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THERMAL SIMULATION OF LOUDSPEAKERS

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0. ABSTRACT

This papers describes a new thermal model for modelling the thermal behaviour of moving coil loudspeakers. The model has been employed in a system to simulate accurately the temperatures of the voice coil and magnet assemblies of moving coil loudspeakers in real-time for any programme material.

The parameters of the model for a particular unit are first measured directly from the loudspeaker unit using a simple technique. These parameters can then be used for simulations without further need for the loudspeaker unit itself. The system has been verified through measurements performed on bass, midrange and tweeter units and some results are presented here.

1. INTRODUCTION

When electrical power is applied to a moving coil loudspeaker the current that flows in the coil causes heating of the drive unit system. This heating effect ultimately limits the power handling of the unit as either the voice coil is damaged or the flux of the magnet system is reduced causing a reduction in sensitivity. Typical voice coil constructions have a temperature limit of approximately 200 degrees Celsius (°C). However, the limit for the magnet can be as low as 90 °C for neodymium materials [1] and as high as 400 °C for ferrite magnets. Other parts of the construction may also limit the power handling, for example, the joint where the coil former is glued to the cone can be sensitive to even moderate temperatures.

The heating effect also causes other side effects such as thermal compression. Due to the increase in temperature, the impedance of the unit also increases causing a lower power to be applied to the unit resulting in a lower acoustic output. The electrical Q of the loudspeaker unit is dependant on the DC resistance of the voice coil, which changes with temperature, thus effecting the loudspeaker system transfer function.

Before it is possible to solve the problems mentioned above we need a knowledge of the actual voice coil and magnet temperatures that occur during operation. Some systems have been developed that measure the change in DC resistance of the voice coil during operation in order to calculate the temperature of the voice coil such as the system developed by Behler [2].

However, a system that could simulate both the voice coil and magnet temperatures accurately without the loudspeaker under operation would be advantageous and allow flexible, repeated simulations to be made at any time, with any signal and without damaging many loudspeaker units in the process. Our requirements for a thermal simulation system were that it should be able to,

- receive a standard digital audio signal
- filter the input signal with a high order crossover to emulate real filters in the loudspeaker system
- introduce an amplifier by means of a voltage gain and clipping function
- calculate accurately the temperatures of the voice coil and magnet assemblies
- run in real time.

2. THERMAL MODELLING A MOVING COIL LOUDSPEAKER

Our first objective is to accurately model the thermal behaviour of a moving coil loudspeaker. A model developed by Henricksen [3] and used by other authors [1,4] is shown in figure 1.

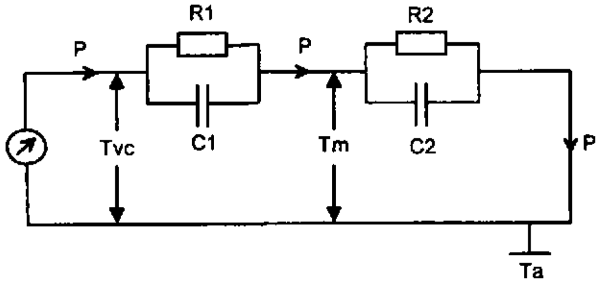

Figure 1 Previously used second order thermal model of a moving coil loudspeaker.

This earlier work has led to this model being widely accepted and has been used for the derivation of temperatures. The model shown above is a lumped-element model consisting of two cascaded parallel RC networks. The current flowing into the model is the power, P, applied to the drive unit and the two RC time constants (R_1C_1, R_2C_2) represent the thermal time constants of the voice coil and magnet systems respectively. T_a represents the surrounding air temperature or ambient temperature and the voltages T_{vc} and T_m represent the temperatures of the voice coil and magnet as lumped elements, above ambient. The s-plane transfer functions (were s = jω) for this model are,

$$T_{vc} = P\frac{R_1 + R_2 + s(R_1R_2C_2 + R_1R_2C_1)}{1 + s(R_1C_1 + R_2C_2) + s^2(R_1C_1R_2C_2} \qquad \textbf{Eqn 1}$$

$$T_m = P\frac{R_2}{1 + s(R_2C_2)} \qquad \textbf{Eqn 2}$$

Consider now a new model, shown in figure 2, below,

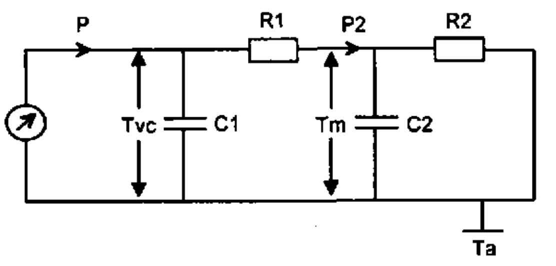

Figure 2 New second order thermal model of a moving coil loudspeaker.

The current flowing into the model is again the power, P, applied to the drive unit and the time constants R_1C_1 and R_2C_2 represent the thermal time constants of the voice coil and magnet systems respectively. T_a represents the surrounding air temperature or ambient temperature. The voice coil temperature above ambient, T_{vc}, is now given by the potential across the thermal capacitance C_1 and the magnet temperature above ambient, T_m, by the potential across the capacitor C_2. The s-plane transfer functions for this model are,

$$T_{vc} = P\frac{R_1 + R_2 + s(R_1R_2C_2)}{1 + s(R_1C_1 + R_2C_1 + R_2C_2) + s^2(R_1C_1R_2C_2}$$ **Eqn 3**

$$T_m = P\frac{R_2}{1 + s(R_1C_1 + R_2C_1 + R_2C_2) + s^2(R_1C_1R_2C_2}$$ **Eqn 4**

By comparing equations 1 and 3, it is clear that the two models can have the same input impedance and are therefore both equally valid for the calculation of the voice coil temperature. However, it is not possible to obtain equal magnet temperature functions.

Consider the step response of the new model. The instant a step is applied, power P flows into the voice coil and energy is dissipated in the coil. The remaining energy, P_2, is fed through to the magnet system. Initially the powers will be different but will become equal when the current flow through C_1 has stopped i.e. thermal conditions in the voice coil have stabilised and steady state conditions prevail. Applying a step input to the model in figure 1, it is seen that equal power, P, must flow into both the voice coil and magnet systems at all times. Hence, there can be no initial settling of the voice coil system to effect the magnet temperature.

It is clear that there is a major difference between the models,

- The previously used model indicates that equal power flows into the voice coil and magnet systems at all times and the temperature indicated to be that of the magnet is not effected by the time taken for the voice coil to heat up. Only under steady state conditions can the model attempt to indicate the magnet temperature. Hence, this model can only be valid for calculation of the voice coil temperature and the temperature indicated to be that of the magnet has no physical meaning for non-steady state conditions.

  It may then be assumed that the instantaneous heating of the magnet system is due to direct induction of eddy currents and the power flow caused by these currents in the magnet. However, the model cannot include the power flow in the magnet due to the flow of eddy currents, as any additional power in the magnet must also flow in the voice coil. Hence, the model can be interpreted as a mathematical model that only creates the correct impedance seen by the power flowing into the voice coil for non-steady state conditions.

- The new model does not have equal power flowing into both the voice coil and magnet under non steady state conditions and the power in the magnet is reduced by the power dissipated in the voice coil, hence the model fits more closely to the thermal behaviour of a physical loudspeaker.

  It is also possible to see that the new model cannot account for the heating effect of eddy currents flowing in the magnet system as this would require an extra current generator feeding power into the junction between the resistors R_1 and R_2. However, from distortion measurements on typical woofers, for example, the distortion component due to eddy current flow is of the order of 1% and many manufacturers include shorting rings in the magnet assembly to reduce further the distortions due to eddy currents by up to 20 dB. This indicates that power flow, and thus the heating effect of eddy currents is small. From the results of implementing the new model it can be seen that any heating effect of eddy current flow is small.

3. A THIRD ORDER THERMAL MODEL

After development of the new second order model it was found that two time constants was not sufficient to model the thermal behaviour accurately. A third order model was then developed and used for the simulation system. This model is shown below, in figure 3.

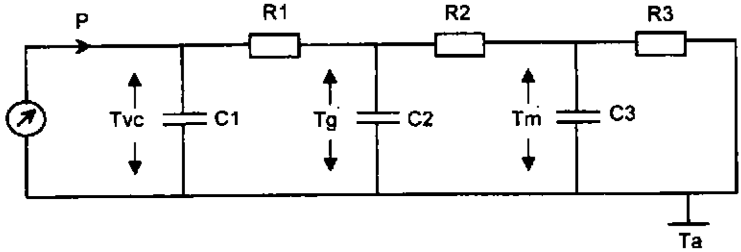

Figure 3 Third order thermal model.

Figure 4 reveals the limitations of the second order model. The figure shows the measured and modelled voice coil temperature step responses for a 170 mm woofer. The measured step response was measured as described in section 4.

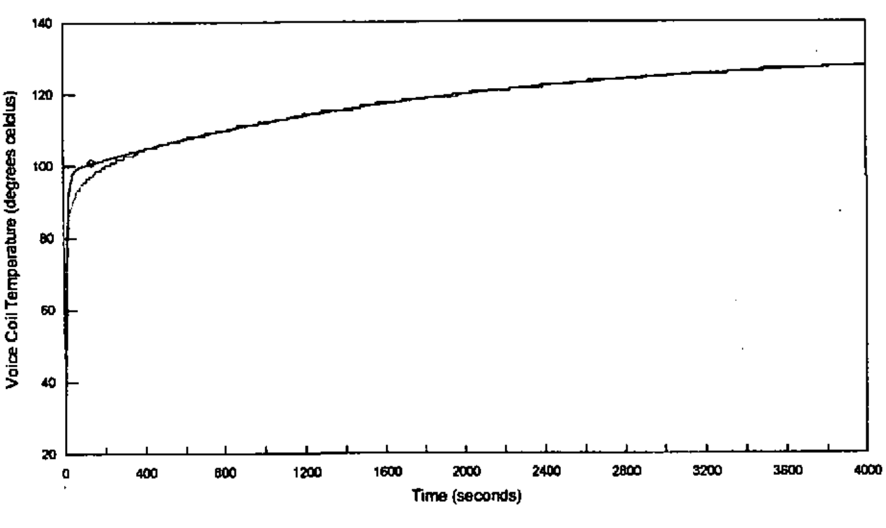

Figure 4 Measured step response and second order model (170 mm woofer).

It is clear that with two time constants it is not possible to model the complete step response of the system. However, three time constants allow the complete thermal behaviour of the drive unit to be modelled. The modelled thermal component values for a 170 mm woofer for the second order model are (to 3 s.f.),

R_1	=	4.94	°C/W	C_1	=	2.96	Ws/°C	(R_1C_1	=	14.6 s)
R_2	=	2.84		C_2	=	741		(R_2C_2	=	2110 s)

and the third order model,

R_1	=	3.93	°C/W	C_1	=	2.36	Ws/°C	(R_1C_1	=	9.26 s)
R_2	=	1.16		C_2	=	71.5		(R_2C_2	=	82.8 s)
R_3	=	2.63		C_3	=	664		(R_3C_3	=	1750 s)

It is seen that the shortest and longest time constants in each model correspond and that the third order model introduces another time constant relatively close to that of the voice coil. This can also be seen in figure 5. Therefore, the temperatures given by the third order model, indicated in figure 3, are the voice coil temperature T_{vc}, the magnet temperature T_m and a third temperature T_g relating to the gap temperature or the temperature of the magnet surface close to the voice coil and the voice coil former, above ambient.

Thoughts that the longest time constant in the third order model relates to the cabinet can be quickly expelled by monitoring the ambient temperature within the cabinet during measurement of the step response. Also, for measurements and simulations with a music signal it is seen how the voice coil temperature quickly cools to the surrounding magnet temperature and in the case of a tweeter it is seen how the magnet temperature (as calculated with the third order model) fluctuates which is clearly not the cabinet temperature (figures 11 - 14). The step response and fitted third order model are shown below,

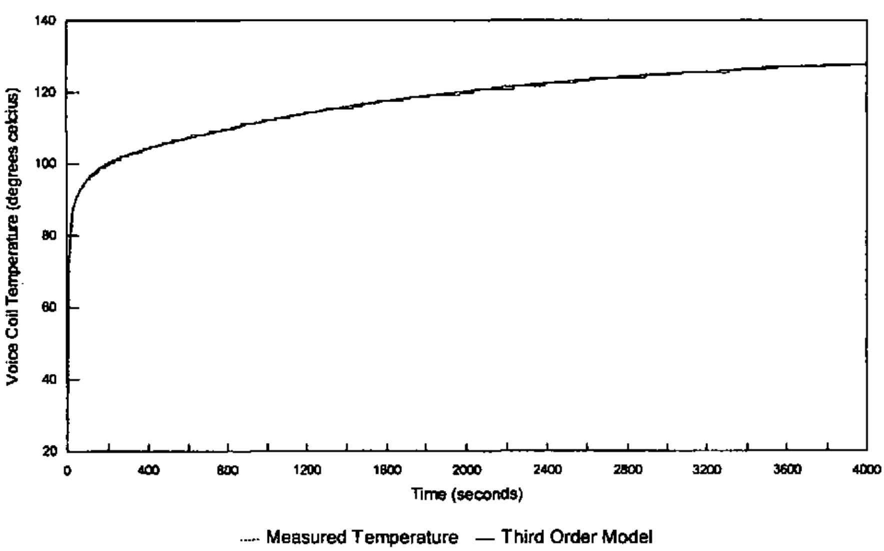

Figure 5 Measured step response and third order model (long measurement, 170 mm woofer).

The voice coil step response of the third order model is of the form,

$$H_{vc}(t) = A_0 + A_1 e^{a_1 t} + A_2 e^{a_2 t} + A_3 e^{a_3} \qquad \text{Eqn 5}$$

Where the coefficients A_n and a_n are related to the thermal component values R_n and C_n and the power P through the inverse Laplace transform. The derivation is lengthy and has not been reproduced here.

Behler [5] also extended the second order model developed by Henricksen to include a third time constant. Behler attributes this to heating of the cabinet, however, the data presented in the paper appears to support otherwise. Values for the thermal components indicate that the third time constant is significantly shorter than that of the magnet and figures showing the measured step response together with the second order model and extended third order model show that the additional time constant has been added shortly after that of the voice coil. However, as described earlier, for temperatures other than that of the voice coil to be extracted from the model only steady state conditions can be considered.

4. MEASUREMENT OF THE THERMAL COMPONENT VALUES

We have seen that the third order thermal model can accurately describe the thermal behaviour of a moving coil loudspeaker. It now remains for the component values, R_n and C_n , in the model to be determined for any drive units of interest. With these parameters it is then possible to use the model in a simulation to obtain the temperatures of the voice coil etc. from a knowledge of the power, P, applied to the loudspeaker unit. The thermal parameters of the model, R_n and C_n , are derived from a measurement of the step response of the loudspeaker. This step response is the rise in voice coil temperature when a constant voltage is applied to the drive unit.

A constant voltage (or step) is applied in the form of a constant amplitude sinewave at a frequency where the impedance phase shift of the loudspeaker unit in the cabinet is zero. At this frequency the loudspeaker presents a resistive load and the precise power dissipated is then known. With an applied rms voltage v, the current flowing in the voice coil is given by,

$$i = \frac{v}{(R_e + R_m)} \qquad \text{Eqn 6}$$

Where R_e is the initial DC resistance of the voice coil and R_e+R_m is the initial magnitude of the impedance at the chosen frequency of zero phase shift. The power, P, is then given by,

$$P = i^2 R_e \qquad \text{Eqn 7}$$

In practice R_e is a function of temperature, given by equation 10. Naturally the reduction in power due to the increasing resistance during the measurement is included in the algorithm to fit the model to the measurements. The voltage is chosen such that the drive unit is not damaged during the measurement which has to be sufficiently long to allow determination of all three time constants of the third order model. The voice coil temperature is then measured while the step is applied to the loudspeaker.

4.1. MEASURING THE VOICE COIL TEMPERATURE

For the purpose of calculating the thermal component values and for verifying the simulation, the voice coil temperature was measured using two methods. Firstly, by measuring the change in DC resistance of the voice coil where a small DC current flow in the coil allows the temperature of the coil to be calculated from the increase in voltage, and secondly, in the special case of a 170 mm woofer, using a thermocouple wound into the voice coil. This woofer was specially constructed by Peerless Fabrikkerne A/S of Denmark.

In each case, the voltage measured is recorded using an 8 bit datalogger inside a personal computer. This gives a measurement resolution of ~0.5 °C for measurements using the change in DC resistance of the coil (the precise resolution is dependent on the particular drive unit) and a resolution of 0.78 °C for measurements using the thermocouple. The datalogger samples data at a frequency of 10 kHz and exports an average at user specified intervals, for example each second.

In practice, two measurements of the step response are made with the same voltage and with the system at the same initial temperature equal to the ambient temperature (which is monitored during measurements to ensure there are no changes to influence the results). The two measurements are a long measurement and a much shorter measurement, the duration of which are determined such that all time constants fall well within the long measuring time. The datalogger exports data at a much higher rate in the short measurement. This allows accurate derivation of all three time constants which are calculated from a curve fitting algorithm that fits the model (described by equation 5) to the measurements.

4.2. MEASUREMENT OF THE LOUDSPEAKER'S IMPEDANCE

For the step response it is necessary to apply a sinewave to the drive unit at a frequency where the impedance of the unit in the cabinet has zero phase shift. Therefore, it is necessary to measure the impedance of the driver in the cabinet. Measurements for this study have been made using a Bruel & Kjær Audio Analyser type 2012. A frequency can then be selected from the measurement where the phase is zero. Note, however, that the phase will shift through zero several times (twice for a driver in a sealed cabinet). The higher of the frequencies should be selected as the gradient of the phase shift is lower and therefore minimises errors caused by slight variations in the frequency for the step response, also the oscillations of the sinewave will not be transposed onto the measurement as the frequency is not close to DC. The temperature at which the impedance measurement is made should also be recorded and the step response measurements made at the same temperature, thus the DC resistance R_e and the value $R_e + R_m$ from the impedance measurement can be used for direct calculation of the power applied during the step response. The impedance curve is also required for calculation of the power in the simulation as described in section 5.3.

4.3 THERMAL COMPONENTS FOR A 170 MM WOOFER

The woofer was placed in a 50 litre sealed cabinet to give a smooth bass response with a -3 dB frequency of 40 Hz. For measurement of the thermal step response a sinewave frequency of 212 Hz was used at 11.12 Vrms. At this frequency the phase shift was 0.03° and the magnitude of the impedance 6.02 Ω. The DC resistance R_e was 5.60 Ω. The ambient temperature during measurement of the impedance and measurement of the step response was 22.5 °C.

Figure 5 shows the first 4000 points of the long measurement, where the rise in voice coil temperature has been recorded at 1 Hz (1 sample per second) for 5500 seconds. The short measurement, although not shown, was measured at a rate of 1 sample every 20 ms for 110 seconds. The first 4096 points of each measurement are then used as target curves for an algorithm to fit the third order thermal model to the measurements. The result of fitting the model to the measurement is also shown in figure 5. The resolution of the measurements is 0.78 °C. The thermal component values for the 170 mm woofer are,

R_1	=	3.927	°C/W	C_1	=	2.358	Ws/°C	(R_1C_1	=	9.26	s)
R_2	=	1.158		C_2	=	71.49		(R_2C_2	=	82.8	s)
R_3	=	2.634		C_3	=	664.3		(R_3C_3	=	1750	s)

4.4. THERMAL COMPONENTS FOR TWO OTHER LOUDSPEAKER UNITS

The thermal components for other loudspeaker units have been measured. An example of two of the units is given here.

The components for a 70 mm midrange unit where measured using a 9 Vrms sinewave at a frequency of 562 Hz. The two measurements where recorded at 5 ms and 1 s intervals for the short and long measurements respectively. The temperature resolution of the measurements was 0.41 °C. The thermal parameters of the model are given below,

R_1	=	5.226	°C/W	C_1	=	1.073	Ws/°C	(R_1C_1	=	5.61	s)
R_2	=	1.439		C_2	=	21.09		(R_2C_2	=	30.3	s)
R_3	=	5.005		C_3	=	392.3		(R_3C_3	=	1960	s)

The measurements have also been performed on tweeter units. The following data is for a 19 mm tweeter with a neodymium magnet and a fluid filled gap. The two step responses where measured using a 2.37 kHz sinewave at 4.11 Vrms. The duration of the measurements was 20 s and 800 s recorded at 5 ms and 200 ms intervals respectively. The measurement resolution was 0.50 °C. The thermal component values for the model are given below,

R_1	=	11.98	°C/W	C_1	=	0.06813	Ws/°C	(R_1C_1	=	0.816	s)
R_2	=	3.065		C_2	=	2.233		(R_2C_2	=	6.84	s)
R_3	=	47.13		C_3	=	8.259		(R_3C_3	=	389	s)

5. IMPLEMENTATION OF THE SIMULATION

As we have seen, it is now possible to model the thermal behaviour of a moving coil loudspeaker and determine the thermal component values in the model. The model can now be used in a simulation. The hardware available for implementation of the simulation was a digital signal processing system that has previously been used for other projects including Programme Material Analysis [6]. The system consists of a Bang & Olufsen Beosystem 2300 CD player equipped with a digital audio output in S/P DIF format. This signal is input to a digital signal processor (DSP). The DSP comprises of four 40 MHz floating-point Motorola DSP96002 boards from Loughborough Sound Images, UK. The host PC is a Compaq SystemPro LT. A block diagram of the complete simulation for one audio channel and a single crossover is shown in figure 6. In practice, two audio channels can each be filtered using a four-way crossover system simultaneously, outputting 16 temperatures (2 channels x 4 x voice coil and magnet temperatures) in real time.

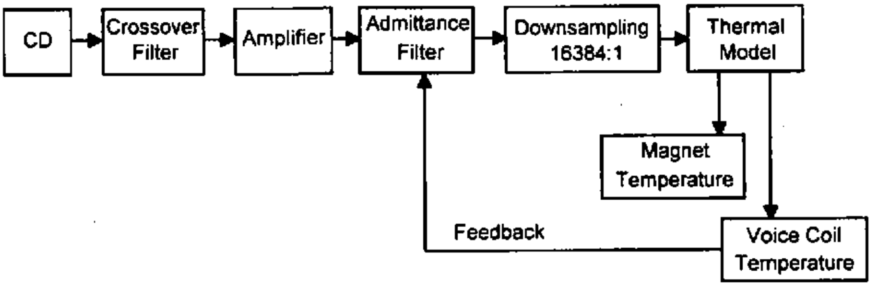

Figure 6 Block diagram of the simulation system.

5.1. INPUT SIGNAL AND CROSSOVER

The input signal is standard digital audio in S/P DIF format from compact disc at a sampling rate of 44.1 kHz. For the purpose of modelling a crossover in the loudspeaker system, the signal can then be filtered using up to a tenth order filter. This IIR filter is implemented in the form of 5 cascaded biquads, to reduce the effects of coefficient sensitivity, and a gain coefficient. If no crossover is required, then the coefficients can simply be set to zero with a unity gain coefficient.

5.2. AMPLIFIER SECTION

For the purposes of modelling an amplifier a simple voltage gain was chosen that scales the voltages to actual level, for example +/- 50 V peak. This is somewhat ideal but it could be argued that amplifiers used are sufficiently linear and of low distortion for this simple model to be accurate.

However, high temperatures within a loudspeaker are generated by large voltages being applied and this often implies clipped output signals from the amplifier. For this reason, the simple amplifier model above has been extended by including a hard clipping function, that clips the signal at a specified level, for both positive and negative signal. The signal now represents the voltage as a function of time, v(t), appearing at the terminals of the loudspeaker.

5.3. CALCULATION OF SIGNAL POWER - AN ADMITTANCE FILTER

To calculate the power applied to the loudspeaker and hence the thermal model, a knowledge of the instantaneous current flowing in the voice coil is needed. If the loudspeaker presented a purely resistive load that was independent of temperature then the power could be calculated from the squared voltage divided by this resistance. However, the loudspeaker has a complex impedance, Z(f,T), that is dependant upon frequency (f) and temperature (T). The current flowing in the voice coil can be calculated by filtering the voltage with the inverse of the impedance, or the admittance function Y(f,T). The current in the voice coil is now given by,

$$i(t,f,T) = v(t)\frac{1}{Z(f,T)} = v(t)Y(f,T) \qquad \textbf{Eqn 8}$$

Where the current in the voice coil is a function of time, frequency and temperature. It can be seen that the admittance function is dependant upon temperature. However, data given by Behler [2], shows that the change due to temperature is almost entirely a shift in DC resistance R_e. Therefore, the simulation considers a single impedance measurement made at normal ambient temperature and introduces the temperature dependence through the change in R_e. This method then avoids having to measure the loudspeaker's impedance at many temperatures. The power flowing into the thermal model in then given by,

$$P(t,f,T) = [i(t,f,T)]^2 R_e(T) \qquad \textbf{Eqn 9}$$

Where, T is initially the start temperature or ambient and then subsequently the voice coil temperature as calculated by the model. R_e at a temperature T for a voice coil wound from copper wire is given by,

$$R_e(T) = R_e(T_0)[1 + \alpha(T - T_0)] \qquad \textbf{Eqn 10}$$

α is the temperature coefficient of copper (0.004 K^{-1}) and $R_e(T_0)$ is the DC resistance of the coil at ambient temperature (or the temperature at which the impedance measurement was made).

Filtering the voltage signal v(t) to obtain the current is performed in the simulation with a sixth order IIR filter. This is sufficient to model the admittance curve for a vented box loudspeaker. Initially a sixth order transfer function in the form of three cascaded biquads is fitted to the impedance measurement. This z-plane transfer function may be written as,

$$Z_1(z) = \left[\frac{a}{b}\right] gain_1 \qquad \textbf{Eqn 11}$$

Where a and b are sixth order polynomials in z. With the increased DC resistance, the new impedance will be,

$$Z_2(z) = Z_1(z) + \delta R_e = \left[\frac{a}{b}\right] gain_1 + \delta R_e = \frac{a(gain_1) + b(\delta R_e)}{b} \qquad \textbf{Eqn 12}$$

Then the new admittance transfer function is given by,

$$Y(z) = \frac{1}{Z_2(z)} = \frac{b}{a(gain_1) + b(\delta R_e)} = \left[\frac{b}{c}\right] gain_2 \qquad \textbf{Eqn 13}$$

To implement the admittance filter at the new value of R_e, it is necessary to reduce equation 13 into the form of three cascaded biquads to avoid sensitivity to coefficient round-off error. However, c is a sixth order polynomial which must be factored into its roots in order to find the three quadratics to form the biquads. With a knowledge that the roots must be real or in complex conjugate pairs, the roots are found within the simulation using an efficient iterative process based on a method by Laguerre [7]. In practice, prior to running a simulation, a data set is created that contains coefficients for 121 admittance filters in steps of 2 °C from a start temperature T_s to T_s+240 °C.

5.4. DOWN-SAMPLING

The processing and calculations in the simulation so far are implemented at a sample rate of 44.1 kHz. This sample rate is much too high for accurate implementation of the thermal model as described next. To avoid this problem the power signal is down-sampled to a frequency of 44100/16384 or 2.692 Hz. The down-sampling is performed using a summation of the power for the previous 16384 samples.

5.5. IMPLEMENTATION OF THE THIRD ORDER THERMAL MODEL

The temperature of the voice coil and magnet given by the thermal model are calculated from the input power signal by equations 14 and 15, below,

$$T_{vc} = P\frac{R_1 + R_2 + R_3 + s(R_1R_2C_2 + R_1R_3C_2 + R_1R_3C_3 + R_2R_3C_3) + s^2(R_1R_2R_3C_2C_3)}{1 + s(R_2C_2 + R_3C_2 + R_3C_3 + R_1C_1 + R_2C_1 + R_3C_1) + s^2(R_2R_3C_2C_3 + R_1R_2C_1C_2 + R_1R_3C_1C_2 + R_1R_3C_1C_3 + R_2R_3C_1C_3) + s^3(R_1R_2R_3C_1C_2C_3)} \qquad \textbf{Eqn 14}$$

$$T_m = P\frac{R_3}{1 + s(R_2C_2 + R_3C_2 + R_3C_3 + R_1C_1 + R_2C_1 + R_3C_1) + s^2(R_2R_3C_2C_3 + R_1R_2C_1C_2 + R_1R_3C_1C_2 + R_1R_3C_1C_3 + R_2R_3C_1C_3) + s^3(R_1R_2R_3C_1C_2C_3)} \qquad \textbf{Eqn 15}$$

It is seen that these are simply third order s-plane transfer functions defining low-pass filters. For the simulation, these have been implemented as digital IIR filters composed of two cascaded biquads for efficient implementation. The coefficients for the filters are calculated from their s-plane equivalents using the bilinear transform method.

Due to the long time constants of the thermal system, the cut-off frequencies for the filters are extremely low relative to a sampling frequency of 44.1 kHz giving rise to filter coefficients that are very close to the unit circle and thus the filter is sensitive to coefficient round-off error. Therefore, to implement the filters accurately, the sampling frequency has been reduced by down-sampling. The new sampling rate gives a Nyquist frequency of ~1.35 Hz. The effect of the digital implementation and errors caused, for example by the characteristics of the digital filter response when approaching the Nyquist frequency, has been evaluated previously [8] and the errors introduced are almost negligible (a temperature error of 0.05 % worst case). With the new sampling frequency, the simulation will calculate voice coil and magnet temperatures approximately three times each second (44100/16384 per second).

6. SIMULATIONS AND MEASUREMENTS WITH MUSIC

Through measurements of the step response of the loudspeaker drive units it is possible to determine the thermal component values of the third order thermal model for each unit. Together with data about crossovers, amplifiers and impedance curves for the loudspeakers it is possible to make thermal simulations for any digital audio signal without any further need for the loudspeaker units.

For verification of the simulation system, the temperature of the voice coil and magnet for each of the three drive units mentioned has been measured and simulated. The Pink Floyd album "Dark Side of the Moon" on EMI Record Ltd was used. The period for the measurements and simulations was 3000 s. This period includes the complete album and several minutes extra. The temperatures were recorded at 1 s intervals for the measurements. The left audio channel was measured. For the 170 mm woofer the voice coil temperature was measured directly with a thermocouple in the voice coil and for the other units the change in DC resistance of the voice coil was used to extract the temperature.

The results presented here show the measurement and simulation for the complete 3000s period for the 170 mm woofer and the 19 mm tweeter. A 600 s period is also shown. Figures 7-10 show results for the 170 mm woofer. The measured voice coil temperature is shown in figures 7 and 9. No crossover filter was used and the peak, unclipped voltage from the amplifier was 45.7 V. Figures 8 and 10 show the simulated temperature of the voice coil and magnet. Figures 11-14 show results for the 19 mm tweeter. The music signal in this case was high pass filtered at 3 kHz with a 24 dB/octave Linkwith-Riley filter. The unclipped peak voltage on the tweeter was 38.6 V. The simulation of the temperatures is shown in figures 12 and 14.

7. DISCUSSION OF RESULTS

Firstly, differences in resolution between the simulations and the measurements should be considered. There are two differences, in time and in temperature.

The measurements of voice coil temperature are recorded at intervals of 1 s. Each of these temperatures is an average of 10000 samples made by the datalogger each second, hence, the measurements are short term averages. The simulations calculate temperatures at intervals of 0.372 s. The effect of this time discretisation will cause small differences in short term peak temperatures. The simulation will indicate slightly higher peak temperatures due to the measured temperatures being calculated from a longer average time.

The second difference is in the resolution of the temperature data. The simulated temperatures are recorded to the nearest 0.01 °C. The temperature resolution of the measurements is limited by the 8 bit datalogger. In the case of the 170 mm woofer, this resolution is 0.78 °C and for the tweeter is 0.50 °C. This effect can be seen as steps in the measurements during periods of gentle heating or cooling.

7.1. DISCUSSION OF RESULTS FOR THE 170 MM WOOFER

The thermal component values determined for this woofer show the time constant of the voice coil to be 9.26 s, the second time constant in the model to be 82.8 s and the time constant of the magnet system to be a little under 30 minutes. Therefore, it is possible for high powers to heat the voice coil to its limiting temperature in seconds.

Consider the measurements and simulations with music. Figures 7 and 8 show the complete 3000 s period for the 170 mm woofer. It is seen that the simulation calculates temperatures above approximately 35 °C to within 1.5 °C of the measurement. Below 35 °C, when the voice coil cools during periods of relative quiet in the music, the simulation indicates lower temperatures than the measurement but the error is never greater than 2 °C. This is caused by the voice coil in the measurement cooling to its surrounding temperature, the temperature of the magnet close to the voice coil. However, the simulation assumes the system is composed of lumped elements and thus the voice coil will cool to a temperature closer to the average temperature of the magnet system. Figures 9 and 10 show the 600 s period and indicate that the simulation reveals more details in the temperature than it has been possible to measure. It is also seen how fast the voice coil temperature rises and falls with an ordinary music signal.

7.2. DISCUSSION OF RESULTS FOR THE 19 MM TWEETER

The thermal time constants for the tweeter are, as expected, much shorter than those determined for the woofer or midrange unit mentioned earlier. The time constant of the tweeter voice coil is 0.82 s and that of the magnet system is only 6 minutes 29 s. If a high power is applied to the tweeter, the voice coil can be damaged in fractions of a second.

Figures 11 to 14 show the simulation of the tweeter temperatures during excitation with a music signal to be very close to the measurements. However, the resolution in the measurement causes detail to be lost, the result being that the simulation indicates higher short term peaks in the voice coil temperature. Comparing figures 13 and 14, the 600 s period, we see the simulated temperature showing every detail of the temperature fluctuations, within 0.7 °C of the measurement. During periods of quiet in the music signal it is seen that the voice coil temperature cools to the magnet temperature in the simulation. This also closely matches the cooling of the measured voice coil temperature. The simulation is much more accurate during periods of quiet for the tweeter because the tweeter thermal behaviour is much closer to a lumped system. Also, the tweeter has fluid in the gap giving more efficient heat dissipation from voice coil to magnet. The short time constant of the magnet also yields a magnet temperature that fluctuates with the music signal.

Comparing the complete 3000 s period for the tweeter, figures 11 and 12, the simulation is very close to the measurement for the initial 1600 s. After this time the simulation slowly falls below the measurement to 1.5 °C lower at the end of the period. This is most likely caused by a small increase in the ambient temperature towards the end of the measurement period that is not included in the simulation.

7.3. POSSIBLE ERRORS IN THE MEASUREMENT OF THE STEP RESPONSE

- The ambient temperature during measurements may change and small variations may be unnoticed.

• During measurement of the step response for derivation of the thermal component values, a sinewave is applied at a frequency of zero phase shift. However, the phase shift may not be exactly zero and during the long measurements may vary within 1 or 2 degrees. This will cause small variations in the power applied.
• The measuring circuit used to measure changes in the DC resistance of the voice coil has itself a step response. However, the time constant of the measuring circuit is approximately 0.1 s and hence is still small relative to the time constant of the tweeter voice coil.
• Some power during the measurement will be dissipated in the mechanical resistance R_{ms} however this is somewhat included directly in the measurement (section 4.).

7.4. POSSIBLE ERRORS IN THE SIMULATION

• The amplifier model in the simulation assumes no distortion of the signal unless hard clipping is implemented.
• The admittance filter used for calculation of the current flowing in the voice coil is a sixth order digital filter calculated from the measured impedance curve of the loudspeaker. The peaks in the impedance and the high frequency increase caused by L_e are modelled using biquad sections. Hence, there will be differences between the digital filter and the true impedance.
• The simulation assumes the increase in temperature causes a simple increase in DC resistance R_e.
• The model does not include a descrete power flow due to eddy currents, however, it appears the heating effect of eddy currents is small.
• During operation of the loudspeaker there is forced air cooling of parts of the system by the movement of the cone. This effect is not included directly in the simulation, however, it is included during measurement of the step response of the loudspeaker and derivation of the thermal component values.
• The thermal model is implemented as digital filters. However, any errors caused by the shape of the filters close to the Nyquist frequency are almost negligible.
• The thermal model assumes the thermal system is composed of lumped elements. Errors caused by this will be most obvious for drive units with large magnets. For typical units this has been overcome by extending the model to a third order system.

8. CONCLUSION

It has been possible to measure the thermal component values for a new third order thermal model for a range of typical loudspeaker units, from a 170 mm diameter woofer with a ferrite magnet to a 19 mm tweeter with a fluid filled gap and neodymium magnet. The physical behaviour of the model and the temperatures within the model relate accurately to the real thermal behaviour of these loudspeaker units. The model has also been verified for steady state and non-steady state conditions.

From the results for the music signals it is seen that the simulations are accurate, with errors between the measurements and simulations being less than 2 °C. For the 19 mm tweeter, which has given the most accurate results, the error on average being approximately 0.7 °C. It is also possible to conclude that the simulation reveals more detail in the temperature of the voice coil than it has been possible to measure.

It can also be concluded from the results that errors introduced by non-linearities, forced cooling, and the effects of the cabinet are small. This is because the simulation is based on a measurement that includes, to a large extent, these effects. Largely, any errors in the system come from errors in the measurement of the step response of the loudspeaker and calculation of the thermal component values. Calculational errors in the simulation are very small.

With an accurate means of simulating the temperatures in a loudspeaker, it is now possible to use this knowledge to determine power handling specifications, eliminate thermal compression and to protect the drive units from damage caused by the heating effect of the signal. Also, with a simulation that does not require connection to the loudspeaker, any investigations into power handling or the development of protection systems can be made without damaging any drive units.

The interested reader is referred to the paper Thermal Simulation of Loudspeakers [8] for further description of the complete simulation system.

9. ONGOING RESEARCH AND DEVELOPMENT

Current activities involve investigating how the temperature is distributed within larger magnet systems which cannot be treated as a single lumped element particularly large magnet assemblies constructed from a ferrite magnet ring and soft iron pole piece etc. The heating effect of eddy current flow within magnet assemblies is also being investigated. Experiments are being devised so that it may be possible to isolate the heating effect of the eddy current flow from the natural conduction of heat from the voice coil to the magnet and thereby determine the power flow due to eddy currents.

The new thermal model is also being used for the design of a thermal protection system for loudspeakers. It is hoped that the results of this further research will be presented in future.

10. ACKNOWLEDGEMENT

Many thanks to Gert Munch of Bang & Olufsen for continued support and interest in this area of research.

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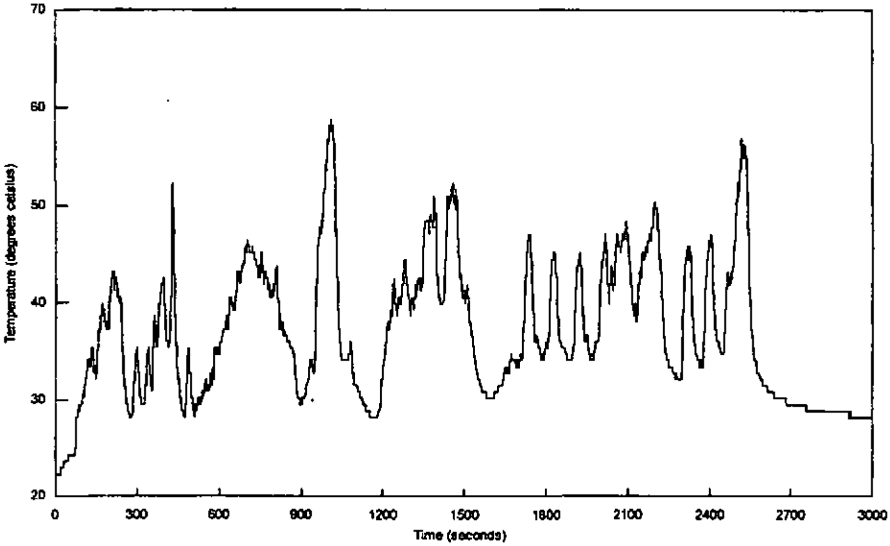

Figure 7 Measured 170 mm woofer voice coil temperature (3000 s period).

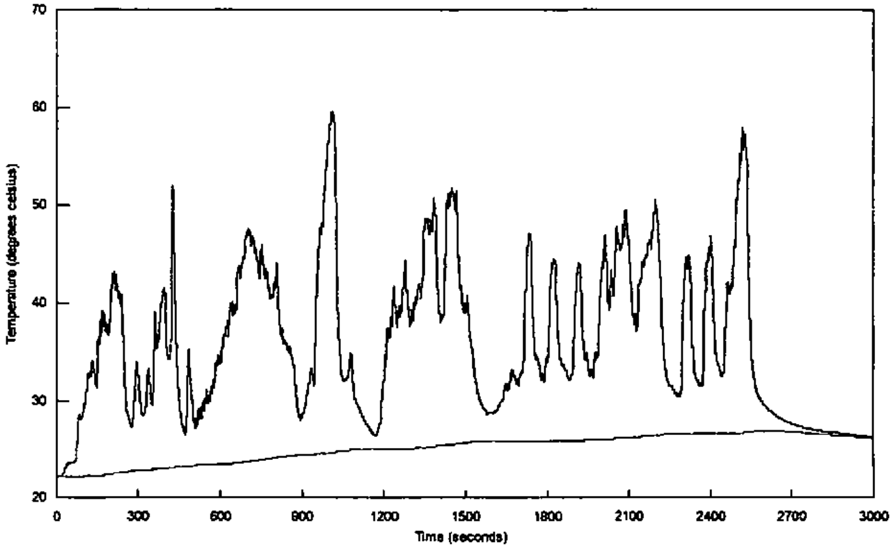

Figure 8 Simulated 170 mm woofer voice coil and magnet temperatures (3000 s period).

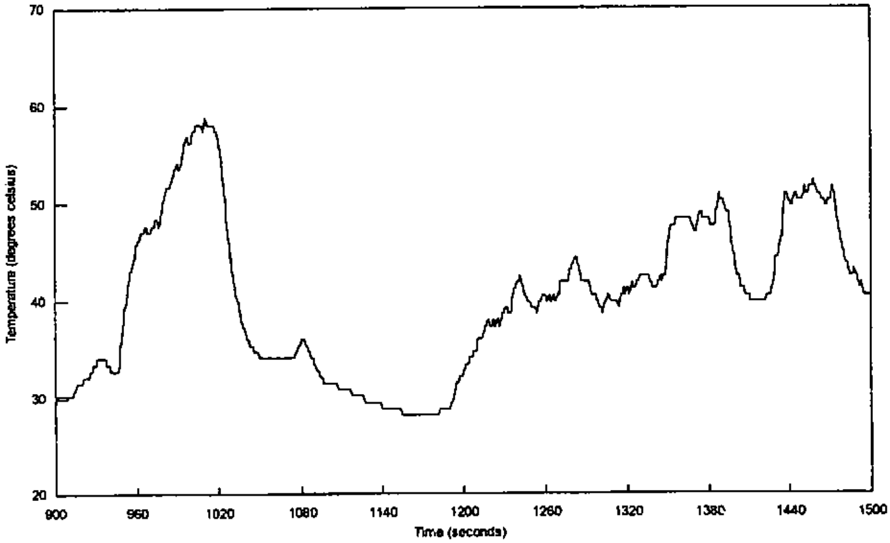

Figure 9 Measured 170 mm woofer voice coil temperature (600 s period).

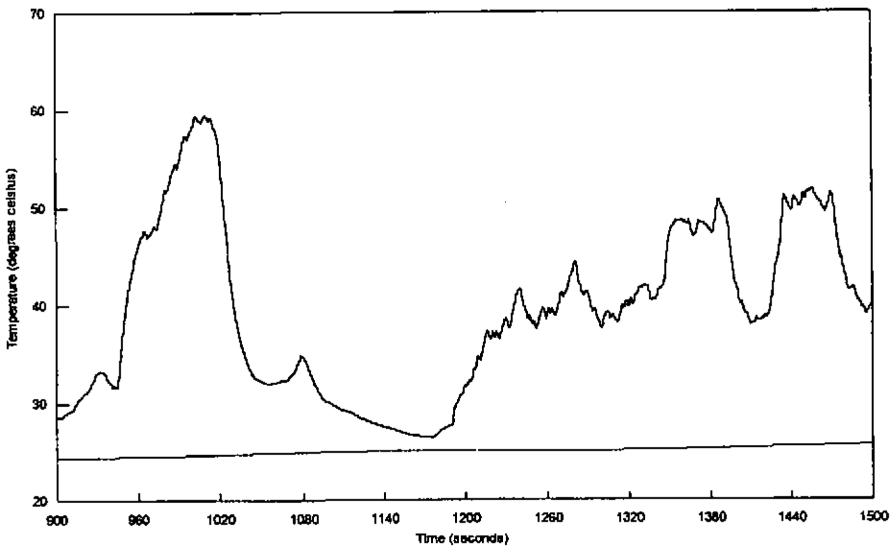

Figure 10 Simulated 170 mm woofer voice coil and magnet temperatures (600 s period).

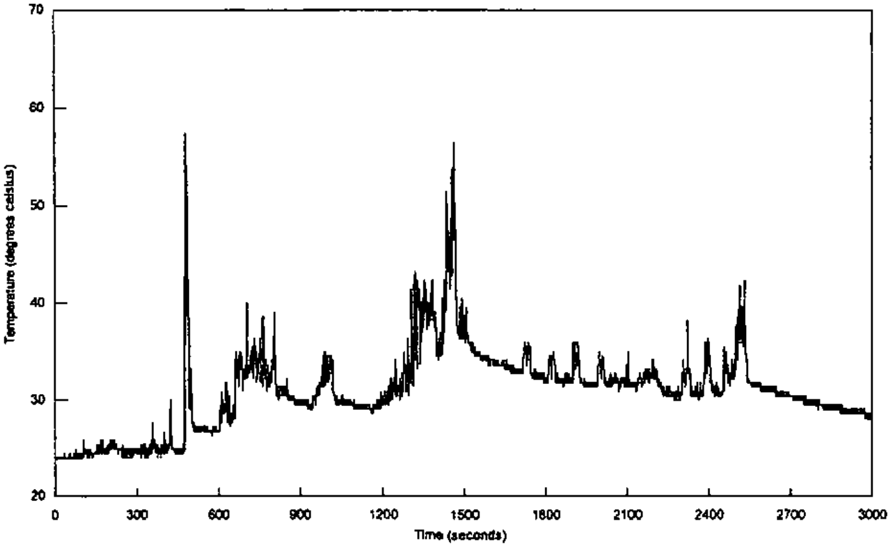

Figure 11 Measured 19 mm tweeter voice coil temperature (3000 s period).

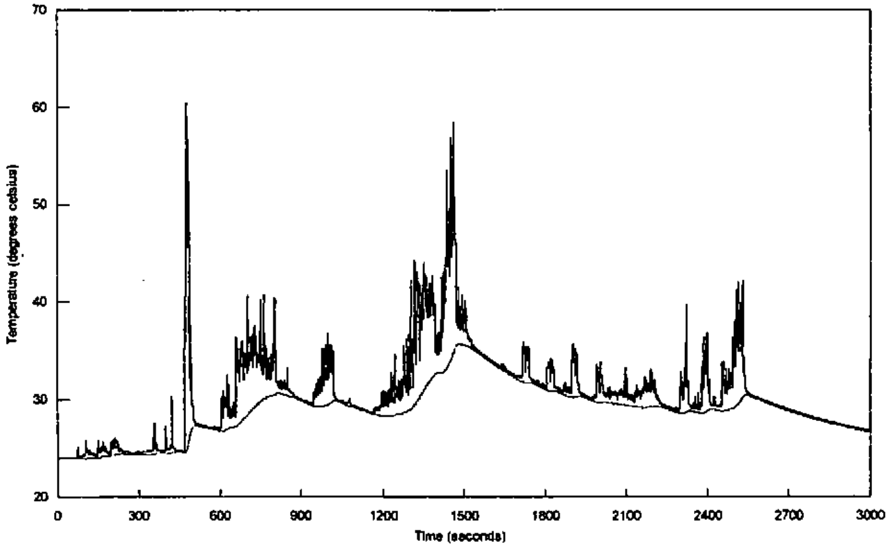

Figure 12 Simulated 19 mm tweeter voice coil and magnet temperatures (3000 s period).

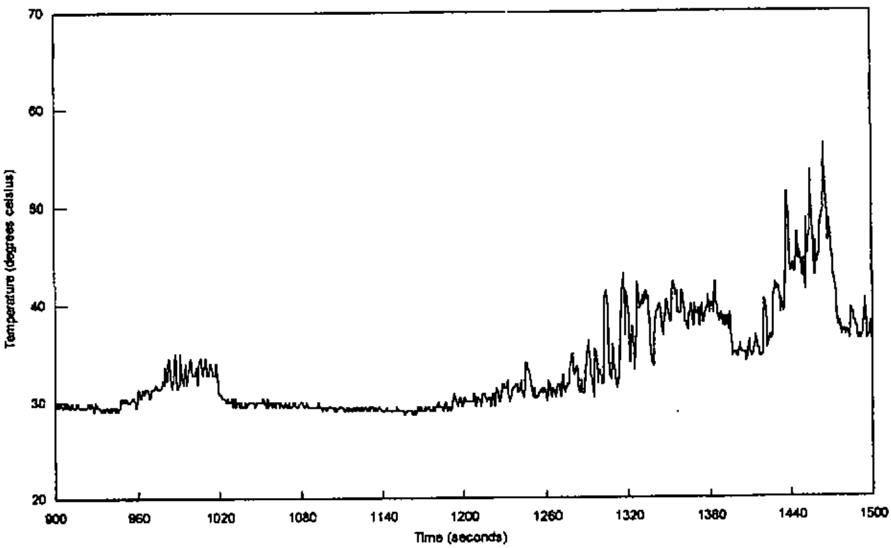

Figure 13 Measured 19 mm tweeter voice coil temperature (600 s period).

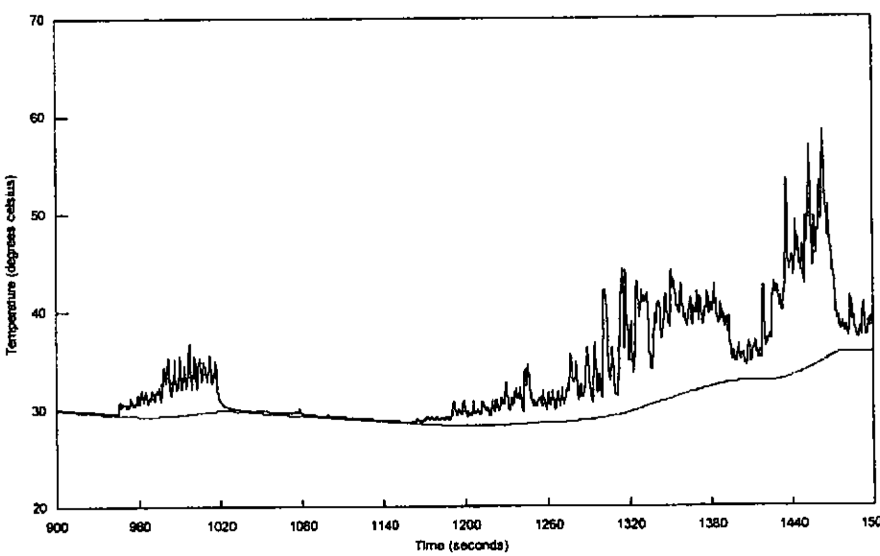

Figure 14 Simulated 19 mm tweeter voice coil and magnet temperatures (600 s period).