

Three-stage Nonlinear Thermal Model for Microspeakers in Mobile Phones

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Since microspeakers are widely used in mobile phones, high power is usually applied to obtain sufficient output sound pressure. However, the electric power is almost converted into heat, leading to the thermal problem in microspeakers. Compared with large loudspeaker, microspeakers are smaller and the under yoke is relatively closed, causing the heat transfer more complex. In this study, a three-stage nonlinear thermal model was proposed for analyzing the thermal behavior in microspeakers. The inside air is a buffer area between the voice coil and magnet, and modeled as a middle stage of the heat transfer. The forced convection is still significant in microspeakers while the eddy current can be ignored. In order to obtain the thermal parameters of the model, a corresponding parameter identification method was put forward. The basic linear parameters and forced convection parameters were all obtained by measuring and fitting the temperature curves of voice coil at different single tones. A series of experiments were conducted to verify the proposed model and parameter identification method, and the results showed good agreement between the measured and predicted temperature curves for different input signals. The proposed model was valid and accurate, and may be helpful for the design and application of microspeakers.

Keyword: Microspeakers, heat transfer, thermal model, mobile phones.

1 Introduction

In the last decade, microspeakers have become widely used in mobile phones¹⁻³. The space left for microspeakers is getting smaller, while the demand of electric power is getting higher to obtain enough output sound pressure. Many new technologies have been applied to drive microspeakers with as much power as possible, such as the smart amplifier and active heat control^{4, 5}. However, the conversion efficiency from the electric energy into the sound is very low, typically less than 0.5%. Almost all the power is converted into heat, which causes the temperature to rise in the voice coil and other microspeaker components. Sometimes, the power is so high that it may even burn out the microspeakers. Heat damage limits the maximum power of microspeakers. Therefore, research about the thermal behavior of microspeakers is important and necessary.

Actually, a great deal of research on the thermal processing of large loudspeakers has been carried out. Henricksen first proposed a linear thermal model and used the equivalent circuit method to analyze heat transfer in large loudspeakers⁶. Then, Zuccatti and Button put forward several two-stage linear models^{7, 8}. They divided the heat transfer into two parts: heat from the voice coil to the magnet system, and heat from the magnet system to the ambient air. Chapman proposed a three-stage linear model, which was more accurate in analyzing the magnet temperature⁹. However, the forced convection and eddy current, which are important to heat transfer in loudspeakers, are not constant and depend on input frequency and vibration of diaphragm. In order to include the influence of these two nonlinear factors, Klippel and Blasizzo proposed nonlinear models respectively^{10, 11}.

In this study, combining the heat transfer theory, a three-stage nonlinear thermal model was proposed for microspeakers. Microspeakers have a relatively closed under yoke, making the heat exchange with ambient air not fast enough. The inside air of microspeakers becomes a buffer area between the voice coil and magnet, resulting a middle stage. The heat

transfer path in microspeakers becomes into three parts: from the voice coil to the inside air, from the inside air to the magnet, and from the magnet to the ambient air. Therefore, a three-stage model was developed and the measurement of the magnet temperature indicated that the three-stage model is accurate and suitable. Besides, the forced convection is still significant in microspeakers though the eddy current can be ignored, leading to a nonlinear model. In order to obtain the linear and nonlinear parameters of the model, a corresponding thermal parameter identification method was put forward. By measuring and fitting the temperature curves at different single tones, all the thermal parameters were obtained. The temperature curves excited with other signals (dual-tone and broadband noise signals) can be predicted by the model and identified parameters, and were found to fit very well with the measured curves. The experimental measurements indicated that the proposed model was valid and accurate in analyzing the thermal behavior in microspeakers, which may help to improve the design and application of microspeakers in mobile phones.

2 Heat Transfer and Thermal Models

2.1 Heat Transfer and Thermal Analogous in Loudspeakers

When electric power is applied to loudspeakers, it will be converted into heat by the current in the voice coil, which then dissipates to the other components and ambient air, leading to a rise in temperature of the components. Combining the heat transfer theory, the thermal behavior in loudspeakers can be analyzed with the equivalent circuit⁶⁻¹¹.

The Joule heat is the power supply and can be analogous to a current source. There are generally two heat sources in loudspeakers: The Joule heat of voice coil, the Joule heat of eddy current in the top plate. Similarly, the temperature difference within the loudspeaker is analogous to the electric potential difference in a circuit.

And then, the heat is transferred to the components and ambient air in three ways: Conduction, radiation, and convection, which are all analogous to electrical resistance, called the thermal resistance. Generally, the radiation can be ignored, and the conduction and convection is the main ways of heat transfer in loudspeakers. Besides, there are two forms of heat convection: Natural convection and forced convection. The forced convection is quite important in cooling the voice coil in low frequency range. Meanwhile, the components store heat energy, and thus can be analogous to electrical capacitance, called the thermal capacitance. The thermal resistance R_T and capacitance C_T are the major elements in thermal equivalent circuit, and defined as:

$$R_T = \frac{\Delta T}{P_T} \quad (1)$$

$$C_T = \frac{\Delta Q}{\Delta T} \quad (2)$$

where ΔT is the temperature change, and P_T is the power of the Joule heat. ΔQ is the energy stored in the component.

Each heat transfer path and component is analogous to a corresponding electric element, as shown in Table 1.

Table 1. Thermal and electrical elements.

Elements	Thermal		Electrical	
	Elements	Unit	Elements	Unit
Potential	ΔT	K	ΔV	V
Current	P_T	W	I	A
Resistance	R_T	K/W	R_E	Ω
Capacity	C_T	J/K	C_E	F
Energy	Q	J	Q_E	C

2.2 Difference in Microspeakers

According to the thermal analogous, a variety of thermal models of large loudspeakers have been proposed. However, there are some differences in microspeakers although fundamental principle is similar with large loudspeakers. Figure 1 shows a sketch of a typical microspeaker. Compared with large loudspeakers, microspeakers have a different structure; the yoke is almost closed, and only a few back vents connect to the ambient air. Therefore, the heat cannot be transferred quickly to ambient air although it can still be transferred through the back vents. This structure results in a rapid rise in temperature of the inside air, and makes it a buffer area between the voice coil and the magnet system. The heat transfer path in microspeakers becomes into three parts: from the voice coil to the inside air, from the inside air to the magnet, and from the magnet to the ambient air. In addition, there is no top plate in microspeakers, so the eddy current can be ignored^{12, 13}, while the forced convection is still important in microspeakers. Therefore, there is only one nonlinear factor, the forced convection, leading to different parameters identification.

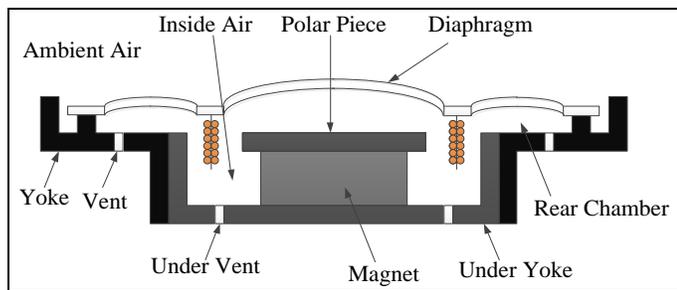


Figure 1. Sketch of a moving-coil microspeaker.

2.3 The Proposed Thermal Model

According to the structure and the heat transfer path of microspeakers, a three-stage nonlinear thermal model was developed, as shown in Figure 2. This model is suitable for microspeakers and can be applied to the frequency range of 20 Hz-20 kHz and driving voltage range below about 10 V.

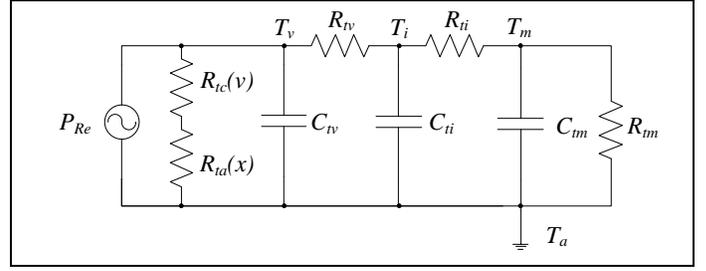


Figure 2. The three-stage nonlinear thermal model.

This model is a three-stage resistance and capacitance circuit (RC circuit): R_{tv} and C_{tv} represent the voice coil, and R_{tm} and C_{tm} represent the magnet system. The inside air is modeled with a resistance R_{ti} and a capacitance C_{ti} . These six basic linear parameters are constant. The resistance $R_{tc}(v)$ and $R_{ta}(x)$ describe the heat transfer caused by the forced convection in low frequency range, which depends on the displacement and velocity of the voice coil. Since the eddy current is neglected, there is only one heat source: the Joule heat of voice coil P_{Re} .

The Joule heat of voice coil is expressed as:

$$P_{Re} = i^2 R_{eT_v} \quad (3)$$

The voice coil DC resistance R_{eT_v} depends on the voice coil temperature T_v .

$$R_{eT_v} = R_{eT_a} (1 + \delta \Delta T_v) \quad (4)$$

where δ is the thermal conductivity coefficient, 0.00393 for copper, and R_{eT_a} is the DC resistance at ambient temperature T_a . $\Delta T_v = T_v - T_a$ is the temperature change in the voice coil. This relationship between the DC resistance and voice coil temperature can be used to obtain the voice coil temperature by measuring the change of DC resistance^{14, 15}.

According to Klippel, the resistance $R_{tc}(v)$ is related to the diaphragm velocity, v_{rms} . The resistance $R_{ta}(x)$ is related to the diaphragm displacement, x_{rms} . These are given respectively as:

$$R_{tc}(v) = \frac{1}{r_v v_{rms}(f)} \quad (5)$$

$$R_{ta}(x) = \frac{1}{r_x x_{rms}(f)}$$

This is a hypothesis to model the forced convection.¹⁰ r_v is the velocity coefficient. r_x is the displacement coefficient.

In order to obtain the linear and nonlinear thermal parameters, a corresponding parameter identification method is put forward.

3 Thermal Parameters Identification and Experiments

3.1 Temperature Curve of the Voice Coil

Temperature curve of voice coil is important in obtaining the thermal parameters. When a constant power applies to microspeakers, each component will eventually achieve a steady-state temperature decided by thermal parameters. The steady-state temperature increments of the voice coil, inside air, and magnet are calculated according to the thermal model.

$$\begin{aligned} \Delta T_{vss} &= \frac{(R_{tc} + R_{ta})(R_{tv} + R_{ti} + R_{tm})}{R_{tc} + R_{ta} + R_{tv} + R_{ti} + R_{tm}} P_{Re} \\ \Delta T_{iss} &= \frac{(R_{tc} + R_{ta})(R_{ti} + R_{tm})}{R_{tc} + R_{ta} + R_{tv} + R_{ti} + R_{tm}} P_{Re} \\ \Delta T_{mss} &= \frac{(R_{tc} + R_{ta})R_{tm}}{R_{tc} + R_{ta} + R_{tv} + R_{ti} + R_{tm}} P_{Re} \end{aligned} \quad (6)$$

where ΔT_{vss} is the steady-state temperature increment of the voice coil, ΔT_{iss} is the steady-state temperature increment of the inside air, and ΔT_{mss} is the steady-state temperature increment of the magnet system.

According to the model, if the time constants satisfy $\tau_v \ll \tau_i \ll \tau_m$, the real-time voice coil temperature increment can be expressed as:

$$\Delta T_v = \Delta T_{vss} - T_1 \exp\left(-\frac{t}{\tau_v}\right) - T_2 \exp\left(-\frac{t}{\tau_i}\right) - T_3 \exp\left(-\frac{t}{\tau_m}\right) \quad (7)$$

where:

$$T_1 = \Delta T_{vss} - \Delta T_{iss}$$

$$T_2 = \Delta T_{iss} - \Delta T_{mss} \quad (8)$$

$$T_3 = \Delta T_{mss}$$

$$\tau_v = R_{tv} C_{tv}$$

$$\tau_i = R_{ti} C_{ti} \quad (9)$$

$$\tau_m = R_{tm} C_{tm}$$

where τ_v is the time constant of the voice coil, τ_i is the time constant of the inside air, and τ_m is the time constant of the magnet. By measuring and fitting the real-time voice coil temperature curve, the parameters in the expression can be obtained and used to calculate the thermal parameters.

3.2 Thermal Parameters Identification Method

First of all, the six basic linear parameters should be acquired. In the high frequency range, the forced convection can be ignored due to the small displacement and velocity of the diaphragm. The eddy current can also be ignored in microspeakers. Therefore, the temperature curves in high frequencies are only determined by the basic linear parameters. The parameters T_1 , T_2 , T_3 , τ_v , τ_i , and τ_m in the Equation (7) can be obtained directly by fitting the temperature curves in high frequencies⁶⁻¹¹. The linear thermal resistances and capacitances are then calculated:

$$R_{tv} = \frac{T_1}{P_{Re}}, C_{tv} = \frac{\tau_v}{R_{tv}}$$

$$R_{ti} = \frac{T_2}{P_{Re}}, C_{ti} = \frac{\tau_i}{R_{ti}} \quad (10)$$

$$R_{tm} = \frac{T_3}{P_{Re}}, C_{tm} = \frac{\tau_m}{R_{tm}}$$

Then, the temperature curves at various frequencies scattered over the low frequency range are measured to obtain the forced convection parameters. The forced convection resistance was calculated using Equation (11) according to the steady-state voice-coil temperature $\Delta T_{vss}(f)$ at low frequencies.

$$R_{tc}(v) + R_{ta}(x) = \frac{1}{\frac{P_{Re}(f)}{\Delta T_{vss}(f)} - \frac{1}{R_{tv} + R_{ti} + R_{tm}}} \quad (11)$$

$$\frac{1}{r_v 2\pi f} + \frac{1}{r_x} = \frac{x_{rms}(f)}{\frac{P_{Re}(f)}{\Delta T_{vss}(f)} - \frac{1}{R_{tv} + R_{ti} + R_{tm}}}$$

With the measured displacement curve and Equations (5) and (11), the coefficients r_v and r_x were fitted. The theoretical values of forced convection resistance at other frequencies can be predicted.

3.3 Experiments

The microspeakers used in this study were the microspeakers TYPE 1511, which are usually used in mobile phones. The experimental equipment was the Klippel Distortion Analyzer system. The LPM module measured the basic parameters of the microspeaker, showed in the Table 2. The temperature curves of the voice coil were measured by the PWT module. Meanwhile, the Joule heat of the voice coil P_{Re} was also measured. The magnet temperature was measured by a thermocouple, shown in Figure 3.

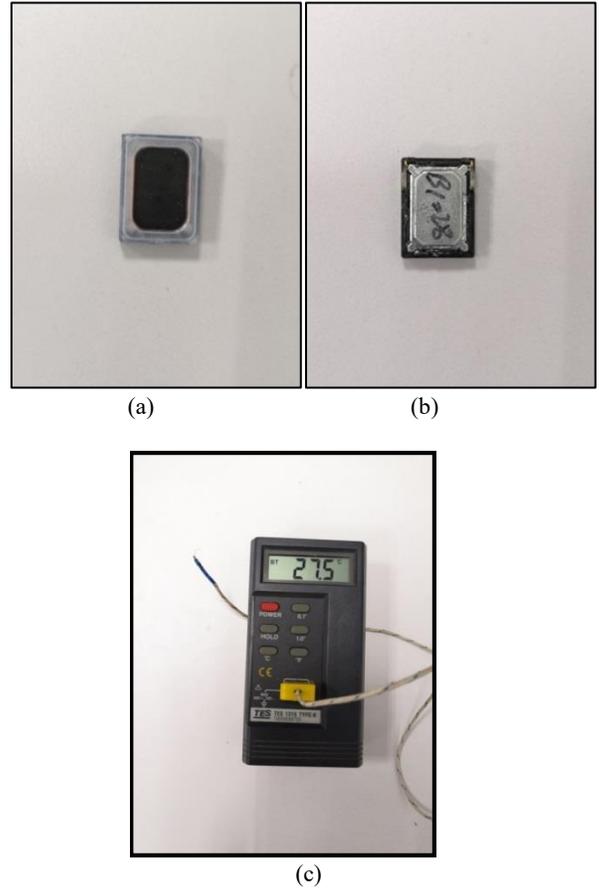


Figure 3. Microspeaker and thermocouple used in this study: (a) The front side of the microspeaker; (b) The back side of the microspeaker; (c) The thermocouple.

Table 2. Basic parameters of the microspeaker.

Parameters	Value	Unit
Size	15×11×3.5	mm
R_{eT_a}	7	Ω
f_s	550	Hz
Frequency range	100-20000	Hz
Rated noise voltage	2.3	V

Since the resonance frequency of the microspeaker is about 550 Hz, the frequency chosen for the linear parameters identification was 5 kHz. The input voltage V_{unit} was set to 1.5 V_{rms} to ensure enough temperature increment, but not to damage the microspeaker. The measured and fitted temperature curves were shown in Figure 4. All the basic linear parameters were then obtained.

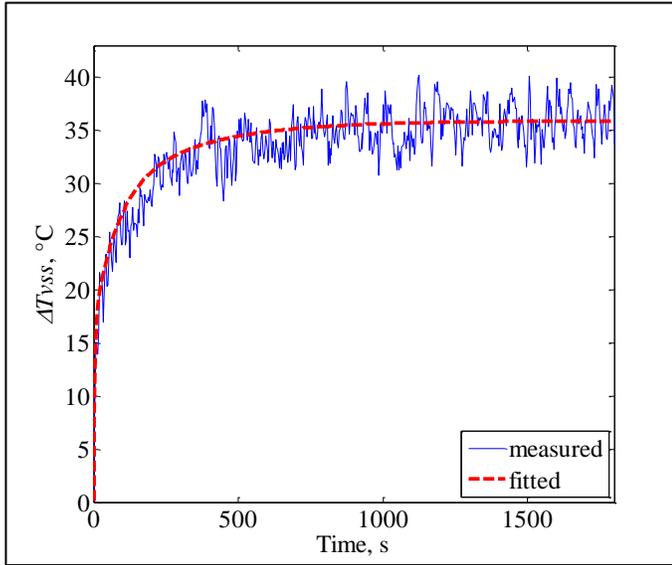


Figure 4. Measured and fitted temperature curves of the voice coil at 5 kHz.

Then, the other frequencies chosen to obtain the forced convection were 100 Hz, 200 Hz, 400 Hz, 600 Hz, 800 Hz and 1000 Hz. The steady-state temperatures of the voice coil in these frequencies were used to calculate the forced convection resistance according to Equations (5) and (11). Meanwhile, the coefficients r_v and r_x were fitted. Figure 5 is the steady-state temperature increments of the voice coil in these frequencies. Figure 6 is the displacement of the microspeaker excited at voltage $1.5 V_{rms}$.

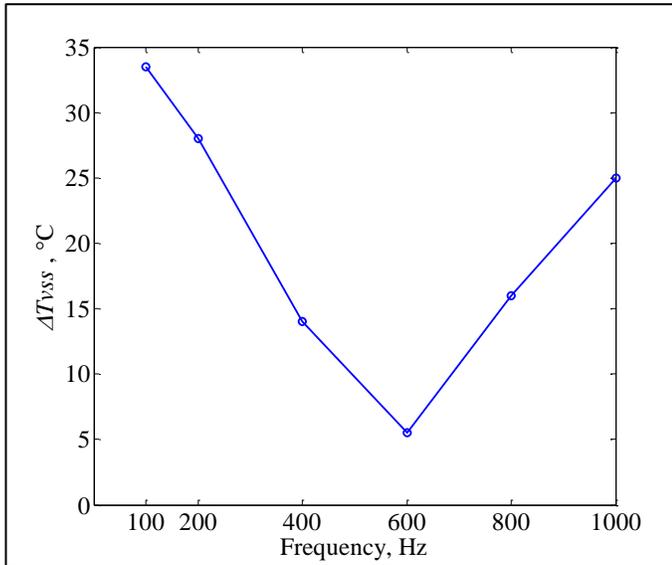


Figure 5. Steady-state temperature increments of the voice coil at low frequencies.

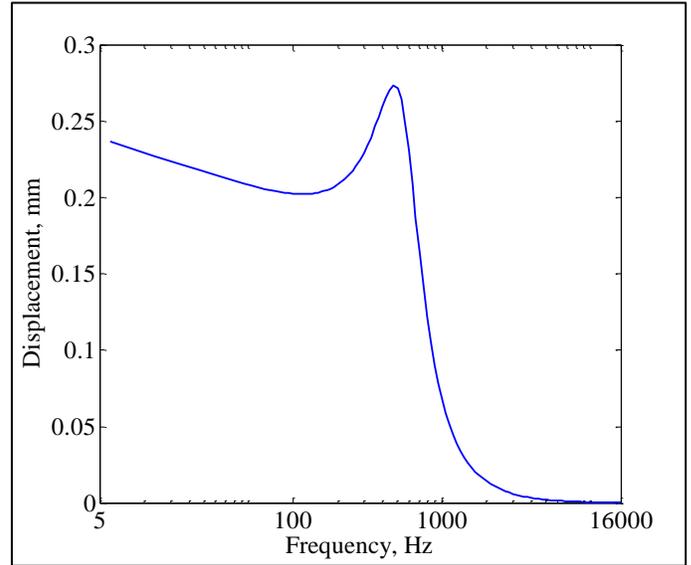


Figure 6. Displacement of the diaphragm at voltage $V_{unit} = 1.5 V_{rms}$. In summary, all the thermal parameters are listed in Table 3.

Table 3. Thermal parameters of the microspeaker with the proposed model.

Parameters	Value	Unit
R_{tv}	67.4	K/W
R_{ti}	46.2	K/W
R_{tm}	30.2	K/W
C_{tv}	0.074	J/K
C_{ti}	1.7	J/K
C_{tm}	9.9	J/K
τ_v	5	s
τ_i	78.5	s
τ_m	299	s
r_v	0.011	J·s/K·m ²
r_x	243	J/K·m ²

4 Verification and Discussion

4.1 Magnet Temperature

With the obtained thermal parameters, the three-stage model can be verified. Since ΔT_{vss} is divided into three parts according to Equation (6), ΔT_{mss} in the three-stage model are much lower than in the two-stage model. Therefore, the temperature increment of magnet ΔT_{mss} is an important index to determine whether the three-stage

model is accurate. A thermocouple was used to measure ΔT_{mss} . This thermometer is a contact thermocouple, TYPE TES 1310, made in Taipei by the TES Electrical Electronic Corporation (maximum error $\leq 0.2^\circ\text{C}$ in the range $-50\sim 199^\circ\text{C}$). By attaching the probe on the under yoke of the microspeakers, ΔT_{mss} was measured while measuring the voice coil temperature. Figure 7 shows the measured ΔT_{mss} and predicted ΔT_{mss} of the three-stage model and two-stage model. Here, the three-stage model is the proposed model and the two-stage model is the Zuccatti-Button model. The predicted ΔT_{mss} was calculated according to the measured ΔT_{vss} with Equation (6).

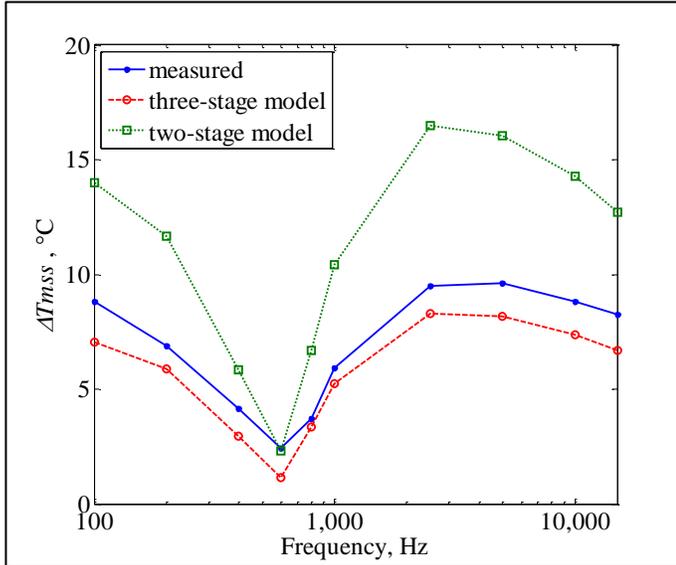


Figure 7. Magnet temperature increments of the microspeaker at different frequencies.

According to Figure 7, there was an obvious deviation between the values of two-stage model and the measured results. However, the three-stage model was better, indicating the three-stage model is accurate for microspeakers.

Recently, some new technologies have been proposed to protect the microspeaker from heat damage, such as the open-loop active heat control (AHC) method. Since the magnet temperature is easier to measured, the temperature of the voice coil is controlled based on the magnet temperature. Therefore, the proposed three-stage model is appropriate when applied to this new technology to protect the microspeakers.

4.2 Dual-Tone and Noise Signal

In order to verify the validity of the model, the temperature curves of voice coil with other input signals were measured. The dual-tone signal and the white noise signal were chosen to cover the low and high frequency range. The chosen dual-tone signals were 300+8 kHz and 100+12 kHz. The band of the white noise was 80-10 kHz, which covered the frequency range in common use. Figures 8 and 9 showed the measured and predicted temperature curves according to the identified parameters.

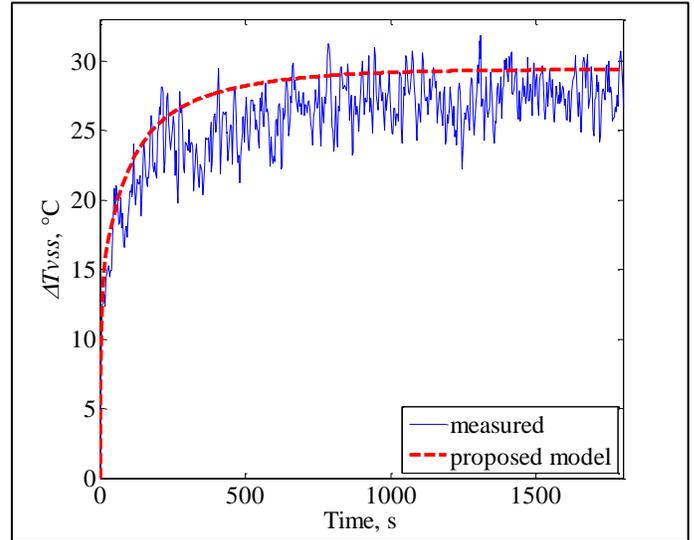
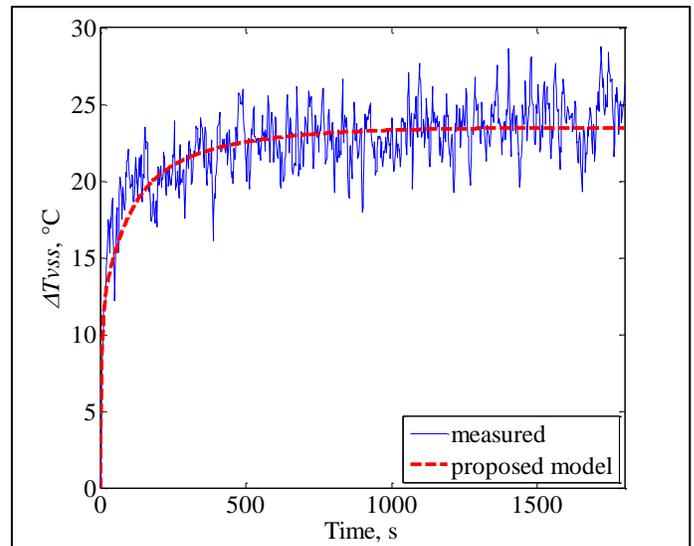
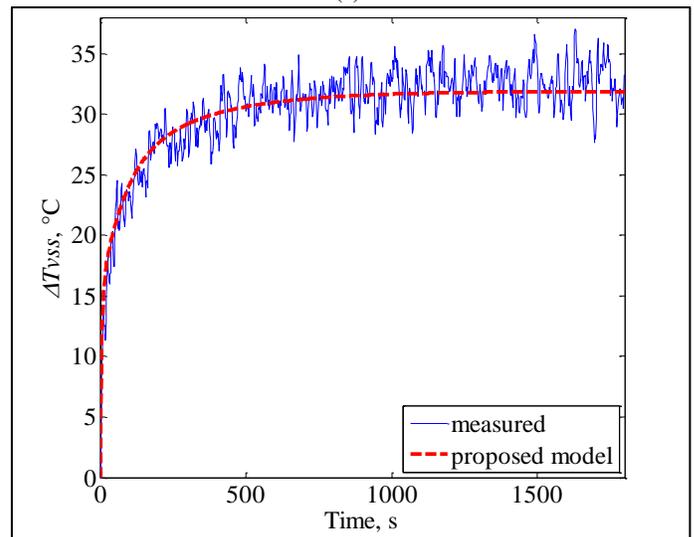


Figure 8. Temperature curve of the voice coil excited by white noise signal.



(a)



(b)

Figure 9. Temperature curves of the voice coil excited by dual-tone signals: (a) 300+8 kHz, (b) 100+12 kHz.

According to Figures 8 and 9, the measured results with other input signals all fitted very well with the predicted results according to the model. This indicated the thermal model is valid and suitable in describing the heat transfer in microspeakers, and the parameters identification method is effective.

The measurement showed the temperature of voice coil was lowest at the resonance frequency, which is due to the powerful forced convection. Although the under yoke of microspeakers is relatively closed, there are still some vents to transfer the heat to the outside air, which are important to the heat cooling in the low frequency range. Therefore, adding some more vents on the under yoke can improve the thermal behavior, and increase the max power and output sound pressure. Of course, this would probably lead to the change of acoustic performance. Therefore, the designer should make a balance between the thermal and acoustic behavior.

5 Conclusion

In this study, a three-stage nonlinear thermal model was proposed for microspeakers in mobile phones. According to the structure differences, the model took into account the influence of inside air and divided the heat transfer into three parts. The measuring results of the magnet temperature indicated the three-stage model was accurate for microspeakers.

In order to obtain the thermal parameters of the model, a corresponding parameter identification method was put forward. As for the two nonlinear factors in large loudspeaker, the eddy current in microspeakers is so small that it can be neglected. Therefore, there is only one nonlinear factor, forced convection, which makes the thermal parameters identification different. In this study, the temperature curves at high frequency were used to obtain basic linear parameters. The curves at frequencies in low frequency range were used to obtain forced convection parameters.

With the identified parameters, the temperature curves of voice coil can be predicted and showed a good agreement with the measured results excited by different input signals. The model is valid in describing the heat transfer in microspeakers, and may help to improve the design and use of microspeakers.

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