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Amplifier Design for New CNT Radiation Gauges in Expansion Tunnels

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Abstract

A new fast response amplifier was designed for a high resistance - low gain operation driving new Carbon Nano Tube thin film radiation gauges *'CNT-RAD'* in hypersonic expansion tunnel experiments. The amplifier response time was measured to be of the order of $1\mu s$, suitable for hypersonic flow experiments with test time of $100\mu s$. The amplifier system was designed with 6 channel capability, a constant voltage offset, and a constant gauge current. It was used successfully, powering and amplifying the signal from *CNT-RAD* gauges with average resistance of $7k\Omega$ and measuring radiative heat flux for a Titan $6.5km/s$ condition in the X2 expansion tunnel.

Sample results presented from the experimental campaign show raw voltage traces of radiative heat flux measurements made with the new *CNT-RAD* gauge and a radiation gauge with a nickel sensing element *TFHG-RAD*. Good signal to noise ratio levels were recorded with both gauges, with stable test time.

Introduction

Thin film heat gauges are used widely in impulse facilities, and turbomachinery research [1]. The sensing element is painted or sputtered on a substrate, and in a more advanced configuration is sputtered to a film that adheres to a complex blade shape. A new gauge was designed to measure radiative heat flux in the shock layer of a scaled model in an expansion tunnel. The gauge uses a Carbon Nano Tube (*CNT*) layer produced in a pyrolysis process as the sensing element of a thin film heat gauge design. It was designed to measure radiative heat flux in hypersonic flows typical of atmospheric entry into Titan, the moon of Saturn.

When a spacecraft enters the atmosphere of Titan, it needs to be protected from the high levels of aerodynamic heating in the shock layer. Convective and radiative heat transfer both need to be accounted for when designing a thermal protection system. While high levels of radiative heat transfer are normally associated with higher entry velocities, for Titan, the atmospheric content of nitrogen and methane contributes to higher levels of radiation at relatively low entry velocities of $6.5km/s$ [2].

The Centre for Hypersonics at The University of Queensland (UQ) has a series of impulse facilities that are used for research of superorbital atmospheric entry flows as well as scramjet development. The X2 and X3 free piston driven expansion tunnels are used to research atmospheric entry flows, and the T4 tunnel is used for scramjet research. The X2 expansion tunnel was used in this study, simulating a Titan $6.5km/s$ condition. The test gas used to represent Titan's atmosphere consisted of 95% N_2 and 5% CH_4, and the freestream enthalpy for this test condition was calculated to be $23MJ/kg$ [3]. This condition simulates peak radiation for Titan entry at the stagnation point, using a test flow with an equivalent flight velocity of $6.8km/s$, Mach 11 and $150\mu s$ of steady test time.

As the test time produced by free piston high enthalpy expansion tunnels is typically of the order of $100\mu s$, it requires the use of fast response equipment for all measurements. The X2 and X3 expansion tunnels use a National Instruments fast response data acquisition (DAQ) system for simultaneous sampling and recording of all measurements. For the reported experiments with the Titan $6.5km/s$ condition, the DAQ card PXI6133 was used, sampling data from a total of 19 channels at $2.5Mhz$. Data was recorded from pressure transducers, triggering signals and radiation gauges. A fast response amplifier to drive the radiation gauges was required to match the fast response DAQ system. The radiation gauges themselves also had to be capable of performing in such short test time. The amplifier used for the nickel thin film gauges HTG3 was designed at UQ with $350kHz$ capability but is limited to gauge resistance of up to 400Ω. Other facilities that use thin film gauges for turbomachinery research have developed custom made amplifiers to comply with application specific demands, such as the High Density Thin Film Heat Transfer Gauge Arrays described by [4].

Thin Film Carbon Nano Tube Radiation Gauge, *CNT-RAD*

A new thin film Carbon Nano Tube Radiation Gauge (*CNT-RAD*), was designed to measure radiative heat flux in the shock layer of a scaled model in an expansion tunnel. The gauge design (shown in Figure 1) was based on Nickel thin film radiation gauges developed by Capra at the University of Queensland [5]. In a radiation gauge configuration, the thin film heat gauge is mounted behind a viewing window, allowing it to measure only the radiative heat flux, where the sensing element is isolated from the convective heat flux. The new *CNT-RAD* gauges uses a Carbon Nano Tube (CNT) film as the sensing element.

The CNT coating was created at the Indian Institute of Science, in a newly developed pyrolysis process [6]. The coating of the substrate was performed in collaboration with IISc, following a procedure developed by Srinath [7]. The use of CNT introduces a great benefit for radiative heat flux measurement. The gauges are effectively black and can be calibrated for the amount of heat flux reflected from their surface. When metallic elements such as Nickel or Platinum are used, a black coating is applied to minimised reflection [5], but the thickness of the coating will effect the response time. Calibration of the radiation gauge that accounts for the black coating is challenging and further development is needed to improve techniques used [2, 5]. This is the main drive to use the CNT as the sensing element in a radiation gauge configuration.

With this benefit comes a challenge, the CNT film created has a high resistivity producing gauges with resistance of 2-10$k\Omega$. A new amplifier and power system had to be designed to be

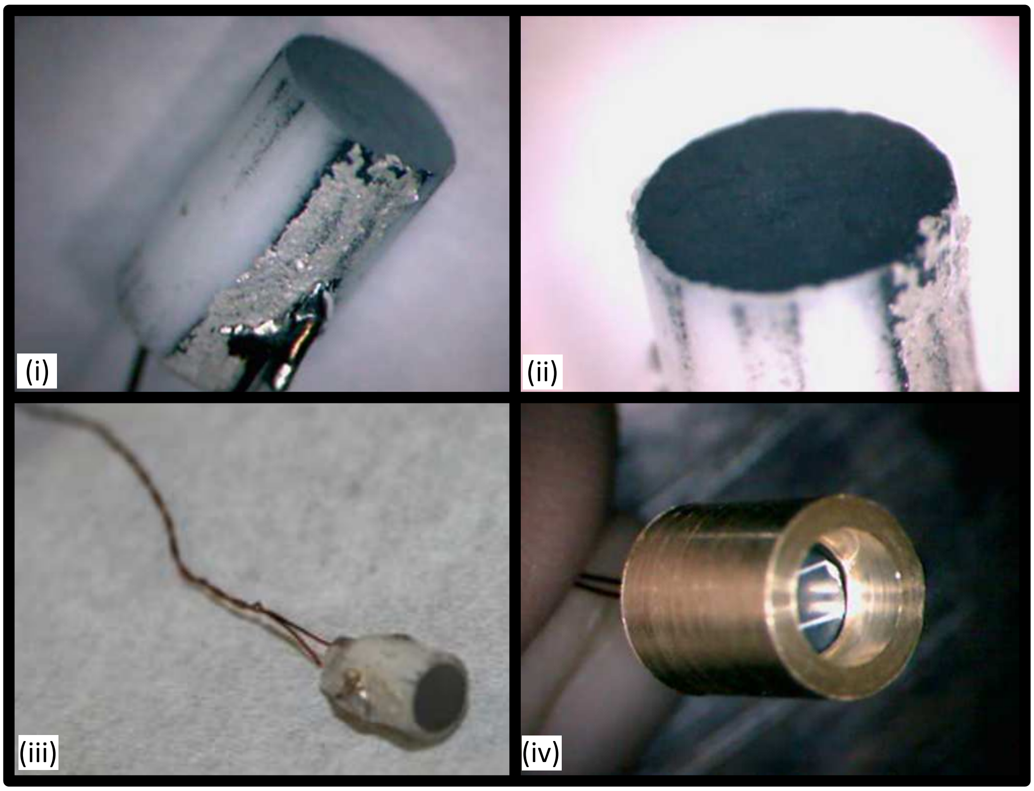

Figure 1: CNT-RAD radiation gauges (i) The polished face of the macor with the CNT coating (ii) The surface of the gauge and the silver connection tabs (iii) Insulated wires soldered to the silver tabs (iv) The assembled gauge in the brass housing behind a window

able to amplify the signal and yet keep a fast response time. The original system used for thin film gauges with a resistance of the order of 100Ω had to be completely redesigned for this purpose.

The *CNT-RAD* Constant Current Excited Gauge Amplifier

The amplifier was designed with fast response time capability to enable it to operate in the expansion tunnel environment with test time of $100\mu s$. Another key requirement addressed by the new design was high resistance operation range, to suit the *CNT-RAD* gauges with resistance range of 5-$10k\Omega$. The amplifier system was designed with 6 channel capability, a constant voltage offset, and a constant gauge current. The detailed design of the amplifier is discussed hereafter, outlining the considerations and the system performance achieved.

The common circuit diagram of the amplifier is shown on Figure 2. Details of the common circuit are shown, and connection to the six channels are also detailed for the first channel. The detailed circuit diagram for the first channel (channel #0) is shown on Figure 3, where the rest of the channels have an identical layout. Each channel circuit is configured for $0.5mA$ constant current excitation to drive the gauge. It also has a constant output offset voltage of -7.5 volts, to offset the output signal to fit the voltage range of the data acquisition system ($\pm 10V$). The circuit diagrams were annotated according to standard common practices for circuit diagrams, and this notation is referenced in this section.

The resistance of the gauge can be calculated using

$$R_g = \frac{V_{out} + V_{OS}}{GAIN \times I} \qquad (1)$$

where $V_{OS} = 7.5V$ is the voltage to be added to the output signal to remove the offset voltage, $GAIN = 3$ is the amplifier signal gain, and $I = 0.0005A$ is the constant excitation current. This circuit configuration allows the gauge resistance to be determined from the output signal both before and during the experiment.

The common six channel circuit consists of two $2.5V$ references (inner circuits with *Z1* and *Z2* on Figure 2). The current reference *Z2* is a reference voltage which is $2.5V$ less than the $+15V$ supply. This reference voltage is connected to the *+ve* input of *U1A*. The amplifier drives the current controlled transistors *Q1 & Q2* to establish a $2.5V$ voltage at the bottom of *R13*, which is relative to the $+15V$ supply. The combined resistances of *R13, R12 & R19* is set to a nominal $5k\Omega$ with $2.5V$ across the $5k\Omega$ resistance, which results in $0.5mA$ flowing in the circuit to the gauge, provided the gauge resistance is in the range of 0 to $11.6k\Omega$.

This range of resistances was determined by calculating the highest amplified voltage that the $\pm 10.00V$ data acquisition system can process. The transistors ensure that a constant static and dynamic current is maintained in the gauge resistance. The gauge is coupled to the junction of *R10* and *R21*, and circuit common ground. The resistor *R21* couples the gauge voltage signal to the gauge output amplifier input terminal. The offset amplifier *U1B* amplifies the second reference of $+2.5V$ voltage (from *Z1*) to a nominal $7.5V$ signal to provide the output offset signal of $-7.5V$ at the gauge amplifier *U2* output. The two reference voltages *Z1 & Z2* are individually trimmed for minimum drift performance, and are distributed to each of the six gauge circuit channels.

The output amplifier gain of three is determined by the three precision resistors, *R22*, *R23*, *R24*. This section describes how the gain of the two amplifiers *U1* and *U2* is applied (where *U1* consists of two parts, $U1A \& U1B$). The output amplifier gain

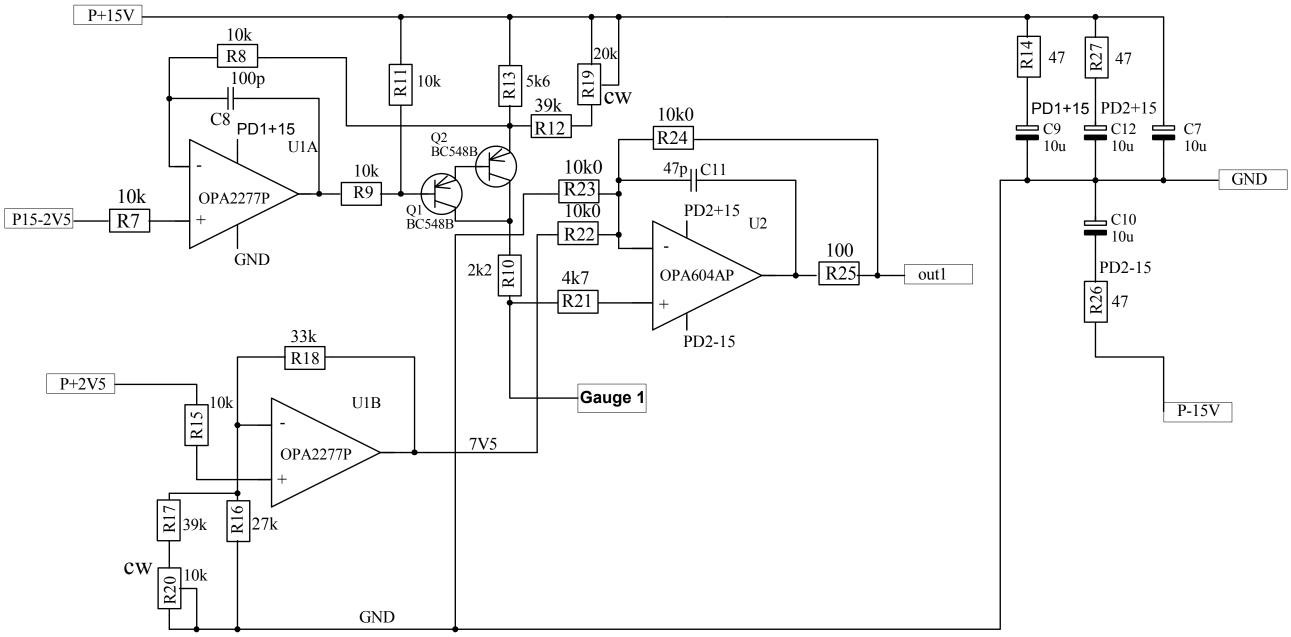

Figure 3: Circuit diagram for channel #0, where for the amplifier each of the 6 channels is identical to this one. All resistors are marked by a serial number (R8, R9 etc.) and the value of the resistance is also notes alongside other details of the design, in accordance with common circuitry conventions.

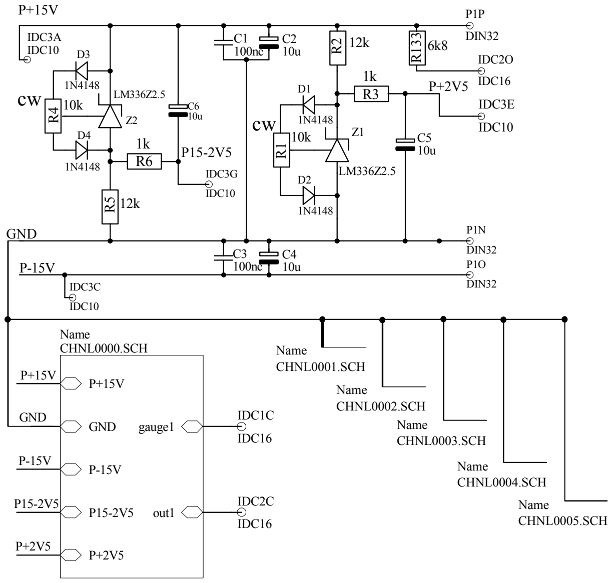

Figure 2: The common amplifier circuit diagram. Note that connections to channel #0 are shown in detail, and the rest of the 5 channels are wired in the same way.

for *U2* (shown in Figure 3) is controlled by the resistor *R23*, in combination with the resistors *R22* and *R24*. The *R22* and *R24* values are established from the offset voltage requirements, and form part of the stage gain. For a required voltage gain, the value for *R23* can be found from

$$R23 = \frac{1}{\frac{1}{\frac{R24}{GAIN_{U2}}} - \frac{1}{R22} - \frac{1}{R24}} \tag{2}$$

The offset amplifier *U1B* (shown on Figure 3) has a gain of three to convert reference voltage P+2V5 (Figure 2-3) from +2.5V to +7.5V. The gain from the combined resistance value of *R16, R17, R20* can be calculated from

$$GAIN_{U1B} = \frac{R18}{\frac{1}{\frac{1}{R18} + \frac{1}{R16} + \frac{1}{R17+R20}}} \tag{3}$$

This is a standard calculation that applies for a non-inverting operational amplifier circuit. The current control amplifier *U1A* has a gain of unity and is a buffer between the current reference voltage P+2V5 and the current driving circuit of (*Q1, Q2* and the combined value of *R13, R12, R19*). The resistor *R8* does not load the combined resistance value established by *R13, R12, R19.*

The overall circuit zero is controlled by the offset amplifier *U1B* gain trim *R20*, and the overall sensitivity is controlled by the gauge excitation current trim of *R19.* The output amplifier signal ranges form -7.5V to +7.5V for gauge resistance from 10$k\Omega$ down to 0Ω respectively. The power supplies used are well regulated $\pm 15V$ supplies, for suitable circuit stability. Replacing the two bipolar transistors used as the current control device, to a mosfet device, can improve the amplifier step response to 1/3μs or better for a 5$k\Omega$ resistance gauge.

Experimental Traces

For the first experiments with the new *CNT-RAD* gauges, a 75mm long cylindrical model was fitted with two *CNT-RAD* gauges, and set up in the test section of the X2 expansion tunnel. Previous experiments by the author with Nickel based Thin Film Heat Gauges in the same configuration [2] were successful in generating measurable signal, but calibration issues were not fully resolved. Hence this was chosen to be a proof of concept condition for the new CNT thin film gauges. The *CNT-RAD* gauges were connected to the *CNT-RAD* amplifier, and the output was fed to the DAQ system. The amplifier performed well, powering and amplifying the first signal from *CNT-RAD* gauges. Radiative heat flux was measured for the Titan 6.5km/s condition in the X2 expansion tunnel for the first time using the newly developed *CNT-RAD* gauges.

Figure 4 shows raw voltage traces from the experimental campaign for one shot where a *CNT-RAD* gauge was mounted alongside a *TFHG-RAD* gauge for qualitative comparison (amplification and offset differ between gauges). The signal of the *CNT-RAD* gauge shows the CNT inverse response to the heat flux, which differs from the behaviour of the nickel sensing element of the *TFHG-RAD* gauge. The start of the test time can be placed at $2125\mu s$, where a parabolic response indicates a constant value of heat flux (when integrating the voltage according to the semi infinite substrate theory given by [8]). Preliminary heat flux and temperature results are plotted on Figure 4, showing the calibrate *CNT-RAD* gauge against results from *TFHG-RAD* (where the later was not calibrated for radiative heat flux).

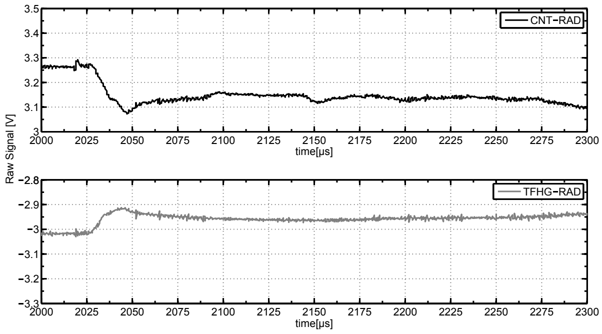

Figure 4: Trace of raw voltage from the experimental campaign, showing the measured raw voltage by *CNT-RAD* & *TFHG-RAD* gauges mounted on a cylindrical model in a Titan $6.5km/s$ flow.

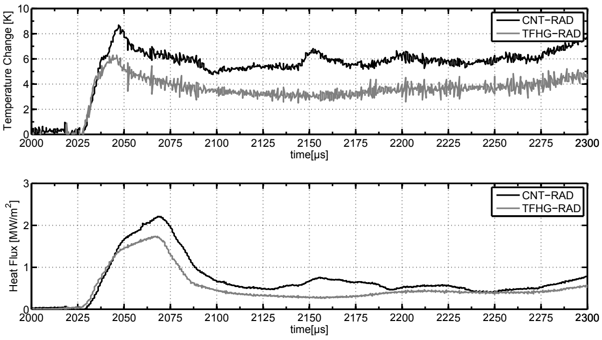

Figure 5: Preliminary calibrated heat flux and temperature processed data from the experimental campaign, showing the measured results from *CNT-RAD* & *TFHG-RAD* gauges mounted on a cylindrical model in a Titan $6.5km/s$ flow.

The heat flux calculated from the *TFHG-RAD* gauges throughout the experimental campaign varied from 50% to 60% of the heat flux measured by the *CNT-RAD* gauges, reaffirming the need for calibration of the nickel based gauges. As expected due to the inherent black coating of the CNT gauges, the measurement was consistently higher. The *CNT-RAD* gauges were stable enough to produce a useful result, however, the signal from the *TFHG-RAD* was cleaner and more stable in comparison. It is postulated that improving the quality of the *CNT* coating, by refining the pyrolysis process, will improve the new gauges performance.

Conclusions

A new design of thin film radiation gauges was developed with Carbon Nano Tube thin film. The *CNT-RAD* radiation gauges were designed to operate in an expansion tunnel environment, and required an amplifier that can handle high resistances as well as fast response time operation. The *CNT-RAD* amplifier was designed for that purpose. It was used successfully, powering and amplifying the signal from *CNT-RAD* gauges and measuring radiative heat flux for a Titan $6.5km/s$ condition in the X2 expansion tunnel. The use of *CNT* as the measuring thin film element for a radiation gauge in hypersonic high enthalpy flow was successful. The main benefit of the new gauge was the ability to calibrate the radiative heat flux absorbed by the black *CNT* coating. Future refinement of the pyrolysis process that was used to crate the film, has potential to improve the gauges stability and performance.

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References

[1] Oldfield, M.L.G, Impulse Response Processing of Transient Heat Transfer Gauge Signals, *Journal of Turbomachinery*, ASME, **130** , 2008, 021023–021023.

[2] Porat, H., Morgan, R.G. and McIntyre, T.J., Study of Radiative Heat Transfer in Titan Atmospheric Entry, in *18th Australasian Fluid Mechanics Conference*, Launceston, 2012.

[3] Porat, H., Sheikh, U., Morgan, R.G., Eichmann, T.N. and McIntyre, T. J., Vacuum Ultraviolet and Ultraviolet Emission Spectroscopy Measurements for Titan and Mars Atmospheric Entry Conditions, in *44th AIAA Thermophysics Conference*, San Diego, 2013.

[4] Anthony, R. J., Oldfield, M. L. G., Jones, T. V., and LaGraff, J. E., Development of high-density arrays of thin film heat transfer gauges., *JSME Thermal Engineering Joint Conference*, Paper No. AJTE99-6159, 1999.

[5] Capra, B. and Morgan, R.G., Radiative and Total Heat Transfer Measurements to a Titan Explorer Model, *Journal of Spacecraft and Rockets*, **49(1)** , 2012,12–23.

[6] Mahanandia, P. and Nanda, K.K., A one-step technique to prepare aligned arrays of carbon nanotubes, *Nanotechnology*, **19** , 2008.

[7] Srinath, S. and Reddy, K.P.J., Experimental Measurement of Aerodynamic Heat Transfer Due to Radiative Transmission in High Enthalpy Flow around a Re-entry Model, in *29th International Symposium on Shock Waves*, Madison, 2013.

[8] Schultz, D. L. and Jones, T. V., *Heat Transfer Measurements in Short Duration Hypersonic Facilities*, AGARD-AG-165, 1973.