CONTROL SYSTEM FOR HOT WIRE ANEMOMETRY

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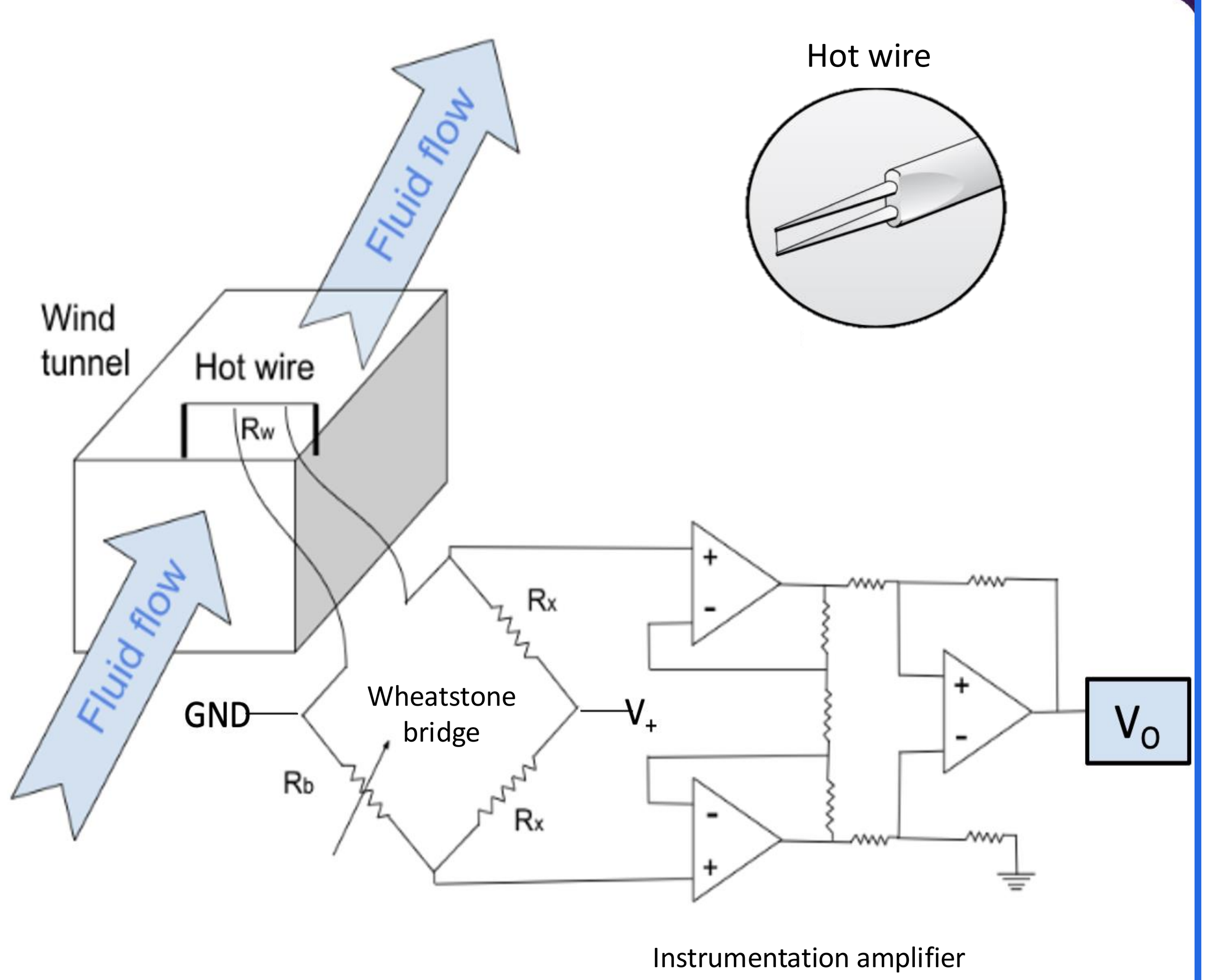
PROBLEM DEFINITION & BACKGROUND

Turbulent Fluid Flow is Ubiquitous but Difficult to Measure

Fig. 1. This is an example of a turbulent flow. It shows eddies and vortices that are both on the centimeter and the millimeter range. [1]

Turbulent flows are characterized by eddies and vortices that are formed due to fluctuations in fluid velocity. Measuring turbulence implies capturing such velocity fluctuations. Traditional fluid velocity measurement techniques like Pitot tubes are not fast enough to capture these fluctuations.

Using a Hot Wire to Measure Turbulent Fluid Flow



DESIGN REQUIREMENTS

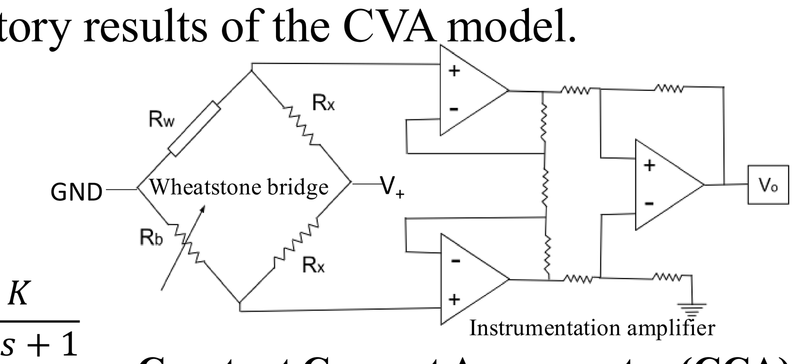
Air flows at 10 – 15 m/s can contain velocity fluctuations up to 15 kHz. In hot wire anemometry, a thin wire (5 μm thick and 2 mm long, usually platinum) is submerged in a flow and comprises a leg of Wheatstone bridge (Rw). Current is supplied to the microscale wire through the Wheatstone bridge. While this current produces Joule heating in the wire, fluid flowing over it convects the heat away causing Rw to change. Therefore, by using principles of heat transfer and electronics, V_0 measured can be correlated with flow velocity to extract high frequency content. However, the ability to measure high frequencies is dependent on the properties of the wire and electrical system, which must be characterized.

DESIGN ALTERNATIVES

The design alternatives considered in this project are Constant Current Anemometer (CCA), Constant Voltage Anemometer (CVA), and Constant Temperature Anemometer (CTA). The CCA circuit does not provide high enough temporal resolution to extract high frequency content from the velocity fluctuations. The CTA and CVA employ feedback mechanisms to improve the temporal resolution. CTA is significantly more complex than the CCA and is not feasible to analyze in the constrained time. Therefore, the below sections fully characterize CCA, CVA, and outline the satisfactory results of the CVA model.

The circuit diagram alongside is the CCA circuitry. Resistors Rx's are in 10's of kilo-ohms to ensure constant current through Rw (wire) is constant. As Rw changes due to heat convection in fluid flow, voltage across the bridge is captured via an Instrumentation amplifier. The differential equation governing the dynamics of the hot wire and the circuitry is used to obtain the transfer function (TF) ($\Delta R_w/\Delta u$) of the CCA model; the TF is a relationship of the change in wire resistance for a step change in fluid velocity. The TF helps in determining the step response of the CCA or CVA system which elucidates the frequencies the system can resolve. The parameter K is governed by the gain of the op-amp, ratio of Wheatstone bridge resistors, and fluid properties of air while τ_w is determined by the thermal properties of the wire. s is Laplace the variable.

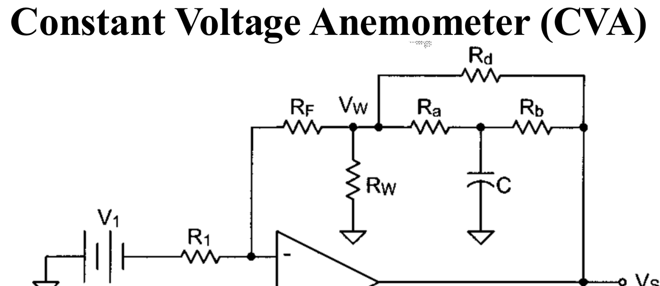
$$\frac{\Delta R_w}{\Delta u}(s) = -\frac{K}{\tau_w s + 1}$$



Constant Current Anemometer (CCA)

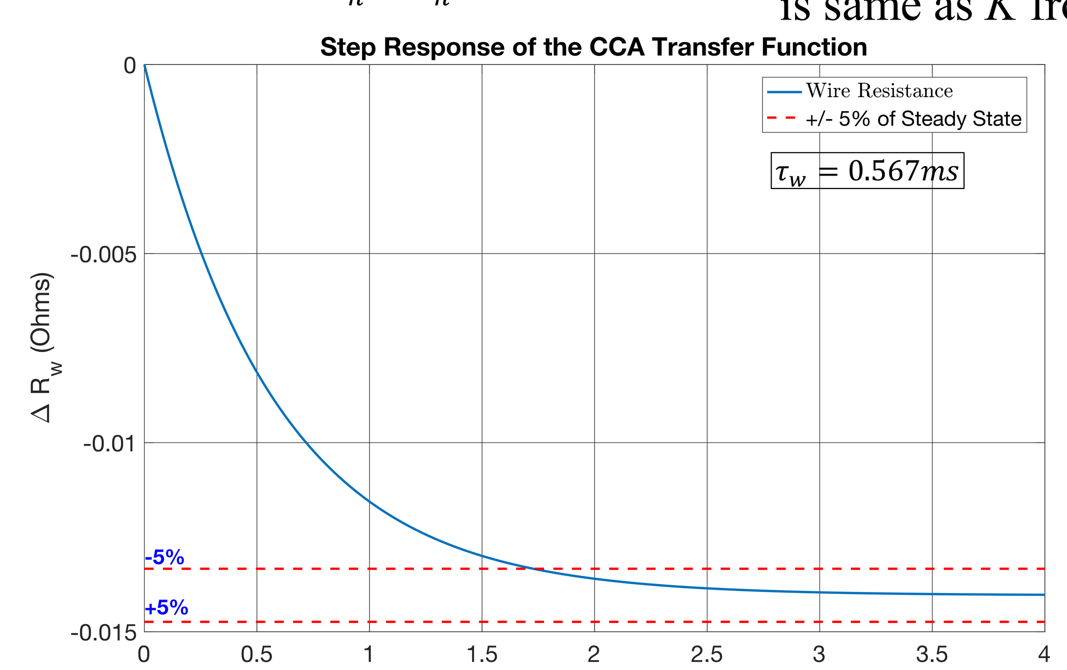
FINAL DESIGN & IMPLEMENTATION

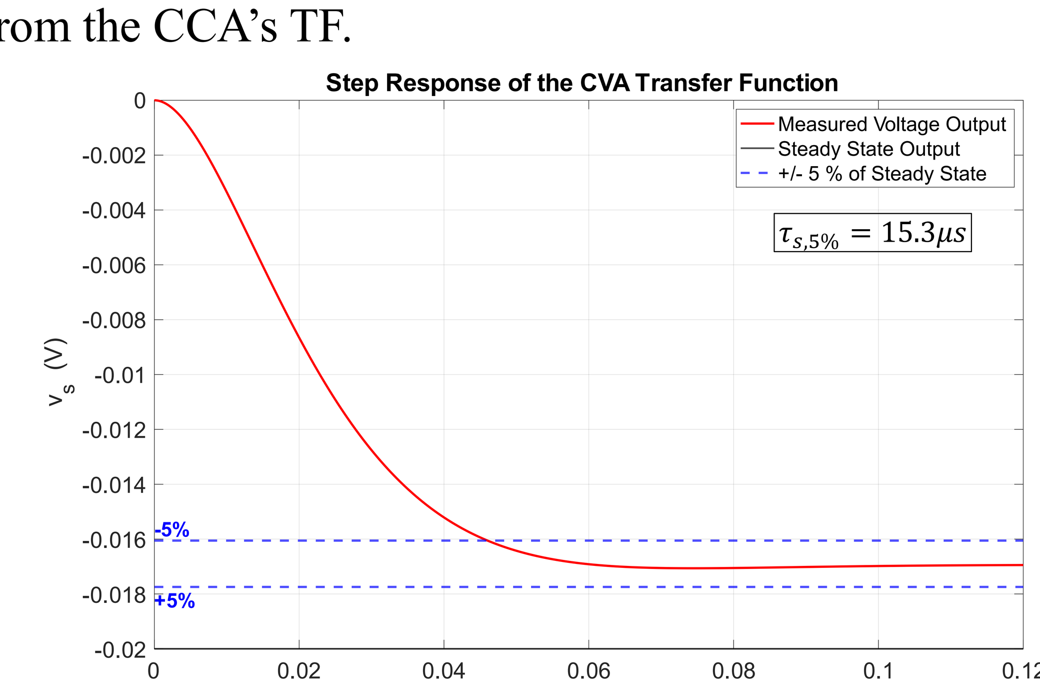
Constant Voltage Anemometer (CVA)



$$\frac{v_s}{u}(s) = \frac{A}{\frac{s^2}{\omega_n^2} + \frac{B}{\omega_n^2}s + 1}\frac{(1+T_c s)}{(1+\tau_w s)}K'$$

The CVA model ensures the voltage across Rw (wire) is constant. The advantage of CVA over CCA is that the CVA can be tuned to give a desired performance whereas the CCA's characteristics are mainly set by the wire's thermal properties (τ_w). The equation alongside is CVA's TF representing the change in measured voltage (v_s) for a step change in flow velocity, u. A is ratio of R2, Rw, and current through Rw and B is depends on Rd, gain-bandwidth product of the op-amp and Tc. K' is same as K from the CCA's TF.





Above are the step responses of CCA's (left) and CVA's (right) step response. The 95% criteria (system reaches 95% of steady state response in three time constants of time) is used to extract time constants of the systems. The time constant, τ_{CCA} of CCA is 0.567 ms. This corresponds to a -3dB frequency of 280 Hzn(-3dB frequency is the frequency at which the system produces a signal attenuation of -3dB). However, the velocity fluctuation the needed to be resolved are upto 15 kHz. The CVA has a settling time, $\tau_{s,5\%} = 15.3\mu s$. This corresponds to -3dB frequency of 10.4 kHz, which is a significant improvement from the CCA. The feedback resistors and capacitors (Ra, Rb, Rd and C) can be tuned to introduce a zero at the location of the wire's pole iso that the dynamics are dominated by op-amp's and Rd's feedback response, encapsulated by B and Tc, which are again determined during the fine-tuning process. The top right figures show experimental results of the CCA and CVA circuits. The CCA graph (left) follows the King's law (a power law relationship) between the measured voltage and flow speed. Similarly, the CVA also follows a power law relationship between the measured voltage and wire resistance. These are the calibration curves that can now be used to estimate wind speed after measuring voltages over some time.

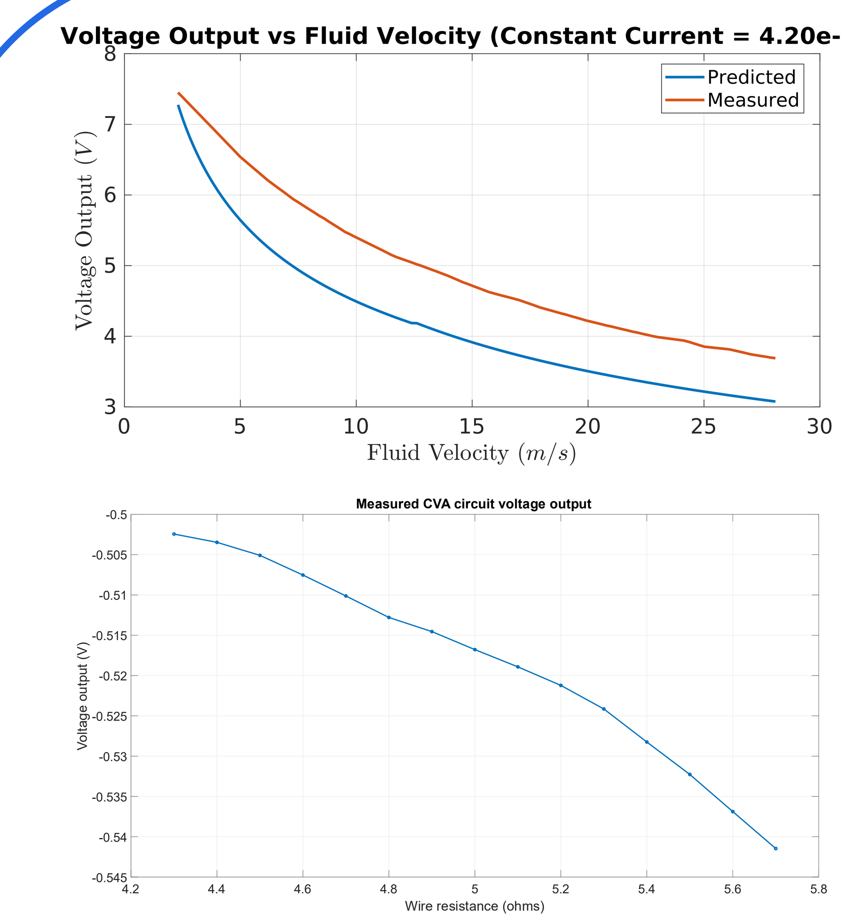


Fig. 2. Top and bottom show figures CCA and CVA operation respectively. Both are callibration curves that can be used to estimate wind speed or wire resistance from voltage measurements.

DESIGN EVALUATION & ITERATIVE PROCESS

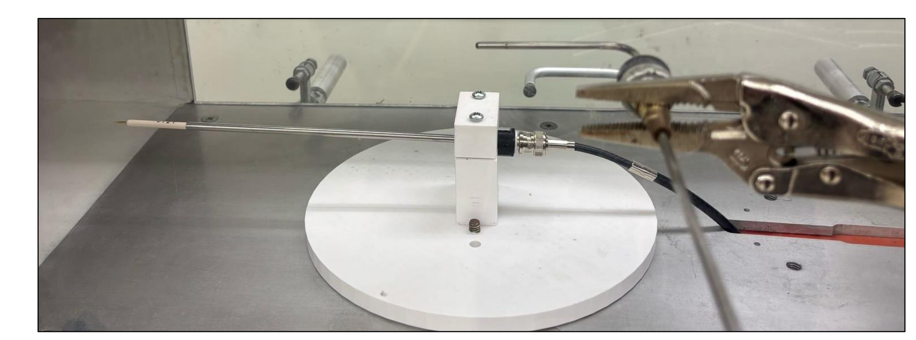


Fig. 3. Hot wire in a wind tunnel for collecting experimental data.

Research was done to understand each of the design alternatives identified – constant current (CCA), constant temperature (CTA), and constant voltage (CVA). For CCA, thermal balance equation guided the analysis in obtaining the transfer function and step response. The wire's first order system combined with the CVA's op-amp response resulted in a higher order transfer function. This transfer function was compensated and finally tuned to give the desired response. The developed circuit was tested in the wind tunnel as shown in Fig. 3.

DISCUSSION, CONCLUSION & RECOMMENDATIONS

Discussion and Conclusion. This project designed, analyzed, and tested two modes of hot wire anemometry, CCA and CVA. The response of CCA has a -3dB frequency of 280 Hz, which is cancelled with a zero in the compensated circuit of the CVA (-3dB @ 10.4 kHz). This results in a much faster response in CVA, one that can be tuned as per the needs of a research lab. This project provides a robust and inexpensive means of hot wire anemometry to small research laboratories that may not be able to afford industrial anemometers

Recommendations. In the future CCA and CVA's step response could be captured in a Wind Tunnel. In addition, the Constant Temperature Anemometer should be characterized. Finally, the advantages and disadvantages of CCA, CVA, and CTA should be cataloged systematically.

REFERENCES

[1] EUMeTrain, "Case Study: 7 July 2004 – Convective Storm in Central Europe," *EUMeTrain Resources*, Apr. 2025. [Online]. Available: https://resources.eumetrain.org/data/3/304/navmenu.php?tab=3&page=6.0.0

[2] G. R. Sarma, "Transfer function analysis of the constant voltage anemometer," Review of Scientific Instruments, vol. 69, no. 6, pp. 2385–2391, Jun. 1998, doi: 10.1063/1.1148964.