Thermal Noise Amplification at Low Frequencies in Thermal Flow Sensors

J.G.J Faber, S2165368, 14-9-2021

***Abstract*—In recent years thermal flow sensors have been created which can measure the direction of sound. These thermal flow sensors have cutoff frequencies up to several kilohertz. This paper discusses the amplification of the thermal noise at low frequencies in such thermal flow sensors. Two different noise models for thermal noise at low frequencies are discussed and compared with measurements. To measure the thermal noise a low frequency amplifier was designed and the noise sources from within the amplifier were identified. With this amplifier, noise measurements were taken in both an oven and a vacuum chamber. The models for noise amplification match the measurements taken. However, noise from external devices and 1/f noise did influence the results in such an extend that more measurements need to be taken to make the results credible.**

***Keywords*—** Self heating, Nyquist-Johnson Noise; Thermal Flow Sensor; Ultra Low Noise Amplifier; Low Frequency Noise Amplification; TCR; temperature Distribution in wires; Amplifier noise

I. Introduction

In recent years, it was discovered that for low frequencies (smaller than the cutoff frequency) the thermal noise gets amplified by the electro thermal feedback effect in wire devices. In a hot wire the thermal noise causes current and voltage fluctuations. Because of the thermal equilibrium effect these fluctuations cause temperature fluctuations. The fluctuations in temperature cause again voltage and current variations. This causes an amplification in noise at low frequencies. It is worth noting that the noise density of flow sensors (or similar single wire devices, for example bolometers or anemometers) is quite small (in the microvolt) and thus quite a hassle to measure which is the reason why the two models for low frequency noise amplification discussed in these papers only have calculated results.[1,2] However this paper takes another approach to this problem. The idea is to measure the amplification of low frequency thermal noise for a thermal flow sensor, to check if the current proposed models are correct. In recent years these thermal flow sensors have been designed in such a way that they are capable of measuring air displacement caused by sound, which implies a cut off frequency in the kilo hertz range. For these measurements a thermal flow sensor will be used specifically Pjetri et al's design from the paper 'A 2D Particle Velocity Sensor with Minimal Flow-Disturbance' which were specially designed to measure sound (see Fig. 1).[3]

II. Two different models for low frequency thermal noise

A flow sensor consist of a sensing wire (could also be multiple, see Fig. 1). This wire is heated using a power source which generates a temperature distribution over the sensing wire (see subsections A and C). When there is for example sound (movement of air) the temperature of the wire gets transported which causes the peak of the temperature distribution to shift on the wire (see Fig. 2).[4] To measure the noise it is important to identify the noise sources in the flow sensor. These are: 1/f noise, Nyquist Johnson noise (thermal noise) and phonon noise. Flicker noise (a type of 1/f noise) is caused by resistance variations[1]. Phonon noise is caused by an exchange of energy between the thermal flow sensor and the surroundings. [5]

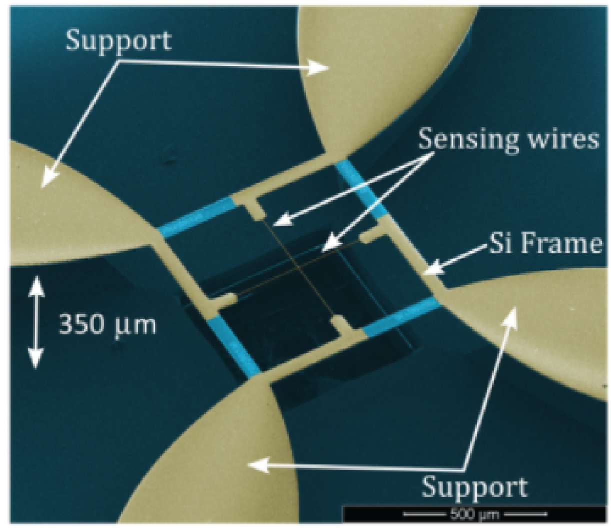

Fig. 1: Picture of the chip[3]

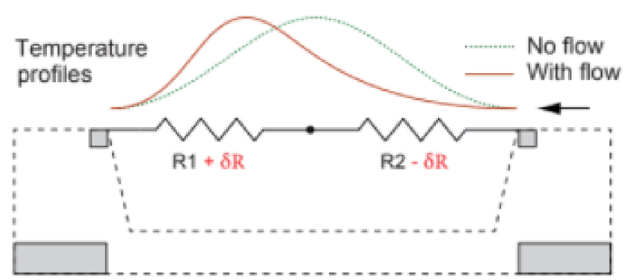

Fig. 2: Effect of the flow on the temperature distribution of a sensing wire[3]

A. Theory of both models

Kohl et al and Piotto et al [1,2] have based their idea on thermal equilibrium and temperature dependent resistor (see subsection b) to argue how the amplification of the thermal noise model at low frequencies looks like. When power (V·I) is dissipated in a wire, heat is generated.

The heat generated in the wire will flow from the heated wire to the lower temperature surrounding air. The flow from the wire to the air could be seen as current flowing from a source through a resistor to the ground but in thermal domain (see Fig. 3) which can be expressed as:

$$V \cdot I = \theta \cdot (T - T_a) \tag{1}$$

The θ represent the thermal conductance (1/thermal resistance). T corresponds to the temperature of the wire and T_a corresponds to the ambient temperature.

As mentioned in the introduction the models use this thermal

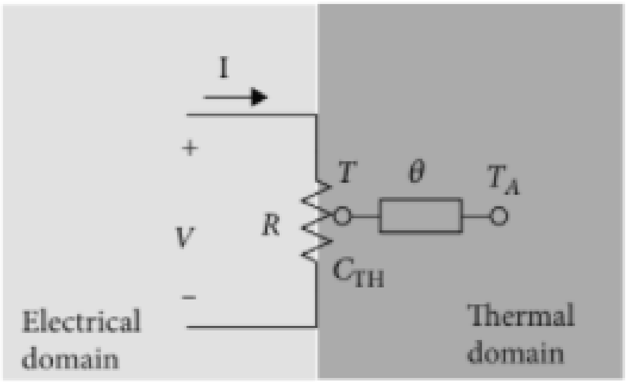

Fig. 3: Electrothermal model of wire[2]

equilibrium model to explain the behaviour of the amplification. The expression that Piotto et al gives for the thermal noise component is[3]:

$$\frac{V_{th}}{\sqrt{Hz}} = 4 \cdot k_b \cdot T_0 \cdot R_0 \cdot (\frac{1}{1 - \alpha \cdot Y_0 \cdot V_0 \cdot I_0})^2 \quad (2)$$

α represents the temperature coefficient of resistance, V_0 represents the DC voltage, I_0 represents the DC current (so $I_0 \cdot V_0$ being the dc power) and Y_0 represents the thermal resistance assuming the thermal conductance is not dependent on temperature (the thermal capacitance C_{TH} is not included in the model). The self heating expression $\alpha \cdot Y_0 \cdot V_0 \cdot I_0$ can be rewritten as $\alpha \cdot (T_0 - T_a)$ (as mentioned in the introduction the noise amplification depends on the thermal equilibrium principle and the dependence of resistance on the temperature). As can be seen from the formula the amplification is dependent on power and thus it will not be affected when it gets heated without any dc voltage or current applied. Kohl et al on the other hand gives the expression :[2]

$$\frac{V_{th}}{\sqrt{Hz}} = 4 \cdot k_b \cdot T_0 \cdot R_0 \cdot (1 + \alpha \cdot Y_0 \cdot V_0 \cdot I_0) \cdot (1 + 2 \cdot \alpha \cdot Y_0 \cdot V_0 \cdot I_0) \quad (3)$$

Both models use self heating expression to calculate the amplification however both propose a different way on how the self heating expression influences the Nyquist Johnson noise.

B. temperature coefficient of resistance

Both models use the TCR (temperature coefficient of resistance) of the sensor to determine the amplification factor. As mentioned in the introduction, when the temperature of the sensing wires increases the resistance also increases. TCR is a parameter which is used to express the resistance change in the sensing wires as a function of temperature change. To be able to check which model is correct, the TCR of the flow sensor needs to be measured. This was done using an oven which takes measurements of the voltage (for 1 μA, 1 μA was chosen such that the heat generated in the wire is negligible) when the temperature is stable within half a degree Celsius for 5 minutes. These measurements were taken for a range of 40 to 120 Celsius. Using

R = R$_{ref} \cdot (1 + a(T - T_{ref})$ (4)

[6] with R representing the measured resistance and R_{ref} representing the resistance at room temperature (23.6 Celsius). T and T_{ref} represent the measured temperature and the room temperature and α represents the thermal coefficient of resistance. With this formula the TCR can be determined. In theory the TCR for bulk platinum is $0.0039K^{-1}$. Because we are dealing with a sensor made of thin film platinum the TCR is going to be lower. The TCR of the thermal flowsensor was measured to be $0.0022K^{-1}$ which is very close to what was measured earlier by Van Baar [7] who found a value of $0.002K^{-1}$ for TCR of platinum thin film.

C. Temperature distribution over the flow sensor wire

The sensors we use to measure the noise are made of thin film and thus when measurements are taken in vacuum the temperature distribution will have a parabolic pattern with boundary conditions such that at the edge of the sensor the temperature increase is equal to 0 (see Fig. 4). The formula does not take room temperature into account and this should be added to the temperature distribution. The temperature at the middle of the wire will be used for the calculations. To calculate the wire behaviour the following model is used:

$$T(y) = \frac{P}{G}(1 - \frac{cosh(y \cdot l \cdot \sqrt{G \cdot R})}{cosh(0.5 \cdot l \cdot \sqrt{G \cdot R})}) \quad (5)$$

[7] This equation normalizes the sensing wire with y = -0.5 and y = 0.5 being the edges of the sensing wire and y = 0 being the middle of the sensing wire. P is the line power, G is the thermal line conductance of the air and R is the thermal line resistance of the sensing wire. Because the measurements are taken in a vacuum, the thermal conductance G can be assumed infinitely small. P can be calculated by $\frac{I^2 \cdot R}{l}$ with R being the resistance of the sensor and l being the length of the sensor wire. The thermal line resistance was calculated with the formula $\frac{1}{a \cdot k}$ with a being the area(height$\cdot thickness(2umx0.15um))and\kappa$ being the thermal line conductivity. The sensors that are used consist of two layers, a silicon nitride layer and a platinum layer. Both having the same size. These two layers act both as thermal resistors that are parallel connected. Because platinum has a much higher conductivity (of 71$\frac{W}{m \cdot k}$[7]) than silicon nitride (of 3$\frac{W}{m \cdot k}$[7]) we can assume that the thermal resistance of the silicon nitride is neglectable (see appendix Fig. 13).

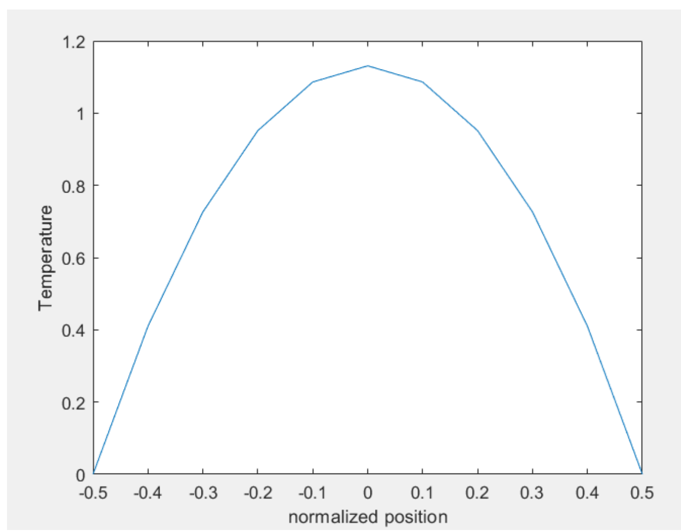

Fig. 4: Normalized temperature distribution in the wire sensor

D. Simulation

Now that both the principles TCR and temperature distribution are discussed, a model for the thin film flow sensor can be created. To determine the voltage corresponding to a particular current we can substitute "eq. (4)" into "eq. (5)":

$$V = \frac{R_{ref} \cdot I \cdot \theta}{\theta - R_{ref} \cdot I^2 \cdot a} \quad (6)$$

With the θ being calculated by

$$G = \frac{P}{\theta} \quad (7)$$

For G the value of 0.000001 $\frac{W}{m \cdot k}$ is assumed because at values lower than 0.000001 $\frac{W}{m \cdot k}$ the temperature distribution does not change when lower values for the conductivity of flow are used in the "eq. (5)", when no power is applied. With the voltage known the temperature of the wire in the middle can be calculated using "eq. (5)". Because of normalization, the middle of the wire corresponds to y = 0. With the maximum temperature known we can determine the resistance using the TCR formula. The maximum voltage is used because when the thermal conductance was calculated the position of the middle of the wire was used to calculate this value. However it is suggested that in further research symmetric points are used on the wire to calculate the average temperature of the wire. Now the high frequency noise, the noise based on Piotto et al's assumptions and the noise based on Kohl et al's assumptions can be determined (see Fig. 5). [2]

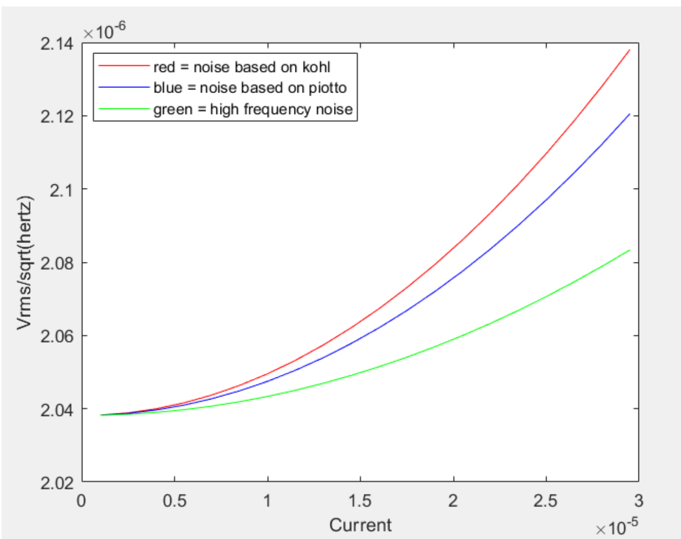

Fig. 5: Theoretical thermal noise of the sensor in vacuum. The high frequency noise represents the thermal noise level without the amplification effect.

III. Measuring noise

For measuring the thermal noise a dynamic signal analyzer is used. The expected noise in a 1 Hz bandwidth is lower than 1 µVrms for the flow sensor. To measure the noise of a flow sensor the noise of the sensing wire needs to be bigger than the noise of the signal analyzer. However when measuring multiple resistors (see appendix Fig. 14) it became clear that the noise of the signal analyzer is bigger than the noise that was desired to be measured. Therefore an amplifier was needed with an amplification factor of 500 or more. When the noise gets amplified more than 500 times it becomes bigger than the noise from the digital signal analyzer. The amplifier also has two restrictions that need to be taken into account. First of all, the amplifier cannot have more noise than the noise that you want to measure. Secondly, the amplification cannot be too big because when the amplification becomes bigger the bandwidth decreases. The bandwidth should be above the cut off frequency, and thus at least a bandwidth of 20 kHz (twice the size of the maximal cut off frequency expected) is suggested.

A. Amplifier design

The amplifier consists of two parts. An amplifier stage and a pre-amplifier stage. The non-inverting amplifier stage was created using the LT6018 opamp. This opamp was chosen because it has only $1.2\frac{nV}{\sqrt{Hz}}$ input voltage noise and a gain-bandwidth of 15 MHz. Two resistors of 15 (R2 in Fig. 7) and 1500 Ω (R1 in Fig. 7) were used to get an amplification of 100, of which only the noise of the 15 Ω resistor gets amplified by the opamp. Resistor R7 (see Fig. 7) was added to bias the opamp. The common source pre-amplifier stage was build with the JFET BF862. This is because the JFET has a negligible input current[8]. A resistor of 8.2 MΩ was put between the gate and the ground to force the V_{gs} to be zero. The transconductance of the JFET was determined to be 0.027 S. By placing a 470 Ω resistor between the power supply and the source obtaining an amplification of 12.75 (Gm·RD = amplification factor) (see appendix Fig. 16). This in total gives the noise an amplification of 1275 which is bigger than the required 500. The bandwidth will decrease with a factor 100, because the gain of the LT6018 increases with 100, and becomes 150 kHz which is bigger than the range the cut off frequency is expected to have.[9,10]

B. Amplifier noise

The amplifier itself has multiple noise sources that need to be taken into account. The amplifier stage has both input current and input voltage and noise from the bias resistor (it is assumed that the resistors used for determining the amplification factor have less noise than the resistors). As mentioned before, the input voltage of the opamp is $1.2\frac{nV}{\sqrt{Hz}}$. The input current is $3 \cdot 10^{-12}\frac{A}{\sqrt{Hz}}$. Both of these noise sources also get amplified by the LT6018. The input current and input voltage are limiting the range of resistors the amplifier can measure. In theory a single stage opamp amplifier would be able to amplify the noise to such an amount that the noise becomes bigger than the noise of the signal analyzer. However the opamp itself also has its own noise that need to be considered. From simulation (see Fig. 6) it can be seen that the input voltage noise of the opamp limits the lowest resistor value that can be measured. The input current of $1.2\frac{nV}{\sqrt{Hz}}$ is increasing linear with the resistance of the sensing wire. The noise caused by the input current increases faster than the thermal noise of the sensing wire. With only an opamp stage the resistance of which the noise could be measured is between 90 and 1820 Ω assuming an amplification of 500 is used (see Fig. 6). [11,12] The noise at the output has still quite some influence from the current noise source making the noise at the output behave more linear than logarithmic. To decrease the influence of the input current (a small increase or decrease of the value of the input current noise could give large variations of the noise at the output) of the opamp and the noise of the amplifier itself by extend, compared to the noise from the thermal noise of the sensor wire, a pre-amplifier can be put before the LT6018 opamp amplifier stage.

The pre-amplifier also has its own noise sources that need to be taken into account. The pre-amplifier has an output voltage noise and noise from the drain resistor. The noise of the drain resistor only gets amplified by the opamp. The noise of the JFET gets amplified by both the opamp and the JFET. The bias resistor connected between the input of the opamp and the ground is negligible seeing that it is parallel connected with the 470 Ω resistor used to bias the JFET. Now that all the noise sources are discussed we could find an expression for each one of them and use those expressions to find an expression for the total noise of the amplifier (see Fig. 7). Noise density at the output from the input current of the opamp:

$$V_{O_A} = I1 \cdot R5 \cdot Aoa \quad (8)$$

$$V_{O_A} = 3 \cdot 10^{-12} \cdot 470 \cdot 100 \quad (9)$$

With Aoa being the amplification factor of the opamp stage. Noise density at the output of the amplifier from the input voltage noise of the opamp:

$$V_{O_V} = V1 \cdot Aoa \quad (10)$$

$$V_{O_V} = 1.2 \cdot 10^{-9} \cdot 100 \quad (11)$$

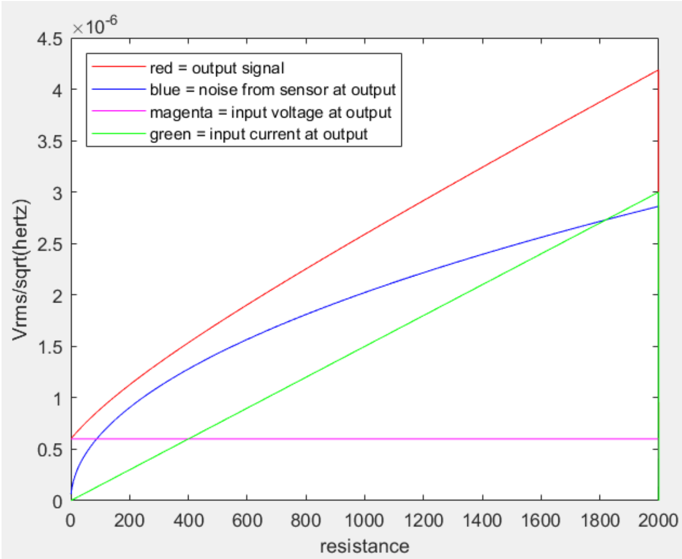

Fig. 6: Simulation noise spectrum at output of a single opamp amplifier with an amplification factor of 500

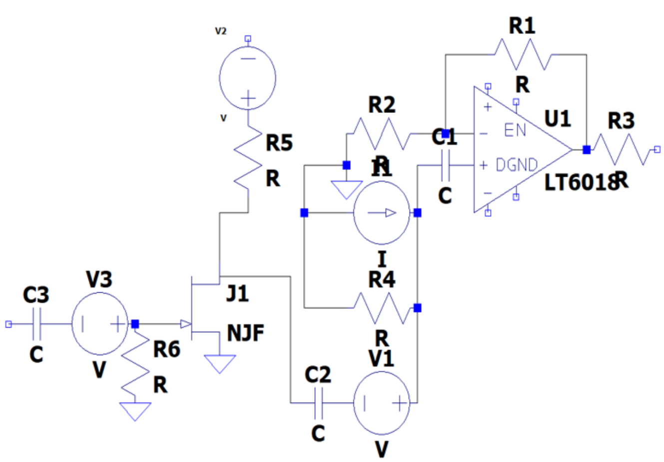

Fig. 7: full amplifier circuit with noise sources

Noise density at the output of the amplifier from the drain resistor:

$$V_{J_{Dr}} = \sqrt{4 \cdot kb \cdot T0 \cdot R5} \cdot Aoa \tag{12}$$

$$V_{J_{Dr}} = \sqrt{4 \cdot kb \cdot T0 \cdot 470} \cdot 100 \tag{13}$$

Noise density at the output of the amplifier for the input voltage of the JFET (V3 in Fig. 7):

$$V_{J_V} = \sqrt{\frac{8 \cdot kb \cdot T0}{3 \cdot gm}} \cdot Aoa \cdot Aj \tag{14}$$

$$V_{J_V} = \sqrt{\frac{8 \cdot kb \cdot T0}{3 \cdot 0.027}} \cdot 100 \cdot 12.75 \tag{15}$$

With Aj being the amplification factor of the Jfet stage. By squaring the noise expressions, adding them and taking the square root an expression for the noise from the amplifier at the output of the amplifier can be obtained.

$$V_O = \sqrt{V_{O_A}^2 + V_{O_V}^2 + V_{J_{Dr}}^2 + V_{J_V}^2} \tag{16}$$

C. *Simulation and resistance measurements*

The amplifier is powered by two 9 volt batteries. The use of batteries for powering the amplifier was specifically chosen because batteries have a lower noise than variable dc voltage sources. Both the amplifier and the batteries are put in a metal box to get rid of any outside noise sources.The metal box is connected with the 3561A dynamic signal analyzer (displays the signal strength against the frequency of the noise) with a coax cable. The signal analyzer uses a flat top window (for high accuracy), has span of 10 kHz which corresponds to the filter bandwidth of 95.485 Hz and is ac coupled. For the measurements various resistors with various resistance have been soldered between the input of the amplifier and ground. The measurements for noise were taken at a frequency (not bandwidth, it corresponds to the voltage frequency of the signal, for thermal noise in theory the power for every frequency of the voltage is the same) of 8000 HZ. By varying the input resistance multiple noise results from the actual amplifier are taken. These measurements are plotted in "Fig. 8" with the simulation of the expected noise of the simulation assuming that the thermal noise of the input resistance is taken into account. As can be seen from the graph the theoretical noise and the measured noise match very closely thus validating that the noise of the flow sensor can be measured accurately.[11]

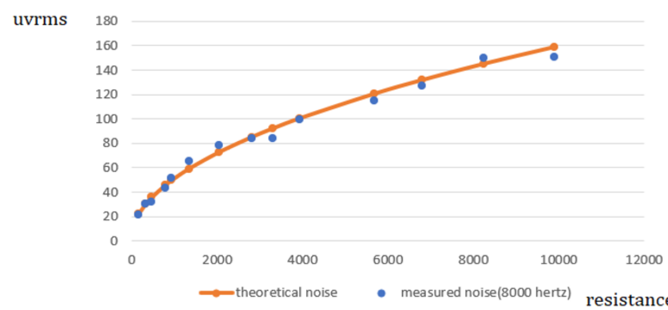

Fig. 8: Noise measurements for various resistances

IV. Low Frequency Noise Measurements

Three flow sensors are soldered together to get a resistance value of 197 Ω (two flow sensors were soldered together to get a resistance of 156 Ω for the vacuum measurements). This was done to increase the resistance. It is good to mention that the flow sensors provided for the experiments did not have the same resistance even though they are supposed to be identical. Two different setups were used to measure the noise. The flow sensors were heated by an oven and the flow sensors were powered by a current source in a vacuum chamber.

A. *Low frequency noise measurements with varying temperature*

1) Theoretical noise: When the flow sensor is heated by an external heat source (instead of the flow sensor being heated by a current) the noise should not be amplifying itself. Thus a baseline can be obtained which can be compared to the measurements of the noise being powered by a current source. First a model can be created for the noise measurements in the oven. For this we can again use the Nyquist Johnson formula:

$$Vn = \sqrt{4 \cdot k_b \cdot T_0 \cdot R_0 \cdot Bw} \tag{17}$$

The R_0 is dependent on the temperature and can be calculated using the TCR the new formula for the noise is obtained:

$$Vn = \sqrt{4 \cdot k_b \cdot T \cdot R_{ref} \cdot (1 + a(T - T_{ref})) \cdot Bw} \tag{18}$$

2) Setup and measurements : The setup consists of an oven, an amplifier (which is shielded), a sensor and a dynamic signal analyzer.

The oven is a big box which heats the inside of the box by powering a coil. Two different devices were used for the measurements. The first device consisted of three thermal flow sensors in series which accumulated to a resistance of 197 Ω. This resistance was also used for the calculation of the theoretical noise at the output of the amplifier taken into account the noise sources of the amplifier. The second device consisted of two Pt100 elements (a platinum resistor used to measure temperature change) in series which accumulate to a resistance of 200 Ω. The noise was measured at a frequency (see the x-axis of "Fig. 11", frequency is the position on the x-axis at which the noise measurements were taken) of 4000 and 9000 Hz and a bandwidth of 95.485 Hz. During the noise measurements the oven was shut down to decrease the noise coming from outside the circuit. As you can see from Fig. 9 the noise of the flow sensor does not

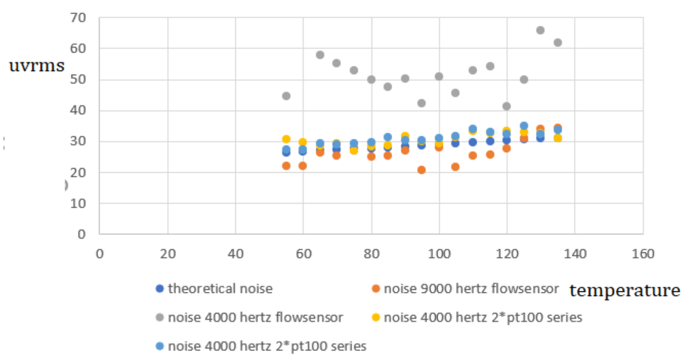

Fig. 9: Noise for different noise temperatures

match the expected thermal noise. This is because there is a lot of thermal fluctuation in the oven (1/f noise) and the thermal flow sensor is thin film and thus very susceptible to these changes (basically there is airflow in the oven due to the differences of temperature in the oven). The Pt100 on the other hand has more bulk properties which include taking longer to change his temperature. The Pt100 followed the expected value of the noise closely. However thermal fluctuations still have influence and the noise also has a small offset because of the higher resistance of the Pt100.

B. Low frequency noise measurements with varying current

1) Theory: When current is applied to the sensor the electro thermal feedback is expected to increase the thermal noise at low frequencies. These measurements are taken in a vacuum because the temperature density spectrum is influenced by sound. The pressure in the vacuum decides the conductivity of the air surrounding the flow sensor. However the wires and the sensor itself can still exert vapors that would increase the thermal line conductivity, in practice, the thermal line conductivity of the surrounding air was calculated to be 0.0026 (by looking at the voltage and current and substituting these parameters in equation 5) and is way off from being infinite small. The temperature distribution is flattened over the wire (see Fig. 10).

2) Setup and measurements: The setup consist of a vacuum chamber with two flow sensors in series which together have a resistance of 156 Ω. The pressure of the vacuum chamber is held between $1.2 \cdot 10^{-4}$ and $3.6 \cdot 10^{-2}$ mbar. The flow sensors are connected to a current source (which also measures the voltage) and the amplifier (see chapter measuring noise) both in parallel. Thus the dynamic signal analyzer can be used to measure the noise. As can be seen from Fig. 11 the noise is not what is expected. The low frequency noise seems to decrease with increasing frequency which could be caused by 1/f noise, the noise from the current source or noise picked up from external devices (for example from the wall outlet). At around 5800 Hz it can be seen that a horizontal line suddenly has a shift in amplitude. This shift disappears when no current is applied. The similar shift around 8200 Hz seems to be

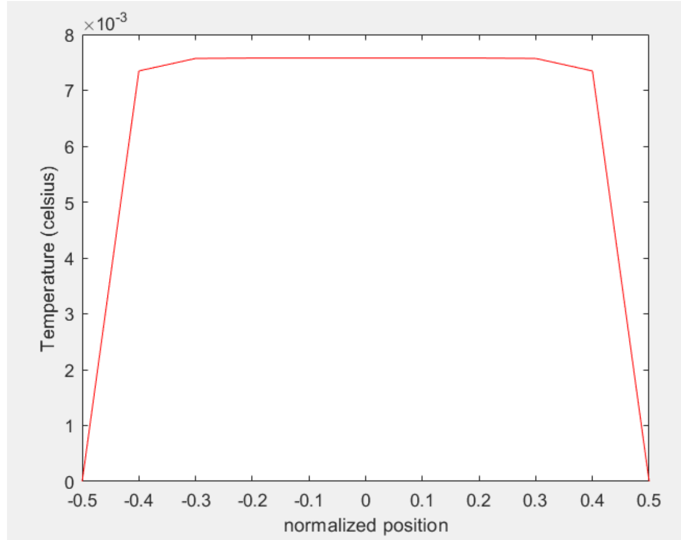

Fig. 10: Thermal distribution of wire for measured thermal line conductivity

present when no current is applied to the flow sensor and cannot represent this change in amplification as according to both Piotto et al and Kohl et al[3,4] this amplification is only present when the sensing wire is powered by a source. To get the most accurate measurements it is desired to measure as close to this frequency. For a noise frequency of 5000 Hz the noise measurements are higher than the expected amplification of the thermal noise proposed by Kohl et al and Piotto et al. At 7000 Hz you expect to see noise equal to thermal

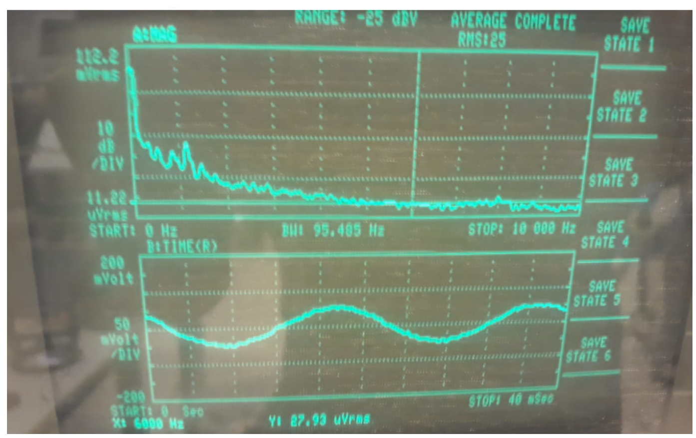

Fig. 11: Screen of the dynamic signal analyzer

noise. As can be seen in Fig. 8 (see Fig. 18 for the corresponding temperature to the current) the thermal noise measurements match the simulation for the thermal noise compared to the current over the flow sensor. Also the noise at 5000 Hz matches both Kohl et al's and Piotto et al's noise model well.

V. Conclusion

A. Results

In this paper the construction of an amplifier was discussed which was used to measure the thermal noise of a series of resistances. These measurements matched the expected thermal noise from the simulations. Secondly thermal noise was measured by placing the sensor in an oven and varying the temperature. From the results it was pretty noticeable that the flow sensor still is influenced a

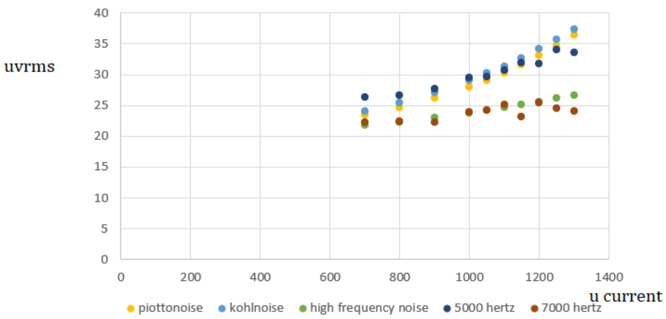

Fig. 12: Low frequency noise measurements in vacuum

lot by 1/f noise. Measurements taken with a Pt100 did give the right results. For the vacuum chamber measurements the simulation matched the measurements for a temperature going from 40 Celsius to 110 Celsius. However it is worth noting that there are still factors that could put this measurement into questioning. In these measurements only the temperature at the middle of the wire was taken into account so that it matches the simulation. Secondly there was still 1/f noise measured and the measurements were also polluted from noise obtained from both the current source and noise coming from external devices. Though all in all I believe these are some promising first results.

B. Improvements

1) Suggestion for oven measurements: As discussed earlier the flow sensor in the oven had problems with thermal fluctuations in the oven. This caused problems when measuring the noise at low frequencies. This however could be solved by using another type oven. Instead of putting the sensor in a big box filled with air it could be put in a block of metal. Than the sensor can be heated by heating the metal block and the movements of air would influence the measurements no more.

2) Suggestion for vacuum measurements: For further vacuum measurements it is suggested to use a battery with a resistor in series and as short as possible wires. By using batteries for the current input of the flow sensor the noise will be limited to only the essential noise sources. Noise from both the current source and from the wall outlet (before the amplifier) will be non existing thus obtaining a noise signal with less external influences. [13]

VI. Acknowledgements

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VII. Appendix

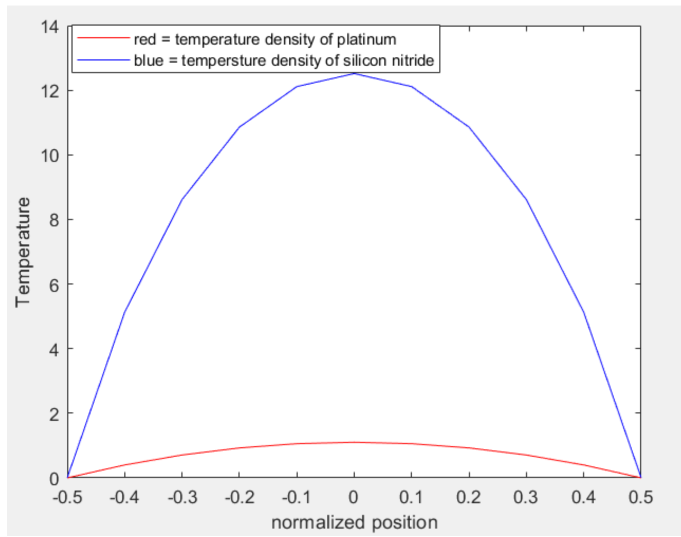

Fig. 13: Temperature distribution of both platinum and siliconnitride

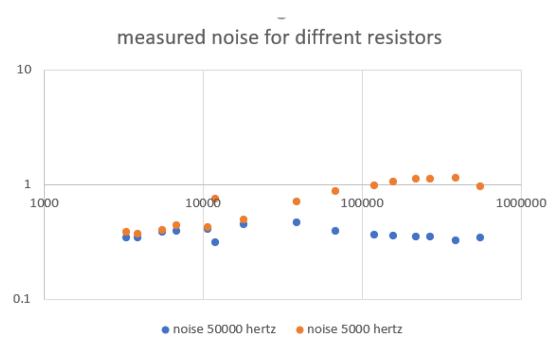

Fig. 14: Thermal noise of resistors with bw of 1 hertz

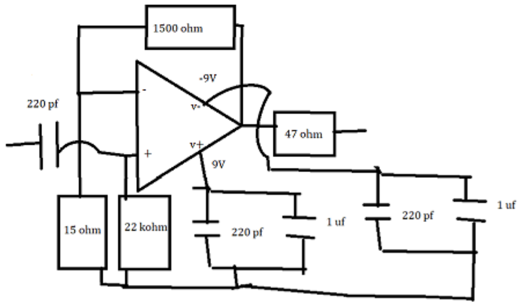

Fig. 15: Amplifier circuit

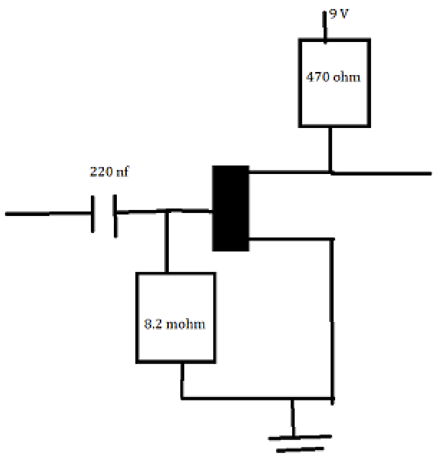

Fig. 16: Preamplifier circuit

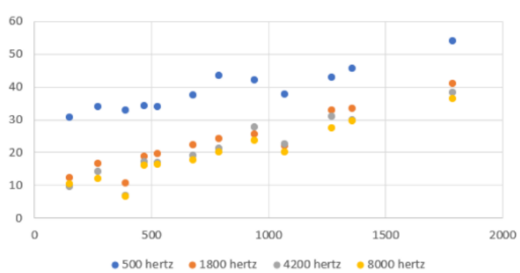

Fig. 17: Thermal noise of resistors with a single stage amplifier of amplification 1000

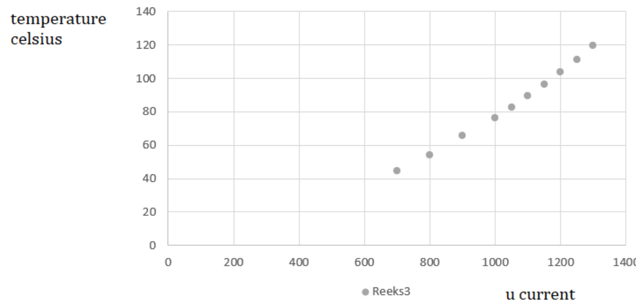

Fig. 18: Temperature at the middle of the flow sensor corresponding to the current going through the sensor

The matlab code contains multiple models for simulating the TCR, temperature distribution of the wire, noise simulations for both the oven and the vacuum and simulation for the noise of both an opamp amplifier and a two stage Jfet opamp amplifier.

```matlab
%% tcr code
resistance1 = 156;
resistance2 = 188.939;
temp1 = 23.6;
a = 0.0022;
temp2 = (resistance2 - ...
    resistance1)/(resistance1*a)+temp1;


%% piotto simulatie
kb = 1.38*10^-23;
T0 = 273.15 + 23.6;%temperature
R0 = 1; %resistance
a = 0.0022;%tempersture coeficient of resistance
y0 = 1; %thermal resistance
I0= 1; %current
W0= I0^2/R0;%power
piottonoise1 = 4*kb*T0*R0*(1/(1-(a*W0*y0)))^2;
kohlnoise = 4*kb*T0*R0*(1+a)*(1+2*a);
hightfrequencynoise = 4*kb*T0*R0;
%% kohl simulation

%% thermal noise czlculation
%coolresult = sqrt(95.485*(3*10^-12*470)^2 + ...
    95.485*(1.2*10^-9)^2 + 4*kb*T0*470*95.485 + ...
    (12.75*sqrt(4*kb*T0*2820*95.485+(8*kb*T0/(3*0.027))*95.485))^2)*100;





noisewithamp = zeros(1,2000);
currentlimit= zeros(1,2000);
voltlimit = zeros(1,2000);
inputvolt = zeros(1,2000);
inputcurrent = zeros(1,2000);
together = zeros(1,1999);
currentvolt =  zeros(1,2000);
currentJfet =  zeros(1,2000);
currentJfet2 =  zeros(1,2000);
onlyamp =  zeros(1,2000);
onlyampnoise =  zeros(1,2000);
onlyampcurrent = zeros(1,2000);
onlyampvoltage = zeros(1,2000);
noisegraphexcel = sqrt(4*kb*T0*940)*1500;

while R0<2000

    noisewithamp(1,R0) = sqrt(4*kb*T0*R0)*1500;
    currentlimit(1,R0)= 3*10^-12;
    voltlimit1(1,R0)= (1.2*10^-9)*100*sqrt(95.485);
    voltlimit2(1,R0) = sqrt(4*kb*T0*470*95.485)*100;
    inputvolt(1,R0) = sqrt(4*kb*T0*R0*95.485)*1157;
    inputcurrent(1,R0) = sqrt(4*kb*T0/R0);
    currentvolt(1,R0) = ...
        3*10^-12*470*100*sqrt(95.485);
    currentJfet(1,R0) = ...
        sqrt((8*kb*T0)/(3*0.04)*95.485)*1157;

    together(1,R0) =  ...
        sqrt(95.485*(3*10^-12*470)^2 + ...
        95.485*(1.2*10^-9)^2 + ...
        4*kb*T0*470*95.485 + ...
        (12.75*sqrt(4*kb*T0*R0*95.485+(8*kb*T0/(3*0.027))*95.485))^2)*100;
    onlyamp(1,R0) = sqrt((3*10^-12*R0)^2+ ...
        (1.2*10^-9)^2 + 4*kb*T0*R0)*1000;
    onlyampnoise (1,R0) = sqrt(4*kb*T0*R0)*1000;
    onlyampcurrent(1,R0) = 3*10^-12*R0*1000;
    onlyampvoltage(1,R0) = 1.2*10^-9*1000;
    R0 = R0+1;
    end
%figure(1);
                                                        %plot(currentlimit,'r');
                                                        %hold on;
                                                        %plot( inputcurrent, 'b');
```

```
%hold off;
%legend({'red = currsenlimit','blue current= ...
    '},'Location','southwest');
%figure(2);
%plot(voltlimit1,'r');
%hold on;
%plot( inputvolt, 'b');

%hold off;
%legend({'red = voltlimit','blue volt= ...
    '},'Location','southwest')
%figure(3);
%plot(noisewithamp,'r');
%figure(4);
%plot(currentJfet,'b');
%figure(5);
%plot(together,'red');
%hold on
%plot(currentvolt,'blue');
%hold on
%plot(currentJfet,'cyan');
%hold on
%plot(inputvolt,'green');
%hold on
%plot(voltlimit1,'yellow');
%hold on
%plot(voltlimit2,'magenta');
%100 -1800
%hold on
%plot(currentJfet2,'black');

figure(6);

plot(onlyamp,'r');
hold on;
plot(onlyampnoise,'b');
hold on;
plot(onlyampvoltage,'magenta');
hold on;
plot(onlyampcurrent,'green');
legend({'red = output signal','blue = noise from ...
    sensor at output ','green = input current at ...
    output', 'magenta = input voltage at ...
    output'},'Location','southwest');
xlabel('resistance')
ylabel('Vrms')
figure(7);
plot(currentJfet2,'black');
xlabel('resistance')
ylabel('Vrms')
%% variable temperature oven
%temperaturenoisemeassimulation = zeros(1,150);
%temperaturenoisemeassimulation2 = zeros(1,150);
%variabletemp = 1;
%resistancetemp = 197;
%kb = 1.38*10^-23;
%a = 0.0023;
%while variabletemp < 150
%    ...
    temperaturenoisemeassimulation(1,variabletemp) ...
    = ...
    sqrt(resistancetemp*(1+a*((variabletemp+273.15)-276.75))*(variabletemp+273.15)*kb*95.485*4)*1275;
%    ...
    temperaturenoisemeassimulation2(1,variabletemp)= ...
    sqrt(95.485*(3*10^-12*470)^2 + ...
    95.485*(1.2*10^-9)^2 + 4*kb*T0*470*95.485 + ...
    (12.75*sqrt(resistancetemp*(1+a*((variabletemp+273.15)-276.75))*(variabletemp+273.15)*kb*95.485*4+(8*kb*T0/(3*0.02
%    variabletemp = variabletemp + 1;
%end
```

```
%%
```

```
%loltemp = 150;
%lolmeas= sqrt(95.485*(3*10^-12*470)^2 + ...
    95.485*(1.2*10^-9)^2 + 4*kb*T0*470*95.485 + ...
    (12.75*sqrt(resistancetemp*(1+a*((loltemp+273.15)-276.75))*(loltemp+273.15)*kb*95.485*4+(8*kb*T0/(3*0.027))*95.485
%figure(7);
%plot(temperaturenoisemeassimulation2,'b');
%% temperature distribution
p = (197*0.00001^2)/0.001;%1cm 1ma 197ohm ...
    I^2*R/L 156 ohm
r1 = 1/(71*0.000002*0.000000015);%1/ak k = 3 a ...
    =0.00015
r2 = 1/(3*0.000002*0.000000015);%1/ak k = 3 a ...
    =0.00015
G = 0.000001; %0.0026
l = 0.001;%1cm
y = -0.5;
z=1;
temperaturedensity = zeros(1,11);
temperaturedensity2 = zeros(1,11);
y2 = zeros(1,11);
while y < 0.6

    temperaturedensity(1,z) = ...
        (p/G)*(1-(cosh(y*l*sqrt(r1*G))/cosh(0.5*l*sqrt(r1*G))));
    temperaturedensity2(1,z) = ...
        (p/G)*(1-(cosh(y*l*sqrt(r2*G))/cosh(0.5*l*sqrt(r2*G))));
    y2(1,z) = y;
    y = y + 0.1;
    z = z+1;
end
figure(8);
plot(y2,temperaturedensity,'r');
hold on;
plot(y2,temperaturedensity2,'b');
xlabel('normalized position')
ylabel('Temperature')
legend({'red = temperature density of ...
    platinum','blue = tempersture density of ...
    silicon nitride '},'Location','southwest');

%% kohl and piotto calculation model

current = 24*10^-6;
a = 0.0022;
refres = 156;
G = 0.000001;%0.0026
r = 1/(71*0.000002*0.000000015);
conductance = ...
    G*(1/(1-(cosh(0)/cosh(0.5*0.001*sqrt(G*r)))));
voltage = ...
    (refres*current*conductance)/(conductance-refres*current*a);
%%
%voltage = zeros(1,29);
%current2 = zeros(1,29);
%counter = 1;
%while counter < 30
    %voltage(1,counter) = ...
        (refres*current*conductance)/(conductance-refres*current*a);
    %current2(1,counter) = current;
    %counter = counter + 1;
    %current = current + 0.000001

%end
%figure(8);
%plot(current2,voltage);
%xlabel('current')
%ylabel('voltage')
```

```
reftemp= 23.6;
refbandwidth = 95.485;
kb = 1.38*10^-23;


%P = (voltage*current)/0.001;

%l = 0.001;
%toptemp = ...
    (P/G)*(1-(cosh(0)/cosh(0.5*l*sqrt(r*G))));

%topres = refres*(1+a*toptemp);
%highnoise = ...
    sqrt(4*kb*refbandwidth*(toptemp+273.15+23.6)*topres)*1275;
%piottonoise = ...
    sqrt(4*kb*refbandwidth*(toptemp+273.15+23.6)*topres*(1/(1-a*toptemp))^2)*1275;
%kohlnoise = ...
    sqrt(4*kb*refbandwidth*(toptemp+273.15+23.6)*topres*(1+2*a*toptemp)*(1+a*toptemp))*1275;
%%
counter2 = 1;
kohlnoise = zeros(1,20);
piottonoise = zeros(1,20);
highnoise = zeros(1,20);
voltage2 = zeros (1,20);
topres2 = zeros (1,20);
current2 = zeros(1,20);
while counter2< 21
    voltage = ...
        (refres*current*conductance)/(conductance-refres*current*a);
    P = (voltage*current)/0.001;
    voltage2(1,counter2) = voltage;
    l = 0.001;
    toptemp = ...
        (P/G)*(1-(cosh(0)/cosh(0.5*l*sqrt(r*G))));
    toptemp2(1,counter2) = ...
        (P/G)*(1-(cosh(0)/cosh(0.5*l*sqrt(r*G))));
    topres = refres*(1+a*toptemp);
    topres2(1,counter2) = refres*(1+a*toptemp);
    highnoise(1,counter2) = ...
        sqrt(4*kb*refbandwidth*(toptemp+273.15+23.6)*topres)*1275;
    piottonoise(1,counter2) = ...
        sqrt(4*kb*refbandwidth*(toptemp+273.15+23.6)*topres*(1/(1-a*toptemp))^2)*1275;
    kohlnoise(1,counter2) = ...
        sqrt(4*kb*refbandwidth*(toptemp+273.15+23.6)*topres*(1+2*a*toptemp)*(1+a*toptemp))*1275;
    current2(1,counter2) = current;
    current = current + 0.000001;

    counter2 = counter2 + 1;
end
figure(9);
plot(voltage2);
figure(10);
plot(current2,kohlnoise,'r');
hold on;
plot(current2,piottonoise,'b');
hold on;
plot(current2,highnoise,'g');
legend({'red = noise based on kohl','blue = ...
    noise based on piotto ','green = high ...
    frequency noise'},'Location','southwest');
xlabel('Current')
ylabel('Vrms')
figure(11);
plot(toptemp2);
figure(12);
plot(topres2);
```