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PAPER

Temperature prediction of the voice coil of a moving coil loudspeaker by computer simulation

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In most cases the increase in voice coil temperature is the major cause for speaker failure. Several techniques have been developed to keep voice coil at room temperature under high power inputs. It is a known fact that rise in temperature causes a rise in the total resistance of the voice coil. Providing negative impedance at the amplifier output to compensate for the increase in voice coil resistance is not a new technique. Here we have developed a thermal model to predict the voice coil temperature at different instants of time through computer simulation without actually measuring the voltage across the voice coil and hence calculate the negative impedance required to counteract the increase in voice coil resistance.

Keywords: Loudspeaker, Voice coil resistance, Negative impedance, Digital to analog converter, Digital filters.

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1. INTRODUCTION

Loudspeakers used in high-power applications are stressed by thermal load, which can be the reason for failure and must be controlled. The voice coil resistance doesn't correspond to the ideal value even at room temperature. Since most loudspeakers are at best only a few percent efficient, the bulk of the input power is dissipated as heat in the motor coil. Surprisingly high temperatures (up to 250°C) may be developed when operating under heavy drive; several factors must be taken into consideration when temperature rises of this magnitude are to be accommodated. It is rather difficult to calculate the actual voice coil temperature under working conditions. The increase in d.c. resistance is appreciable and provides some degree of self-limiting with regard to the maximum power drawn from a given source. It also adds a degree of non-linearity, depending on the thermal time constants of the motor coil. The heat causes voice coils to rise in actual impedance. When this happens, the output of the driver is reduced for any given source voltage. In order to compensate for the increase in resistance at the design stage itself, it is necessary to measure the voice coil temperature under operating conditions.

The output of a driver operating under high power conditions is reduced due to power compression. Many articles discussing the power compression in loudspeakers have appeared over the last few years.[2,5,6,13] Providing negative impedance to improve damping is not a new technique, with AST (active servo technology) a significant improvement in bass extension compared to conventional drives has been achieved by the application of positive feedback to create a negative output impedance at the amplifier output to counteract the electrical impedance of the drive unit.[1]

The effects of increased heat from the voice coil is explained in detail in Ref. 2), that the heat causes mechanical stress to paper, cloth parts and adhesives. It is found that large diameter voice coils are far less susceptible to dynamic compression than are smaller ones, *i.e.* a large voice coil in low frequency transducers with an increased surface area reduces the heat build up in transducers. It has also been suggested that the effects of dynamic compression must be anticipated and compensated for at the design stage.[3] Many technological developments that provide better heat conduction away from the voice coil, for example using ferrofluids and the materials and adhesives capable of withstanding temperatures up to 250°C have been made. When the damping factor is large, *i.e.* the amplifier output resistance is near zero, a six dB change in sensitivity has been observed as the coil temperature approaches 250°C, and Q changes by a factor of 2 affecting the transient response and the frequency response.[4] Detailed analysis of heat transfer mechanisms and temperature induced sensitivity and frequency response changes have been described. The problem of change in sensitivity and Q factor caused by temperature induced voice coil resistance variation has been discussed in Refs. 5, 6). It has been explained in Ref. 7) that all the professional manufacturers specify sensitivity at very low power levels, the same place distortion is measured but the equipment is usually used at high power levels. Also it has been stressed that there is a need for the transducer manufacturer to accurately measure the power compression factors, distortion levels, and real world performance of their drivers at their upper power ratings.

A method of measuring the voice coil temperature is discussed in Ref. 8) and the technique of current drive in loudspeakers is used for improving transient response in Ref. 9). The technique of UCUV [unequal current unequal velocity] feedback has been applied to the speaker system to reduce the distortion and to decouple the system Q factor from enclosure and driver parameters.[10] It has been concluded by E.de.Boer that motional feedback or feed forward system may be immune to voice coil resistance provided that it doesn't cause changes of loop gain.[11] The technique of making the amplifier output impedance dynamic consisted of the power amplifier with a self balancing bridge in which the amplifier forms one arm of the bridge, with a VCR [voltage controlled rectifier] in the other arm which is the means of achieving balance. Electronic means of protecting against the burning of voice coil due to resistance changes is given in Ref. 12).

A feedback technique to make the amplifier output impedance dynamic to maintain a constant total resistance has been discussed. To counteract the temperature induced coil failure in loudspeakers electronic means of indicating warning against excessive temperature has also been discussed.[13] Several popular voice-coil magnetic gap configurations is explained in Ref. 14) by using large-diameter massive aluminum coils to insure large surface area and high thermal capacity with minimum mass. Since there exists working temperature limitations for loudspeaker materials, it is important to know the temperature reached by the various parts, in particular the voice coil, as increase in its temperature affects the performance of the drive unit.

So far the methods of calculating the voice coil temperature knowing the d.c. resistance involved interrupting the power fed to the driver for a short while to measure the d.c. resistance. Recently a measuring system for the evolution of the voice coil temperature under operating conditions has been explained which measures the voice coil temperature without interrupting the power fed to the drive unit.[15]

A very simple digital technique of providing negative impedance by predicting the temperature of the voice coil as it heats up and the associated increase in voice-coil resistance using an appropriate thermal model through computer simulation is discussed.

2. THEORY

The variation of voice coil temperature rise with time for any speaker for a given power input is of the form shown in Fig. 1. The most commonly used electrical analog of this curve is a cascaded combina-

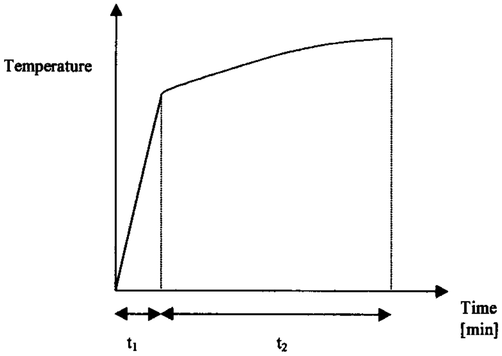

Fig. 1 Variation of voice coil temperature with time.

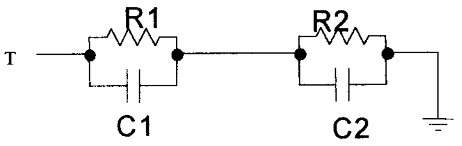

Fig. 2 Thermal model of the speaker in free air. T, temperature of voice coil; ground-ambient temperature; R_1, thermal resistance of path from coil to magnet structure; C_1, zone thermal capacitance of voice coil and nearby surroundings; R_2, thermal resistance of magnet structure to ambient air; C_2, thermal capacitance of magnet structure.

tion of two parallel RC circuits as shown in Fig. 2. Stating the equivalences: thermal power-electric current and temperature-voltage. Thermal resistances are represented by electric resistors, thermal capacities by electric capacitors and thermal energy by electric charge. The value of the resistors and capacitors in Fig. 2 are calculated by knowing the time constants t_1 and t_2 from Fig. 1. Such that; $t_1 = R_1C_1$ and $t_2 = R_2C_2$.

The response of this circuit is found to be identical to that of two low-pass filters connected in series for a step input. Since digital filters can be easily implemented using software. Recursive digital filters are used to simulate the behavior of the speaker with the time constants derived from the electrical analog circuit.

The filter output corresponds to the temperature of the voice coil. By knowing the filter output at a particular instant of time the voice coil temperature and hence the increase in resistance can be calculated. All this was done through computer simulation. The graph of normalized temperature and the normalized filter output is shown in Fig. 3. In this work we used the DAQ [data acquisition] card along with the LABVIEW [Laboratory virtual instrument engineers work bench] software to acquire data and to implement digital filters.

From Fig. 4 the voltage across the load is

$$V_{RL} = (e_i \pm i_o r_s A) g_v - i_o r_s \qquad (1)$$

$$= e_i g_v \pm i_o r_s (A g_v \mp 1) \qquad (2)$$

$$= eig_v \pm r_o i_o \qquad (3)$$

$$\text{where} \quad r_o = r_s (A g_v \mp 1) \qquad (4)$$

is the output impedance of the amplifier.

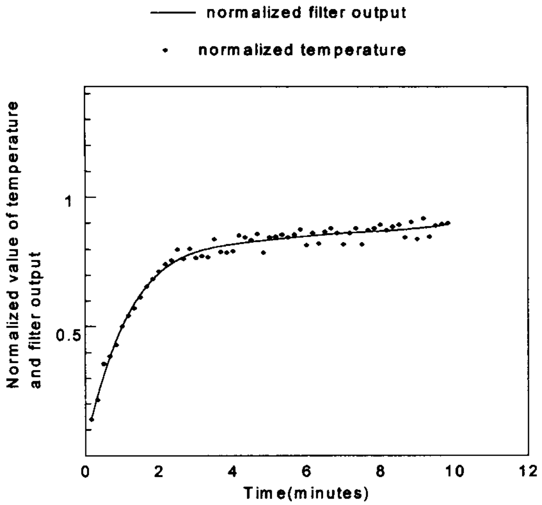

Fig. 3 Voice coil temperature with time compared with the voice coil temperature predicted by the thermal model.

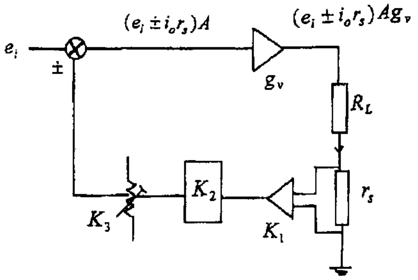

Fig. 4 Block diagram of the feedback system.

$A = K_1K_2K_3$: total gain of the feedback path.
r_s : current sensing resistor.
g_v : the gain of the power amplifier.

Voice coil resistance at any temperature is given by the following equation:

$$R_T = R_t[1 + \alpha(T_T - T_t)] \qquad (5)$$

α : the temperature resistance coefficient.
T_T : some elevated temperature in degrees Celsius.
T_t : room temperature, normally 20°C.
R_t : the voice coil resistance at room temperature.
e_i : the input voltage.
i_o : the load current.
R_T : the voice coil resistance at any temperature T.

$$R_T = R_t[1+\alpha(\Delta T)] \tag{6}$$

$$R_T - R_t = R_t\alpha\Delta T = r_o \tag{7}$$

r_o is the negative impedance required to compensate for the increase in voice coil resistance. Where $\Delta T = T_t - T_r$ is the temperature rise above ambient.

Comparing Equations (4) and (7)

$$R_T\alpha\Delta T = r_s(Ag_v \mp 1) \tag{8}$$

$$\left(\frac{R_T\alpha\Delta T}{r_s} \mp 1\right)\frac{1}{Ag_v} = K \tag{9}$$

This constant K multiplied by the corresponding increase in resistance gives the theoritical value of the binary number to be supplied to the 8 bit multiplying DAC from the DAQ card.

3. EXPERIMENT

Measurements were made with a 10204 DVC woofer from Madisound speakers. A sinusoidal signal in the frequency range 20 Hz–20 kHz was used for the test. The voltage input to the power amplifier is sampled at regular intervals of time initially the voice coil temperature rise is rapid hence data is acquired every 10 s for 10 min. Then the sampling interval was changed to 10 min and the acquisition is continued for 10 h. A relay control circuit is used to acquire data at regular time intervals. The block diagram of the set up to acquire data is shown in Fig. 5 and the final experimental set up is shown in Fig. 6. The program predicts the voice coil temperature and the corresponding

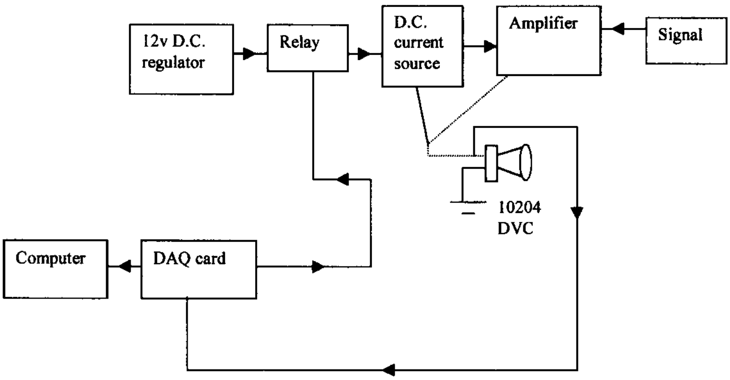

Fig. 5 Block diagram of the experimental set up to acquire data.

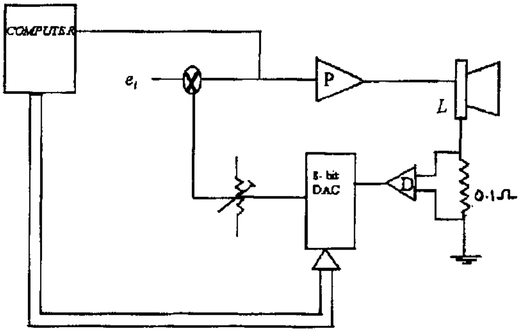

Fig. 6 Experimental setup. P, power amplifier; L, loudspeaker (model-1024DVC); r_s, current sensing resistor; D, differential amplifier; e_i, input voltage; K_3, variable resistance.

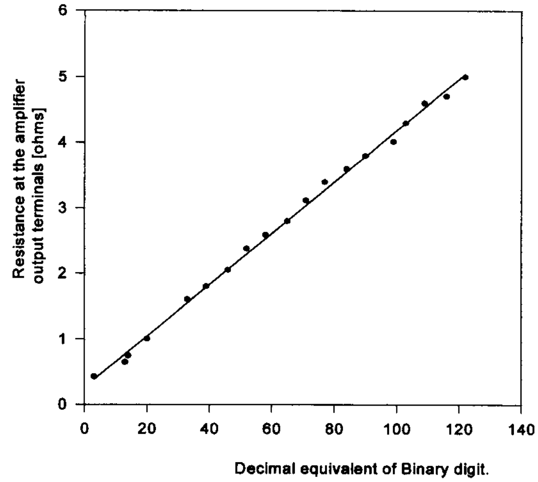

Fig. 7 Graph of resistance *vs.* Binary number.

increase in voice coil resistance and the correct binary number required to provide the negative impedance. Figure 7 shows a graph of binary number required to provide the appropriate negative impedance at the amplifier output terminals. An 8-bit multiplying DAC is used in the feedback path to make the amplifier output impedance dynamic. Measured and predicted values of the voice coil temperature and the increase in voice coil resistance at different power inputs are given in Table 1. Measurements were made by connecting different value resistors to simulate the effect of increase in voice coil resistance with time and with the binary number calculated from the simulation. Frequency response measurements were made with and without the resistors in the circuit and with and without feedback. The experimental set up to measure the frequency response is shown in Fig. 8 and the results are shown in Fig. 9 and Fig. 10. It is clear that the

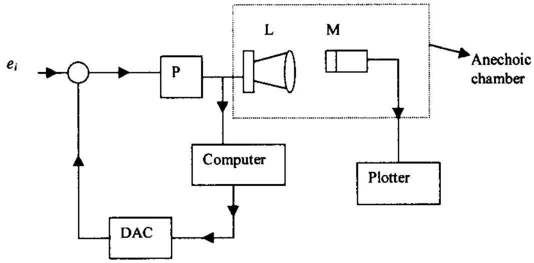

Fig. 8 Experimental set up to measure frequency response. e_i, input voltage. L, loudspeaker. M, microphone. P, power amplifier.

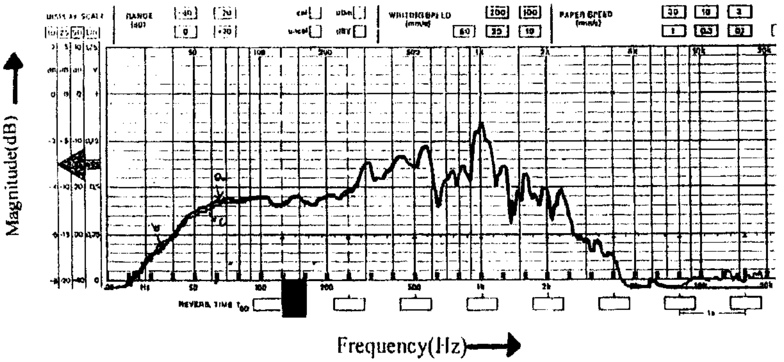

Fig. 9 Frequency response measured under the conditions of driving power 40 W.
(a) Immediately after power ON.
(b) After power compression (after 5 min).
(c) With feedback compensation.

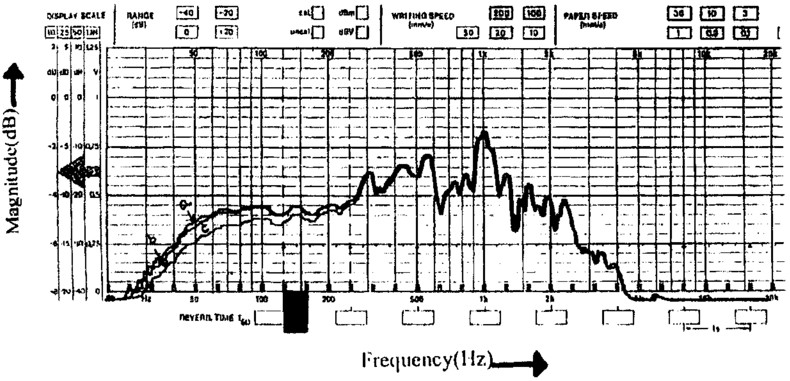

Fig. 10 Frequency response measured under the conditions of driving power 40 W.
(a) Immediately after power ON.
(b) After power compression (after 10 h).
(c) With feedback compensation.

Table 1 Compares the values of the temperature and the voice coil resistance predicted from the thermal model with that from the actual measurement.

Power (W)	Time (min)	Thermal model (predicted values)		Experimental (measured values)	
		Resistance (Ω)	Temperature (°C)	Resistance (Ω)	Temperature (°C)
40	10	1.00	36.35	1.03	37.71
	30	1.16	42.16	1.17	43.00
	940	1.79	65.06	1.76	63.97
60	10	1.63	59.25	1.60	58.20
	30	1.83	66.52	1.80	65.43
	940	2.64	95.96	2.60	94.50

values calculated by the simulation are in close agreement with the measured values and the circuit does provide the appropriate negative impedance to compensate for the increase in voice coil resistance. There is an approximately maximum 4% deviation between the measured and the predicted values.

4. CONCLUSIONS

The effects of temperature-induced changes in the resistive part of the driver's electrical impedance were considered. To achieve low power compression, the temperature rise of the voice coil of the drive unit and the associated increase in resistance must be taken care of. For this the maximum temperature reached by the voice coil must be known. To predict the voice coil temperature at different time intervals using a simple thermal model and to negate the increase in voice coil resistance, a feedback technique to provide negative impedance as predicted by the thermal model has been explained. The thermal model is found to be the easiest method to predict the voice coil temperature and corresponding compensating techniques can be implemented at the design stage itself to protect the speaker from thermal damage at high power inputs.

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