and get better sound quality with maximum volume.

SmartPA system consists of

- Power amplifier with current and voltage sensing:
- SmartPA speaker protection algorithm which protects the speaker from excursion and temperature damage (This is based on the mechanical and electrical characteristics of the speaker)

This article discusses the speaker modeling and protection based on the TI SmartPA algorithm.

Contents

List of Figures

List of Tables

Trademarks

All trademarks are the property of their respective owners.

1 Speaker Basics

1.1 Speaker Structure

In a speaker, similar to motor driver, current flows through windings and magnetic field is created. Windings (voice coil) move in magnetic field because of the magnetic force. The cone membrane (all the moving parts including diaphragm, frame, suspension, and so forth) is attached firmly to the windings and will move the same way, leading to sound. This is the basic principle of a speaker. It is a type of electroacoustic transducer.

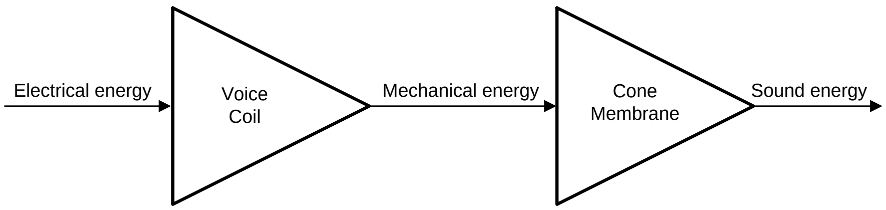

Figure 1. Energy Transfer in Speaker

$$F = BIl \tag{1}$$

$$V_{BEMF} = Blv \tag{2}$$

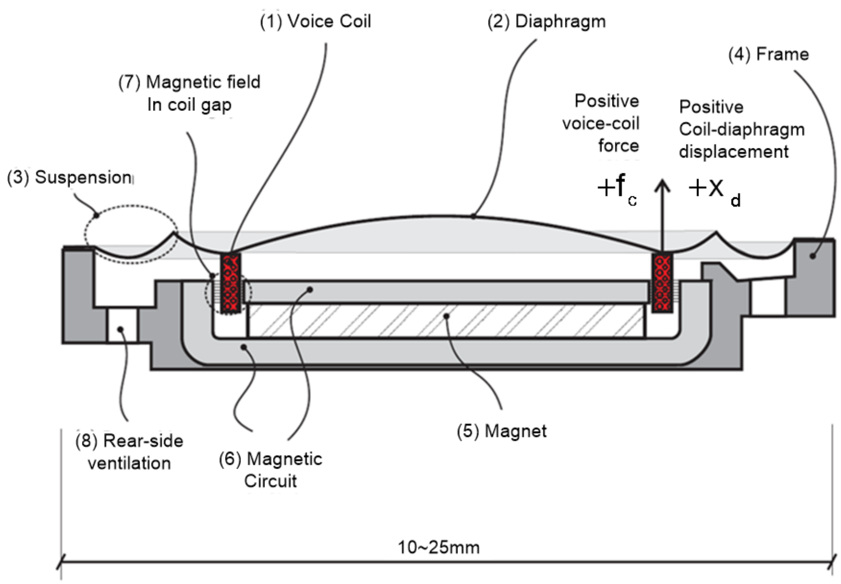

Figure 2. Typical Speaker Structure

1.2 Classical Electro-Motive Model

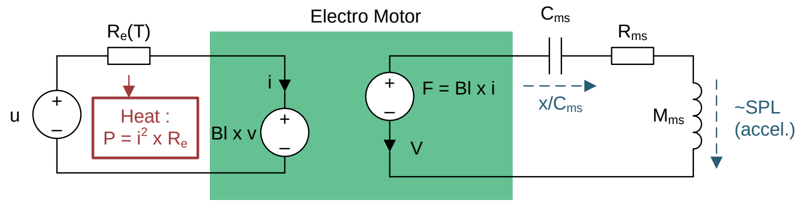

Figure 3. Electro-Motive Model of Speaker

Table 1. Main Parameters in Speaker Electro-Motive Model

Electro-Motive Parameter	Description	Unit
R_{ms}	Mechanical damping factor	N × s/m
M_{ms}	Mechanical mass	g
C_{ms}	Mechanical compliance	mm / N
Bl	Force factor	T × m
R_E	DC resistance of the speaker	Ω
u	Amplifier voltage	V
i	Voice coil current	A
v	Velocity of membrane	m/s
F	Mechanical force in magnetic field	N
X	Membrane excursion	m

Table 1 describes how the speaker converts electrical energy to mechanical energy. Speakers act as a type of transformer. The difference from regular electro-magnetic transformer is that the secondary side is mechanical dimension instead of electrical dimension. The primary side of the system can be taken as an electrical circuit, where excitation signal u is audio input. In this closed circuit, part of voltage drop is across the DC resistance, while the other part of voltage drop results from back electromotive force (induced from windings cutting the magnetic field, for example, BackEMF).

$$V_{BEMF} = Blv = u - 1 \times R_e(T) \tag{3}$$

Similar to a transformer, the power delivered to secondary is:

$$P_1 = V_{BEMF} \times i = Blv \times i \tag{4}$$

Corresponding impedance is:

$$R_1 = \frac{Blv}{i} \tag{5}$$

The secondary side is a mechanical system. The power is proportional to ampere force and velocity of membrane.

$$P_2 = F \times v = Bli \times v = P_1 \tag{6}$$

Take v as voltage and F as current, the equivalent mechanical resistance is:

$$R_2 = \frac{v}{F} = \frac{v}{Bl \times i} \tag{7}$$

The equivalent turns ratio is:

$$TR = \frac{Bl \times v}{v} = Bl \tag{8}$$

According to principle of transformer, ratio of R1 and R2 is:

$$\frac{R1}{R2} = TR^2 = (Bl)^2 \tag{9}$$

For a transformer, turns ratio is the most important parameter. It describes how the voltage and power is transferred from one side to the other side. Get back to the speaker "transformer system", the "turns ratio" Bl is the most important parameter to determine the sensitivity from electrical system to mechanical system. In other words, Bl decides how fast Mms will be moving. So obtaining Bl is a critical step for the characterization of a speaker.

Now let's try to focus on the mechanical system alone. Take the moving part (voice coil and membrane) as an object, and the mass of this moving part is Mms.

Three kinds of forces are imposed on Mms:

1. Elastic force F_C (measured by compliance Cms, the higher Cms, the smaller elastic force)
2. Viscous resistance force F_R measured by Rms (a higher Rms indicates larger resistance and damping)
3. Outside force from ampere force F (Bl × i according to electro-magnetic principle)

$$F_C = \frac{x}{C_{ms}} \tag{10}$$

$$F_R = R_{ms} v \tag{11}$$

$$F = Bl \times i \tag{12}$$

According to Newton's Second Law,

$$\begin{aligned} M_{ms} a &= F - F_C - F_R \\ &= Bl \times i - \frac{x}{C_{ms}} - R_{ms} v \end{aligned} \tag{13}$$

2 Speaker Impedance and Excursion Model

For certain input level and frequency, impedance and excursion (excursion doesn't mean absolute excursion, it describes transfer function from input voltage to excursion, with a unit of mm/V) of speaker are dependent on first five parameters in Table 1. See Equation 14 and Equation 15 for details.

$$Z_{BMEF}(s) = \frac{(Bl)^2}{sM_{ms} + R_{ms} + \frac{1}{sC_{ms}}} = \frac{\frac{(Bl)^2}{M_{ms}} s}{s^2 + s\frac{R_{ms}}{M_{ms}} + \frac{1}{M_{ms}C_{ms}}} \tag{14}$$

$$Z_{exc}(s) = \frac{Bl}{sR_E} \frac{1}{\left(sM_{ms} + \left(R_{ms} + \frac{(Bl)^2}{R_E}\right) + \frac{1}{sC}\right)} = \frac{Bl}{M_{ms}R_E} \frac{1}{\left(s^2 + s\frac{Rms + \frac{(Bl)^2}{R_E}}{M_{ms}} + \frac{1}{M_{ms}C_{ms}}\right)} \tag{15}$$

Above the electrical and mechanical parameters are basic physical parameters in a speaker. However, they are not easy to measure once speaker is manufactured. Also, they still can't describe clearly enough to help us to understand how the system works. T/S parameters are introduced to better describe the resonance system as a whole.

Take speaker as an oscillation system and equations above can be rewritten as below:

$$Z_{BMEF}(s)=\frac{(Bl)^2}{M_{ms}}\frac{s}{\left(s^2+s\frac{\omega_s}{Q_{ms}}+\omega_s^2\right)} \quad (16)$$

$$Z_{exc}(s)=\frac{Bl}{M_{ms}R_E}\frac{s}{\left(s^2+s\frac{\omega_s}{Q_{ms}}+\omega_s^2\right)} \quad (17)$$

This system oscillates at certain frequency, resonance frequency

$$f_s=\frac{\omega_s}{2\pi}=\frac{1}{2\pi\sqrt{M_{ms}C_{ms}}} \quad (18)$$

Impedance transfer function is also limited by mechanical quality factor:

$$Q_{ms}=\frac{1}{R_{ms}}\sqrt{\frac{M_{ms}}{C_{ms}}} \quad (19)$$

Equation 19 shows how each element in mechanical system has effect on the mechanical quality factor. Higher Qms causes the bandwidth to narrow, which causes the system to oscillates with less damping. The lower Qms leads to an opposite effect.

While impedance is influenced mainly by mechanical part, excursion value is measured by both electrical and mechanical system. Total quality factor Qts is introduced here.

$$Q_{ts}=\frac{1}{R_{ms}+\frac{(Bl)^2}{R_E}}\sqrt{\frac{M_{ms}}{C_{ms}}} \quad (20)$$

Qts reveals quality factor of the combination of electrical and mechanical system. Since they are in series, and electrical quality factor is introduced as Qes,

$$Q_{ts}=\frac{Q_{es}Q_{ms}}{Q_{es}+Q_{ms}} \quad (21)$$

We have Qes as below:

$$Q_{es}=\frac{R_E}{(Bl)^2}\sqrt{\frac{M_{ms}}{C_{ms}}} \quad (22)$$

Table 2. Thiele/Small (TS) Parameter

Driver model parameter (Thiele/Small)	Description	Unit
f_s	Resonance frequency of electro-motive system	Hz
Q_{ts}	Total quality factor	/
Q_{ms}	Quality factor of mechanical system	/
Q_{es}	Quality factor of electrical system	/

3 Speaker Model Measurement

Based on speaker model specified above, we use the characterization tool in PPC3 (PurePath Console 3) to measure each parameter. (Details about PPC3 is available in Smart Amp Quick Start Guide provided in the Reference section.)

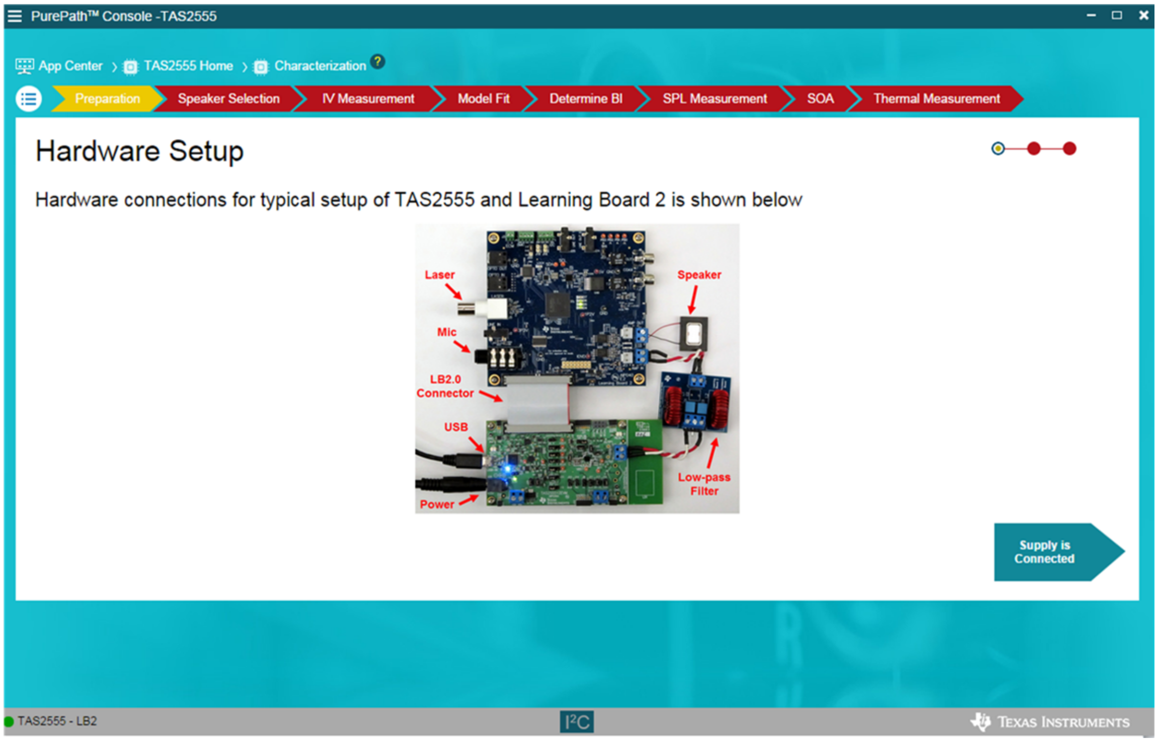

Figure 4. Speaker Characterization by PPC3 and Learning Board 2

First, Sweep speaker with a certain range of frequencies (usually 3KHz). Get the impedance curve. Fitting the impedance curve into model as shown in Equation 16:

$$Z(s) = R_E + Z_{BEMF}(s) = a + k\frac{s}{s_2 + b \times s + c} \tag{23}$$

As the DC resistance, RE can be obtained directly:

$$R_E = a \tag{24}$$

According to the relation between T/S and physical parameters,

$$\frac{(Bl)^2}{M_{ms}} = k \tag{25}$$

$$\omega_s = \frac{1}{\sqrt{M_{ms}C_{ms}}} = \sqrt{c} \tag{26}$$

$$\frac{\omega_s}{Q_{ms}} = \frac{R_{ms}}{M_{ms}} = b \tag{27}$$

There are three formulas, but 4 parameters Mms, Cms, Rms and Bl are unknown. Bl should be input before all the other 3 parameters are derived. It can be either from speaker vendor or from laser measurement. Once Bl is known, Mms, Cms and Rms can be derived from Equation 25, Equation 26, and Equation 27.

$$M_{ms} = \frac{(Bl)^2}{k} \tag{28}$$

$$C_{ms} = \frac{1}{c \times M_{ms}} = \frac{k}{c \times (Bl)^2} \tag{29}$$

$$R_{ms} = b \times R_{ms} = b \times \frac{(Bl)^2}{k} \tag{30}$$

Then according to Equation 17, excursion curve can be fit based on the five physical parameters of speaker.

For Iphone 7 speaker, below in Table 3 is the characterization result of different physical parameters:

Table 3. Main Physical Parameters of Iphone 7 Speaker

Driver model parameter (physical)	Description	Unit	Value
R_{ms}	Mechanical damping factor	N × s/m	0.305
M_{ms}	Mechanical mass	g	0.116
C_{ms}	Mechanical compliance	mm / N	0.21
Bl	Force factor	T × m	0.841
R_E	DC resistance of the speaker	Ω	7.35

And according to Equation 14 and Equation 15, impedance and excursion simulated with matlab. Figures as below Figure 5:

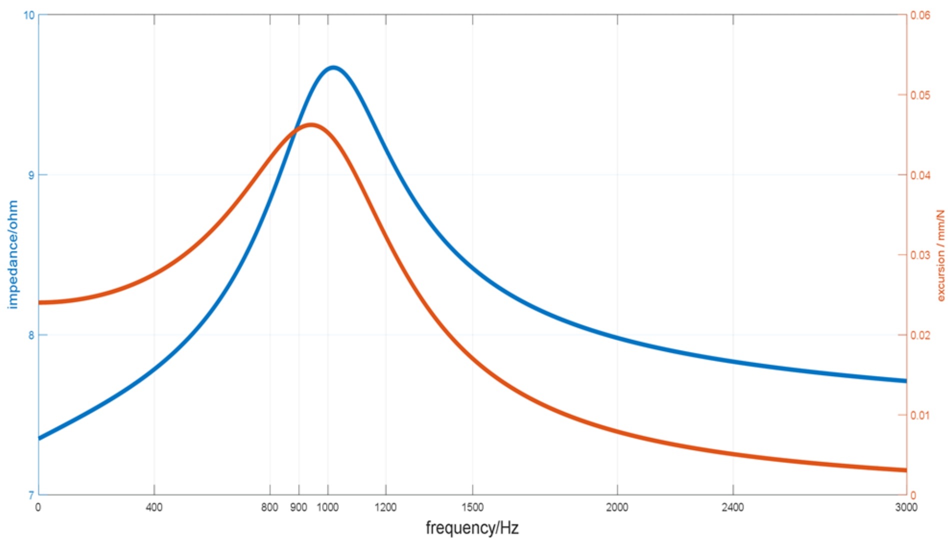

Figure 5. Impedance and Excursion Simulation Result with Matlab Based on Speaker Model

TS parameters can be derived based on the five physical parameters:

$$f_s = \frac{1}{2\pi\sqrt{M_{ms}C_{ms}}} = \frac{1}{2\pi\sqrt{0.116 \times 0.21 \times 10^{-6}}} = 1020\ \text{Hz} \tag{31}$$

$$Q_{ms} = \frac{1}{R_{ms}}\sqrt{\frac{M_{ms}}{C_{ms}}} = \frac{1}{0.305}\sqrt{\frac{0.116}{0.21}} = 2.43 \tag{32}$$

$$Q_{ts} = \frac{1}{0.305 + \frac{0.841^2}{7.35}}\sqrt{\frac{0.116}{0.21}} = 1.85 \tag{33}$$

$$Q_{ts} = \frac{Q_{ms}Q_{es}}{Q_{ms} + Q_{es}} \tag{34}$$

$$Q_{es} = \frac{Q_{ms}Q_{ts}}{Q_{ms} + Q_{ts}} = \frac{2.43 \times 1.85}{2.43 - 1.85} = 7.75 \tag{35}$$

The calculation of TS parameters and simulation curves of impedance and excursion match with characterization results well.

Figure 6. Impedance and Excursion Characterization Result with PPC3 and LB2

4 SmartPA Temperature and Excursion Protection Algorithm

A block diagram of the SmartPA algorithm is shown below:

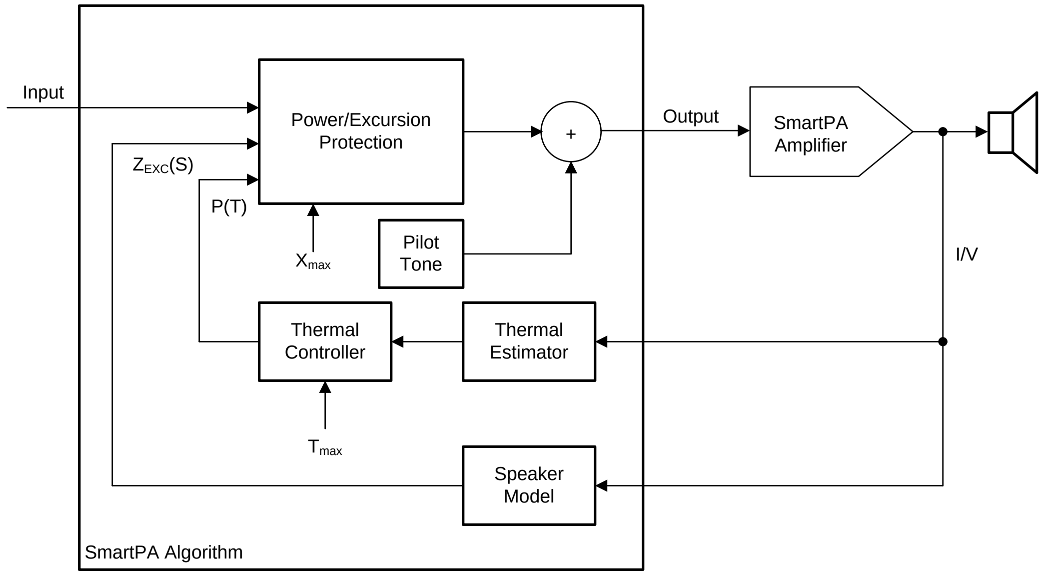

Figure 7. Smart amp Algorithm

The speaker temperature and the speaker model is derived from I/V sense. This is used to adaptively modify the input signal in the Power/Excursion protection block so that the output provided to the speaker is within the excursion and thermal limit of the speaker. The excursion and thermal protection algorithm is discussed in detail in the following sections.

4.1 Excursion Protection Algorithm

For excursion protection, excursion is first calculated from the input signal based on the speaker model. Then the excursion will be compared with the maximum excursion before deciding if protection kicks in. If the excursion exceeds limit Xmax, input will be attenuated otherwise the input signal will pass through unchanged. Since over excursion could possibly damage the system in a short time, a time delay is inserted in feedforward signal chain, to make sure excursion estimation and comparison are finished before signal is fed to protection.

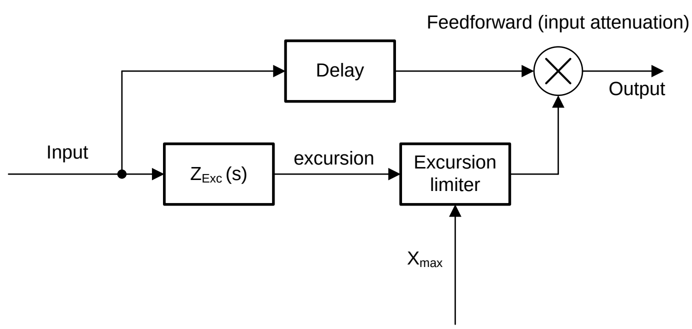

Figure 8. Excursion Protection System in Smart Amp Algorithm

Equation 15 is the excursion model when input voltage is 1 V. So total excursion Exc(s) should be,

$$Exc(s) = u(s) \times Z_{Exc}(s) \tag{36}$$

If switched to time domain by doing inverse Laplace transform on Z_{Exc}(s), final excursion is convolution of input signal and $L^{-1}(Z_{Exc}(s))$

$$\text{Exc}(t) = x(t) \times L^{-1}(Z_{\text{Exc}}(s)) \tag{37}$$

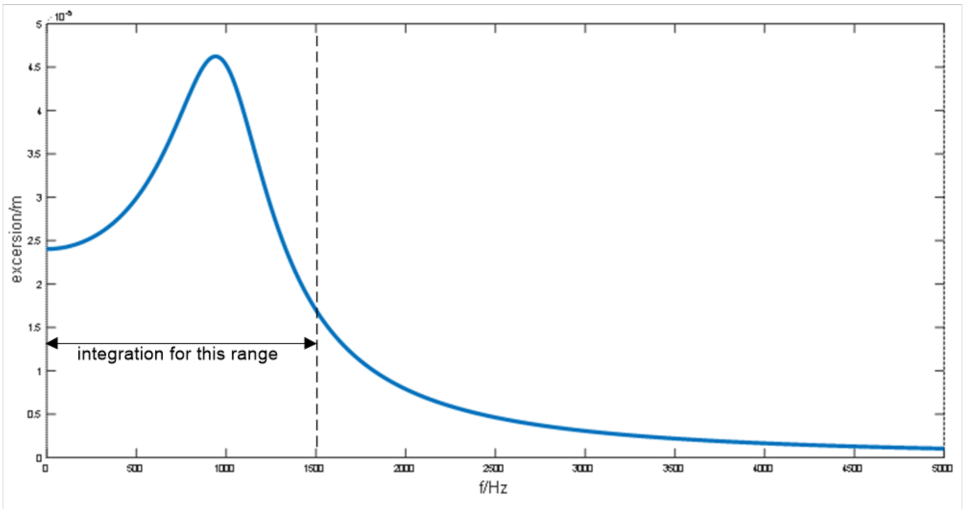

Figure 9. Excursion Approximation in Low Frequency Range

This is how excursion is calculated and protected.

As the speaker keeps working, speaker model can change, which will have effect on the estimation accuracy. So the speaker model should be updated dynamically to ensure proper protection. Figure 9 shows how speaker model is updated. This update is finished in feedback module.

The speaker model update is mainly based on impedance model. If speaker output voltage and current is V(s) and I(s) for frequency domain, respectively, then:

$$I(s) = \frac{V_{\text{BEMF}}(s)}{Z_{\text{BEMF}}(s)} \tag{38}$$

$$V_{\text{BEMF}}(s) = V(s) - I(s)R_E \tag{39}$$

And $V_{BEMF}(s)$ is the backemf.

Equation 38 is converted into time domain by inverse Laplace transform as below,

$$V_{\text{BEMF}}(t) = I(t) \times L^{-1} Z_{\text{BEMF}}(s) \tag{40}$$

As is shown in Figure 9, an adaptive filter is used to update the speaker impedance model. Output voltage and current of the speaker are detected as V(t) and I(t), respectively using the sensing circuit of the SmartPA amplifier. Back-EMF is estimated as $V_{BEMF\_est}(t)$ based on original impedance model according to Equation 40, and $V_{BEMF\_est}(t)$ is compared to the actual backemf $V_{BEMF\_est}(t)$ (=V(t) — $I(t)R_E$) from detection and the error e(t) is obtained:

$$e(t) = V_{\text{BEMF\_est}}(t) - V_{\text{BEMF}}(t) \tag{41}$$

The speaker model parameters are modified dynamically till e(t) is small enough to be close to zero, which means the model is accurate enough to forecast the impedance and excursion.

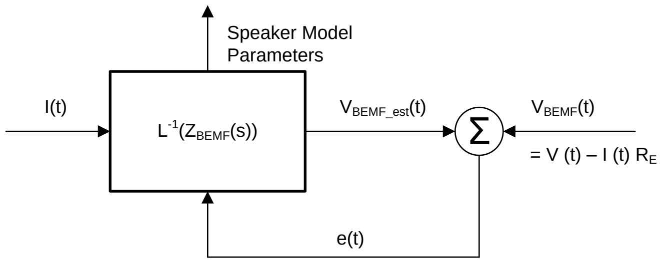

Figure 10. Speaker Model Update Algorithm

TS parameters are calculated using updated physical parameters. For actual backemf we need to measure R_E. At very low frequencies, the backemf is almost zero so Equation 39 becomes,

$$0 = V(s) - I(s)R_E \tag{42}$$

hence,

$$R_E = \frac{v(t)}{I(t)} \tag{43}$$

A pilot tone at low frequency (for example 60Hz.) is used to estimate R_E × R_E is also used for thermal protection which is discussed in the next section.

4.2 Thermal Protection Algorithm

Thermal protection algorithm is divided into three main parts. Thermal estimator, thermal controller and power protection. Temperature T is first estimated from I/V feedback using pilot tone based on the relation between DC resistance and temperature, as is shown in Equation 43 and Equation 44. Then T is compared with temperature limit Tmax to decide if it has exceeded the limit.

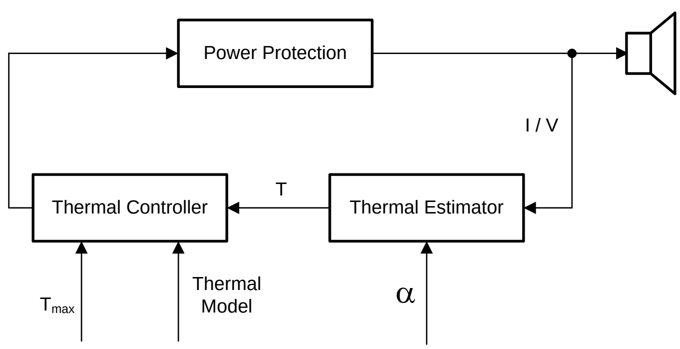

Figure 11. Thermal Protection in Smart Amp Algorithm

$$R(T) = R_e(T_A) + \alpha(T - T_A)R(T) \tag{44}$$

$$T = T_A + \frac{\frac{R - R_e(T_A)}{R}}{\alpha} \tag{45}$$

The second important part is thermal controller. It controls the power protection block based on temperature. This is done using a thermal model of the speaker. For the speaker, thermal model is shown in Figure 11. Voice coil and magnet pole are both included. Thermal resistance and thermal capacitance are introduced to model the transient temperature behavior and it can predict how temperature changes as time goes by under different input power.

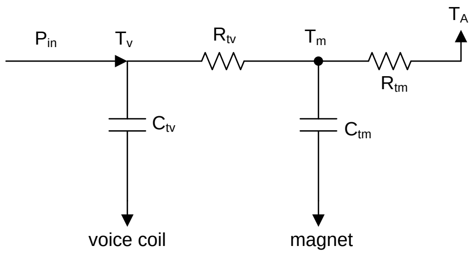

Figure 12. Typical Thermal Model of Speaker

Using Iphone 7 speaker as an example, thermal resistance and capacitance (shown in Table 4) can be calculated from the characterization result shown in below curve in Figure 12 by learning board 2.

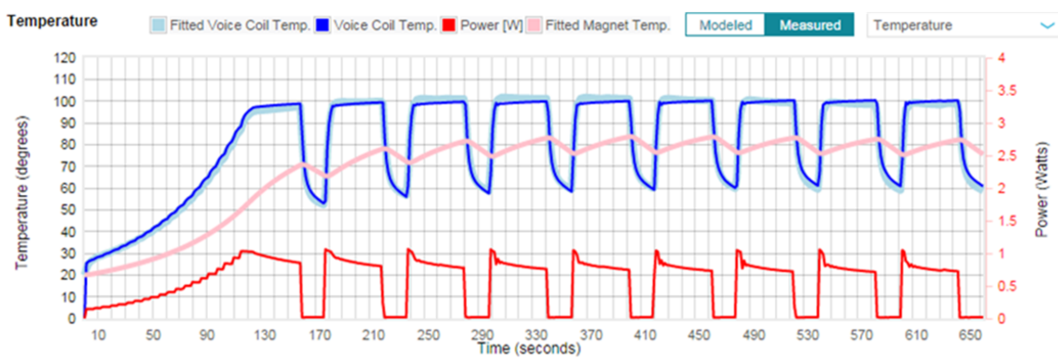

Figure 13. Thermal Characterization Method in PPc3 and Learning Board 2

Table 4. Main Thermal Parameters of Iphone 7 Speaker

Thermal parameter	Description	Unit	Value
Rtv	Thermal resistance of voice coil	K/W	76.9
Ctv	Thermal capacitance of voice coil	J/K	0.0549
Rtm	Thermal resistance of magnet pole	K/W	495
Ctm	Thermal capacitance of magnet pole	J/K	0.832

From Figure 11, Power flows to the voice coil and magnet system, each with a time constant, denoting the temperature rising speed respectively. This time constant can be calculated from thermal models shown in Table 4.

Time constant for voice coil is:

$$\tau_v = R_{tv} C_{tv} = 76.9 \times 0.0549 = 4.22\ \text{s} \quad (46)$$

Time constant for magnet part is:

$$\tau_m = R_{tm} C_{tm} = 495 \times 0.832 = 411.8\ \text{s} \quad (47)$$

This means, temperature of voice coil can rise much faster than the magnet as the power increases. Also for this case, temperature of voice coil is our main concern. Algorithm take s advantage of the time constant and decides how to allocate power properly to make system work nearly the thermal limit while ensure safety.

In power protection module, signals are attenuated according to the power output from the thermal controller. This keeps the voice coil temperature within the thermal limit.

5 References

- Thiele/Small Parameters
- Smart Amp Quick Start Guide
- W. Marshall Leach Jr, Introduction to electro-acoustics and audio amplifier design, published by Kendall Hunt

IMPORTANT NOTICE FOR TI DESIGN INFORMATION AND RESOURCES

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265