Lecture #06 Hotwire anemometry: Fundamentals and instrumentation

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Sources/ Further reading:
Tropea, Yarin, & Foss, "Springer Handbook of Experimental Fluid Mechanics," Part B Ch 5.2
Jorgensen, "How to measure turbulence with hot-wire anemometers—a practicle guide," Dantec Dynamics

Technical Fundamentals -1

Thermal anemometers

- Measure the local flow velocity through its relationship to the convective cooling of electrically heated metallic sensors.
- Hot wire anemometers: for clean air or other gas flows

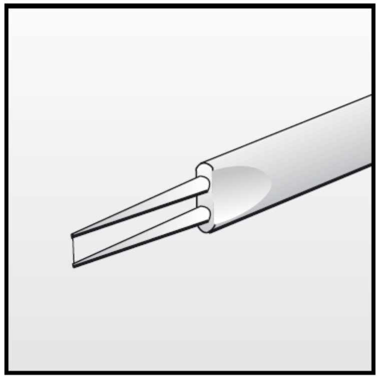

Fig. 1. 5 µm dia. plated tungsten wire, welded to the prongs.

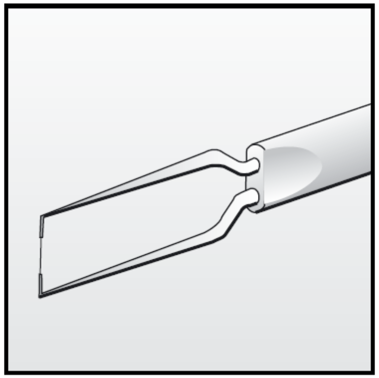

Fig. 2. 5 µm dia. plated tungsten wire, gold-plated at the ends to provide active sensor length of 1.25 mm.

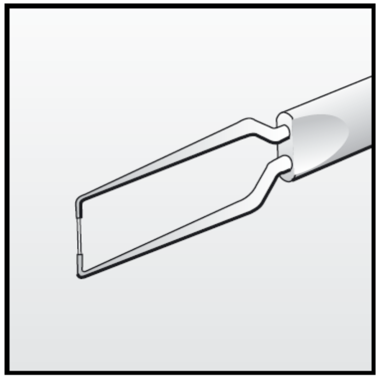

Fig. 3. 70 µm dia. quartz fiber with nickel film, gold plated at the ends to provide active sensor length of 1.25 mm.

- Hot film anemometers: for liquid or some gas flows

Fig. 4. Tip of conical probe.

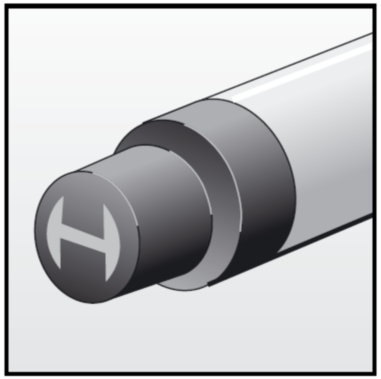

Fig. 5. Tip of flush-mounting probe.

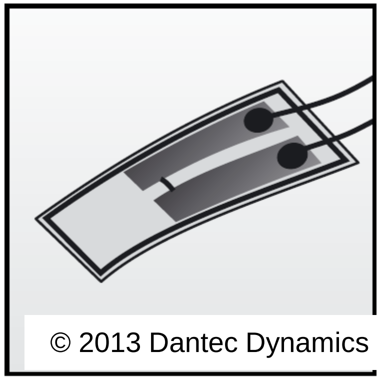

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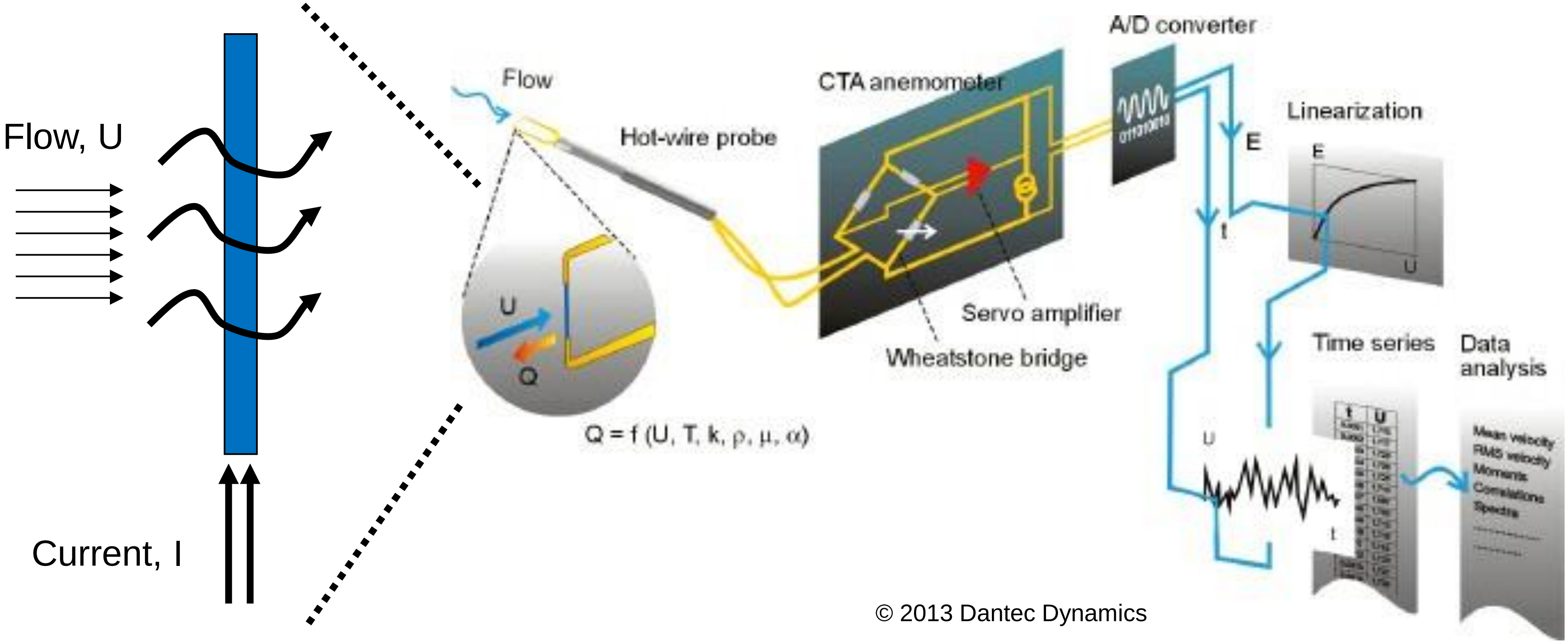
Fig. 6. Glue-on probe.

Hot wire sensor operation

The electric current (i) flowing through the wire generates heat ($I^2 R_w$). In equilibrium, this must be balanced by heat lost (primarily convective) to the surroundings.



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Hot wire sensor operation

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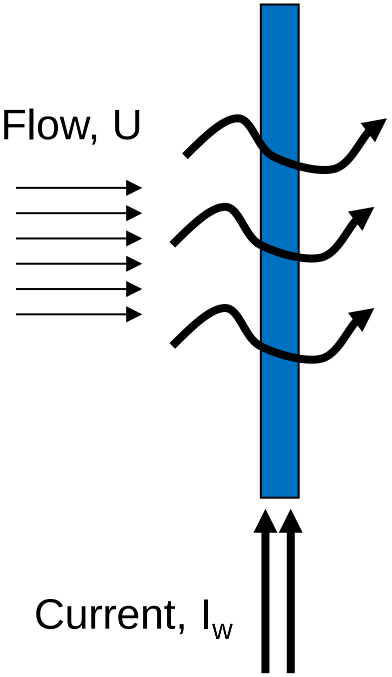


$$R_w I_w^2 = (T_w - T_a)\Phi_{conv}(U)$$

R_w – resistance of hot wire
I_w – current through hot wire
T_w – hot wire temperature
T_a – ambient temperature

$$a_w = \frac{R_w - R_a}{R_a} \sim (T_w - T_a)/T_a$$

R_a – wire resistance at ambient conditions
a_w – overheat ratio

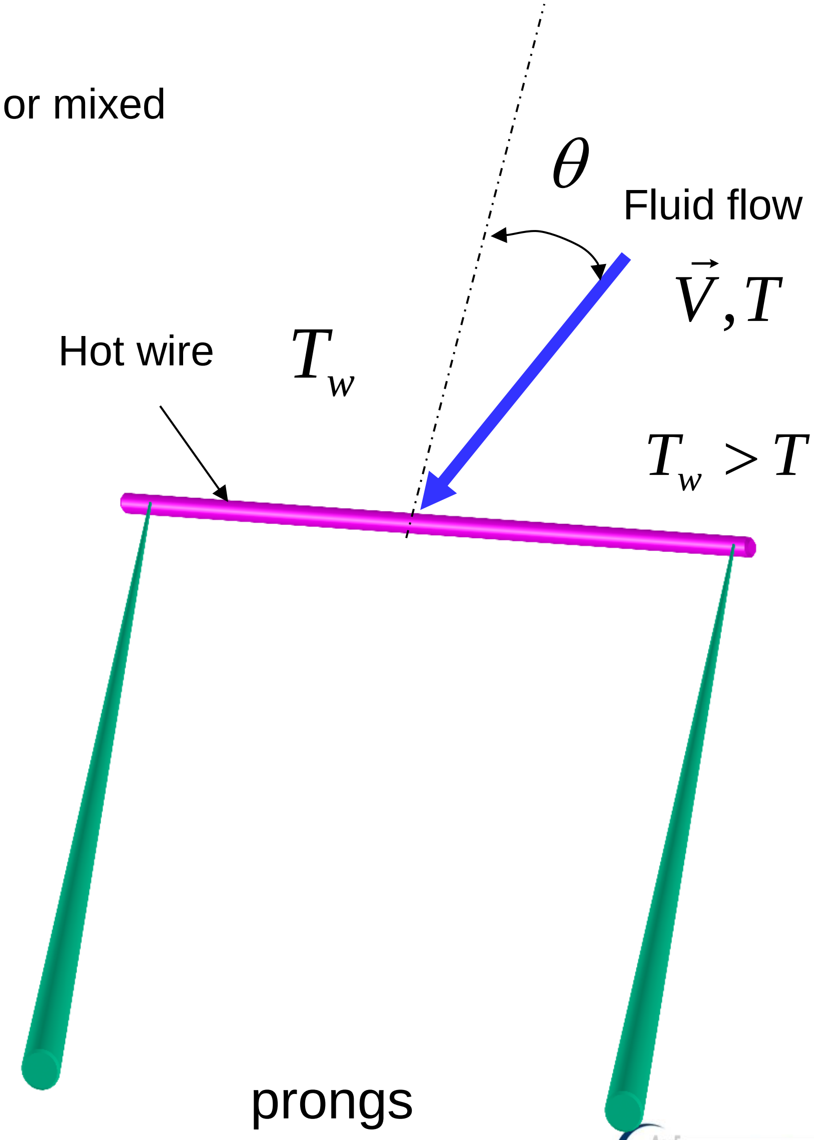
For unsteady flow: (m – mass, c – heat capacity)

$$m_w c_w \frac{dT_w}{dt} = R_w I_w^2 - (T_w - T_a)\Phi_{conv}(U)$$

Technical Fundamentals

Heat transfer characteristics:

- Convection (natural convection, forced convection, or mixed convection depending on Richardson numbers)
- Conduction to the supporting prongs
- Radiation: <0.1%, is negligible.



$$Nu = \frac{\dot{q}}{\pi d k (T_w - T)} = Nu(\mathrm{Re}, \mathrm{Pr}, Gr, M, Kn, a_T, l/d, \theta)$$

$$\mathrm{Re} = \frac{\rho U d}{\mu}; \qquad \mathrm{Pr} = \frac{\nu}{\gamma}$$

$$Gr = \frac{g\alpha (T_w - T) d^3}{\nu^2}; \qquad M = \frac{V}{c}$$

$$Kn = \frac{\lambda}{d} = \sqrt{\frac{1}{2}\pi c_p / c_v}\,\frac{M}{\mathrm{Re}}$$

$$a_T = \frac{T_w - T}{T}$$

Technical Fundamentals

Following King's Law (1915),

$$Nu = (A + B\,\mathrm{Re}^{n})(1 + \frac{1}{2} a_T)^{m}$$

According to Collis and Willams (1959):

$$Nu = (0.24 + 0.56\,\mathrm{Re}^{0.45})(1 + \frac{1}{2} a_T)^{0.17}, \qquad for \quad 44 < \mathrm{Re} < 140$$

$$Nu = 0.48\,\mathrm{Re}^{0.51})(1 + \frac{1}{2} a_T)^{0.17}, \qquad for \quad 0.02 < \mathrm{Re} < 44$$

For a given sensor and fixed overheat ratio, the above equation establishes the relationship between the voltage output, E, of the hot-wire operation circuit and the flow velocity

$$\frac{E}{T_w - T} = A + BV^{n}$$

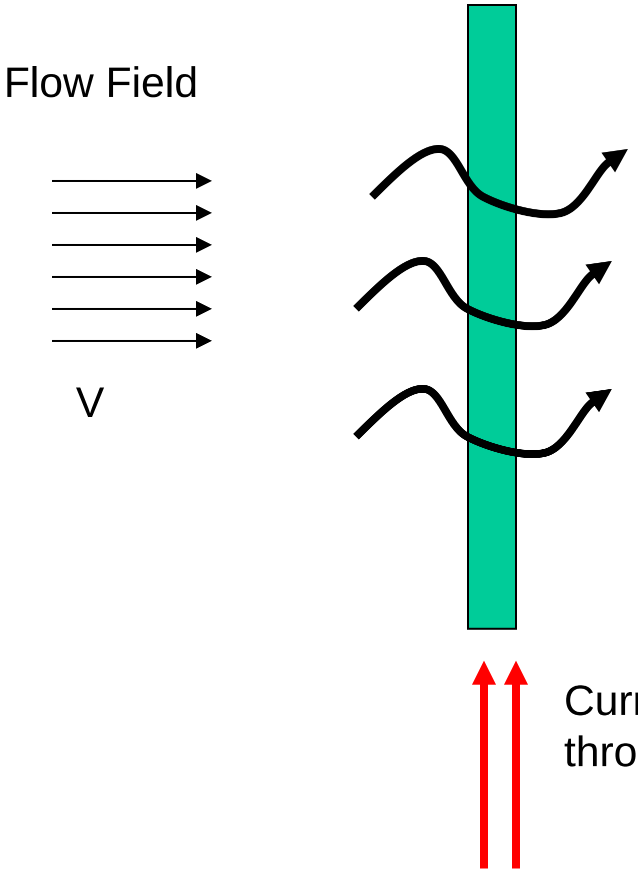
Wire temperature cannot be measured directly, but can be estimated from its relationship to the wire resistance, R_w, directly measured by the operating bridge.
For metallic wires:

$$R_w = R_r[1 + a_r(T_w - T)]$$

a_r:thermal resistivity coefficient

T_r:reference temepature

Technical Fundamentals



The hot wire is electrically heated.

If velocity changes for a unsteady flow, convective heat transfer changes, wire temperature will change and eventually reach a new equilibrium.

The rate of which heat is removed from the sensor is directly related to the velocity of the fluid flowing over the sensor

Technical Fundamentals

- For a sensor placed in a unsteady flow, the unsteady energy equation will become:

$$mc\frac{dT_w}{dt} = i^2 R_w - \dot{q}(V, T_w)$$

m: the mass of the sensor

c : specifich heat of the sensor

$\dot{q}$: convective heat flux $\dot{q}=\dot{q}(V,T_w)$

The above equation has three unknowns: i, T_w (or R_w) and V

To render this equation solvable, one must keep with the electric current, i, or the sensor temperature (T_w) constant, which can be achieved with the use of suitable electric circuits.

The corresponding methods are known as:
(1). Constant-current anemometry
(2). Constant-temperature anemometry

Constant-current anemometry

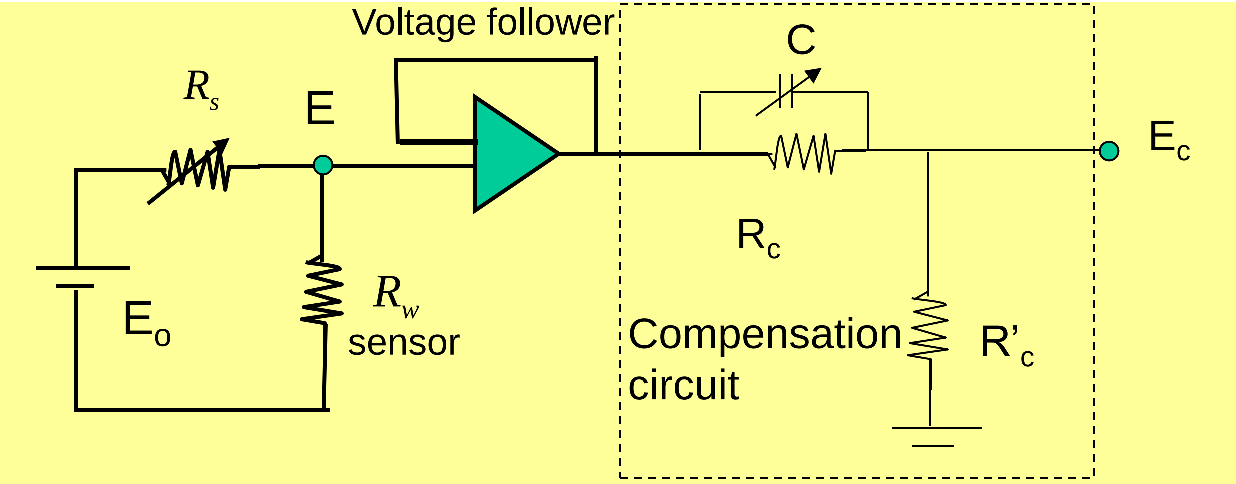
$R_s >> R_w$

$$i = E_o / (R_s + R_w)$$
$$\cong E_o / R_s \cong const$$

The voltage output will be

$$E = i \bullet R_w$$

The unsteady energy equation is highly-nonlinear.



When linearized in the vicinity of an operation point, namely at a particular flow speed, V_{op}, and sensor temperature, T_{wop} , it leads to the following first-order differential equation:

$$\tau_w \frac{dT_w}{dt} + (T_w - T_{wop}) = K_T (V - V_{op})$$

τ_w : a time constant, which is proportional to the overheat ratio, and a static sensitivity, K_T

Since voltage, E, is proportional to, Rw , which, in turn, is linearly related to T_w, the linearized E-V relationship will be:

$$\tau_w \frac{dE}{dt} + (E - E_{op}) = K(V - V_{op})$$

τ_w : is usually ~ 1ms for thin hot-wire and ~ 10 ms for slim cylindrical hot-film.

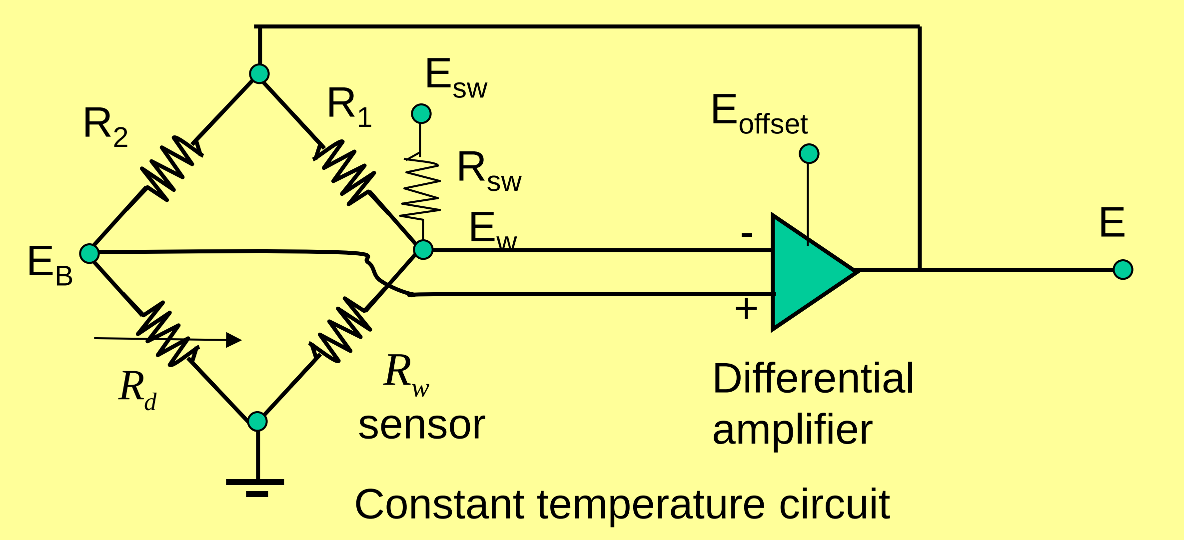
For flow with variable velocity or temperature, overheat ratio will vary as well.
Flow low speed flow, it may result in "burnout", for high-speed flow, sensitivity is low

Constant-temperature anemometry (CTA) - 1

- Electric current through the sensor is adjustable continuously through an electric feedback system, and in response to the changes in convective cooling, to make the temperature of the hot wire keep in constant.
- The unsteady energy equation becomes steady equation
- Dynamic response of the anemometer is the same as its static response with a wide frequency range.

$$mc\frac{dT_w}{dt} = i^2R_w - \dot{q}(V,T_w) \Rightarrow i^2R_w - \dot{q}(V) = 0$$

Constant-temperature anemometry (CTA)-2



Constant temperature circuit

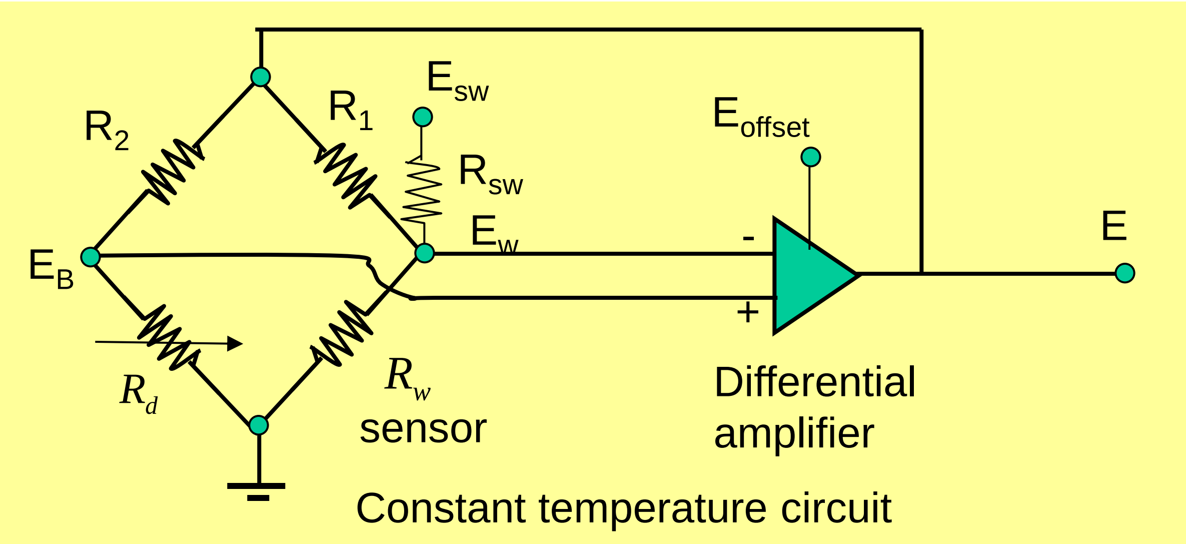
- Sensor, R_w, comprises one leg of the Wheatstone bridge.
- An adjustable decade resistor array, R_d, compress opposite leg of the bridge.
- The bridge ratio R_2/R_1 is fixed, and $R_2/R_1 \approx 10\sim20$ to make sure to supply most of the available power to the sensor
- The two midpoints of the bridge are connected the input of a high-gain, low noise differential amplifier, whose output is fed back to the top of the bridge.
- If $R_2/R_d = R_1/R_w$, then $E_B - E_w = 0$, the amplifier output will be zero.
- If R_d is increased to a value R'_d, the resulting bridge imbalance will generate an input imbalance to the amplifier.
- The amplifier will create some current through both legs of the bridge. The additional current through the hot wire will create additional joule heating, which tend to increase its temperature and thus its resistance, until the resistance increases sufficiently to balance the bridge once more.

Constant-temperature anemometry (CTA)-3

Temporal response determined by electronics.

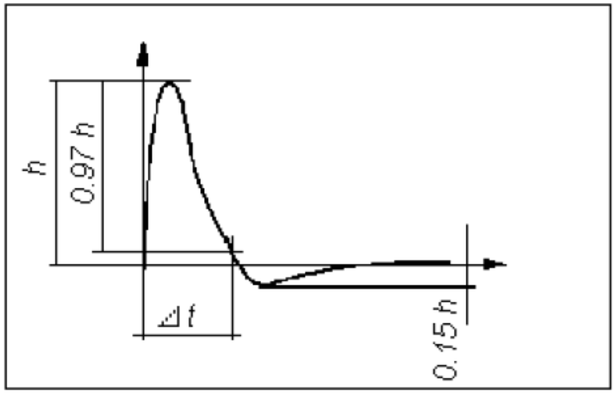
Sensor bandwidth is set using the square-wave test:

- Expose probe to velocity
- Connect oscilloscope
- Apply square wave to bridge
- Adjust filter and gain for 15% undershoot
- Determine Δt for 3% regulatio
- Determine bandwidth (-3 dB): $f_c = \dfrac{1}{1.3 \cdot \Delta t}$ (wire probes) $f_c = \dfrac{1}{\Delta t}$ (fibre-film probes)

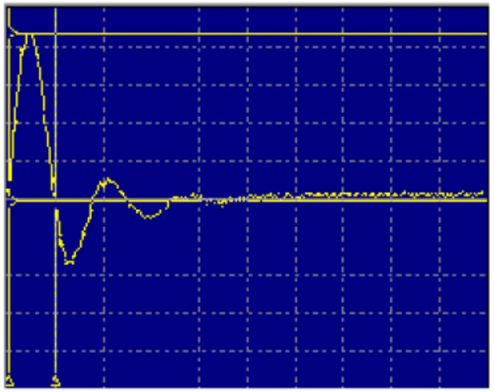


Constant temperature circuit

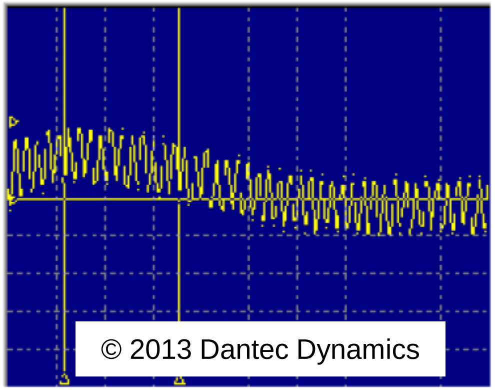
Correct square wave test, U= 30 m/s



Too high gain



Too long cable (10 m instead of 5 m)



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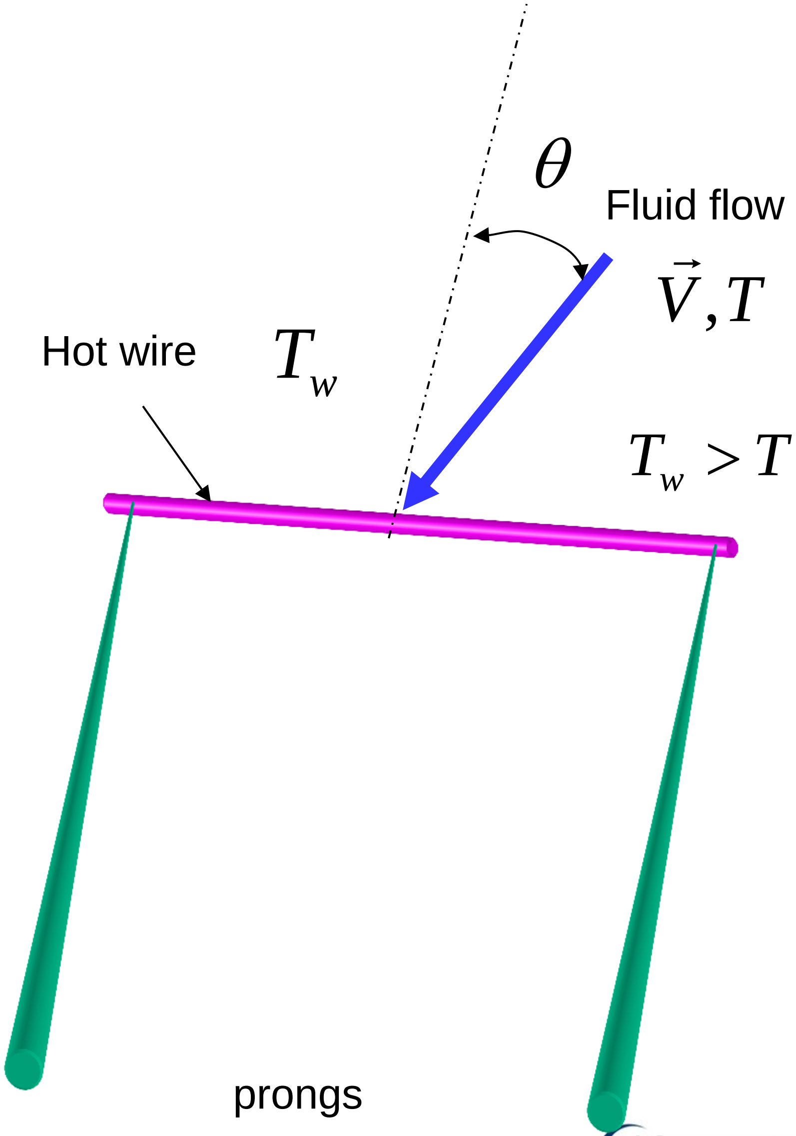
Various effects and error source

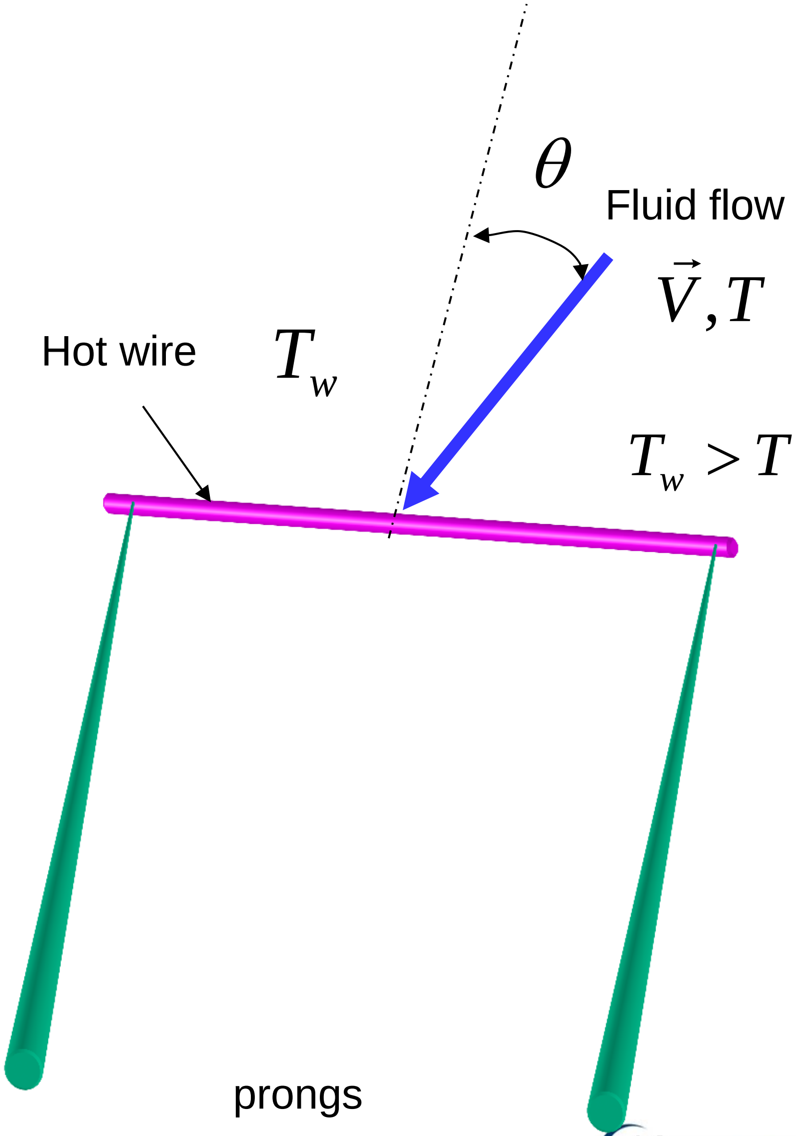
- Velocity orientation effects:
  - Effective cooling velocity

    $V_{eff} = V \cos\theta$.
  - In reality, flow velocity tangential to the sensor would result in cooling.
  - $V_{eff} = V (\cos^2\theta + k^2 \sin^2\theta)^{1/2}$
  - Typical values of k^2 are 0.05 and 0.20.



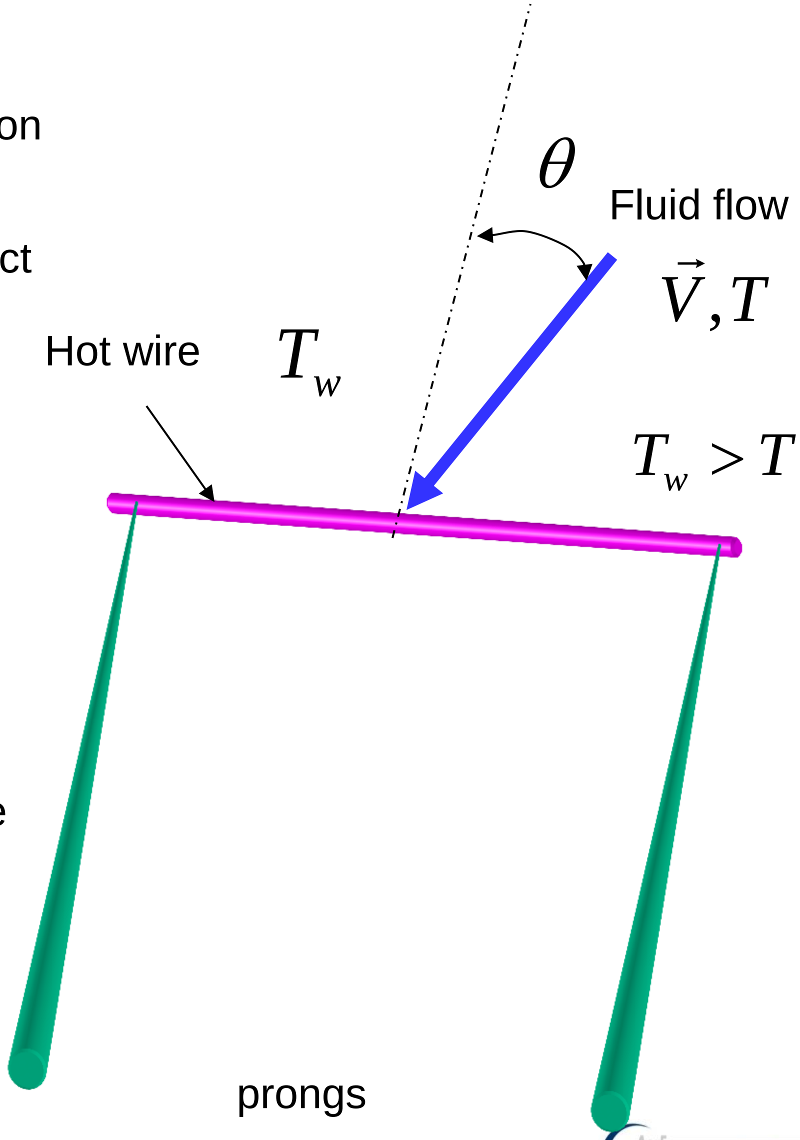
Various effects and error source

- Prong interference effects:
  - Interference of the prongs and the probe body may produce additional complications of the heat transfer characteristics.
  - For example a stream in the binormal direction will produce higher cooling than a stream with the same velocity magnitude but in the normal direction.
  - In reality, $V_{eff} = (V_N^2 + K^2 V_T^2 + h^2 V_B^2)^{1/2}$
  - V_N, V_T and V_B are the normal tangential and binormal velocity components.
  - Typically, h^2=1.1~1.2
  - To minimize the effect, it usually use long and thin prongs. Tapered prongs are also recommended.



Various effects and error source

- Heat conduction effects:
  - Previous analysis is based on 2-D assumption with $l/d = \infty$.
  - In reality, the effect of end conduct may effect the accuracy of the measurement results
  - Cold length, $l_c = 0.5 * d\, ((K_w^2/K)(1+a_R)/Nu)^{1/2}$
  - K_w is thermal conductivity of the sensor
  - K is thermal conductivity of the fluid
  - a_R is overheat ratio
  - Effect of the sensor length l/l_c
  - A recent study has demonstrated that end conduction effects are expected to decrease significantly as the Reynolds number increasing



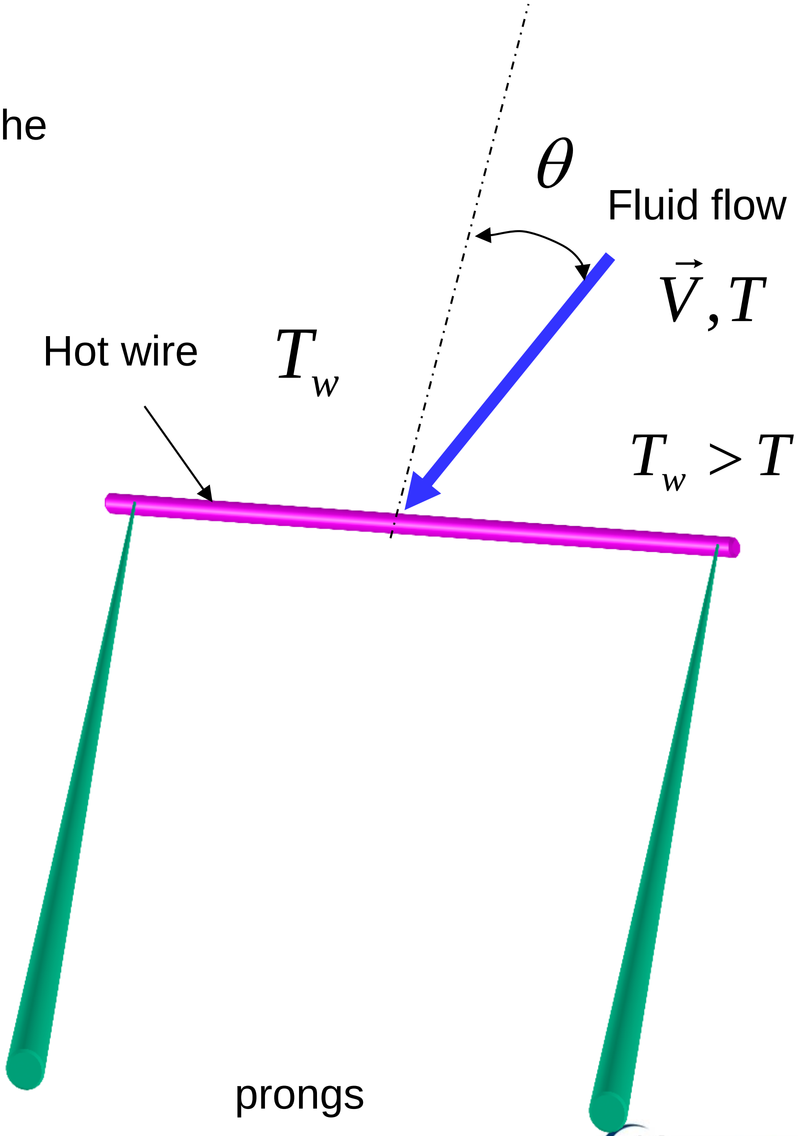
Various effects and error source

- Compressibility effects:
  - The velocity and temperature fields around the sensor become quite complicated when M>0.6.

$$\begin{aligned} V &\Rightarrow S_V \\ \rho &\Rightarrow S_\rho \\ T_0 &\Rightarrow S_{T_0} \\ For\ M \geq 1.2 &\quad S_V = S_\rho \end{aligned}$$

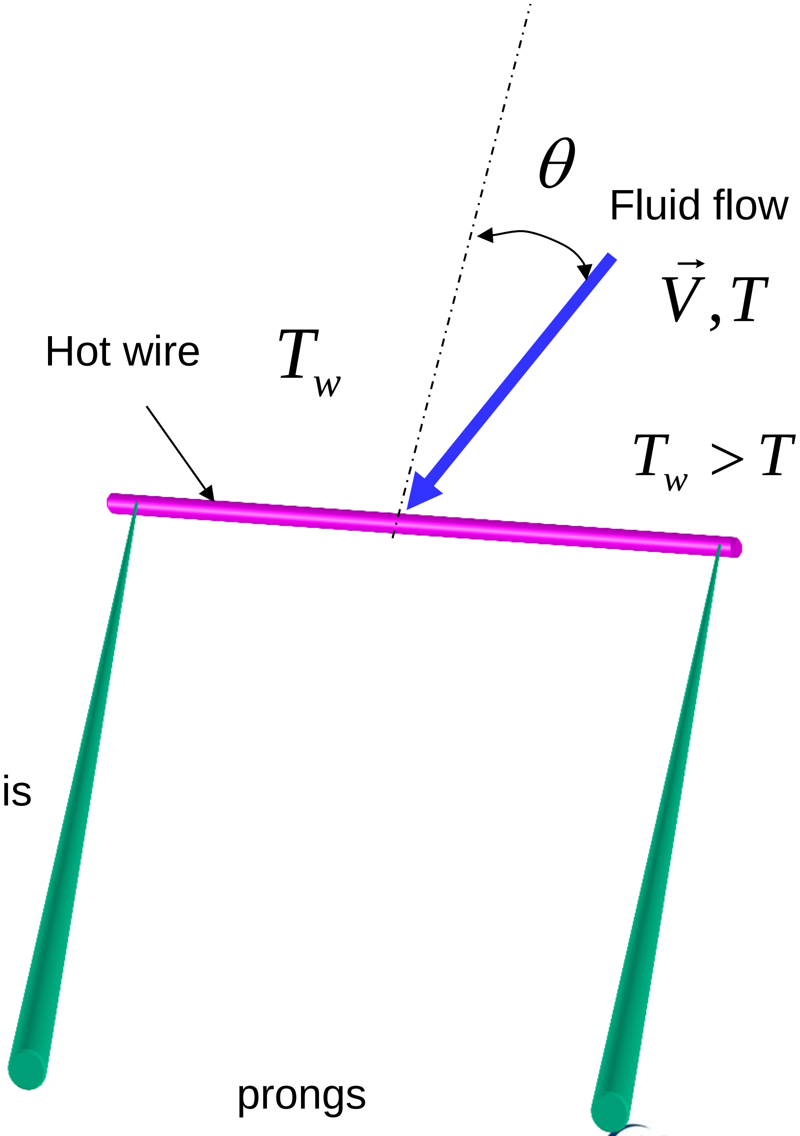
Modified King's law for compressible flow:

$$E^2 = A + B(\rho V)^n$$
$$n \cong 0.55$$



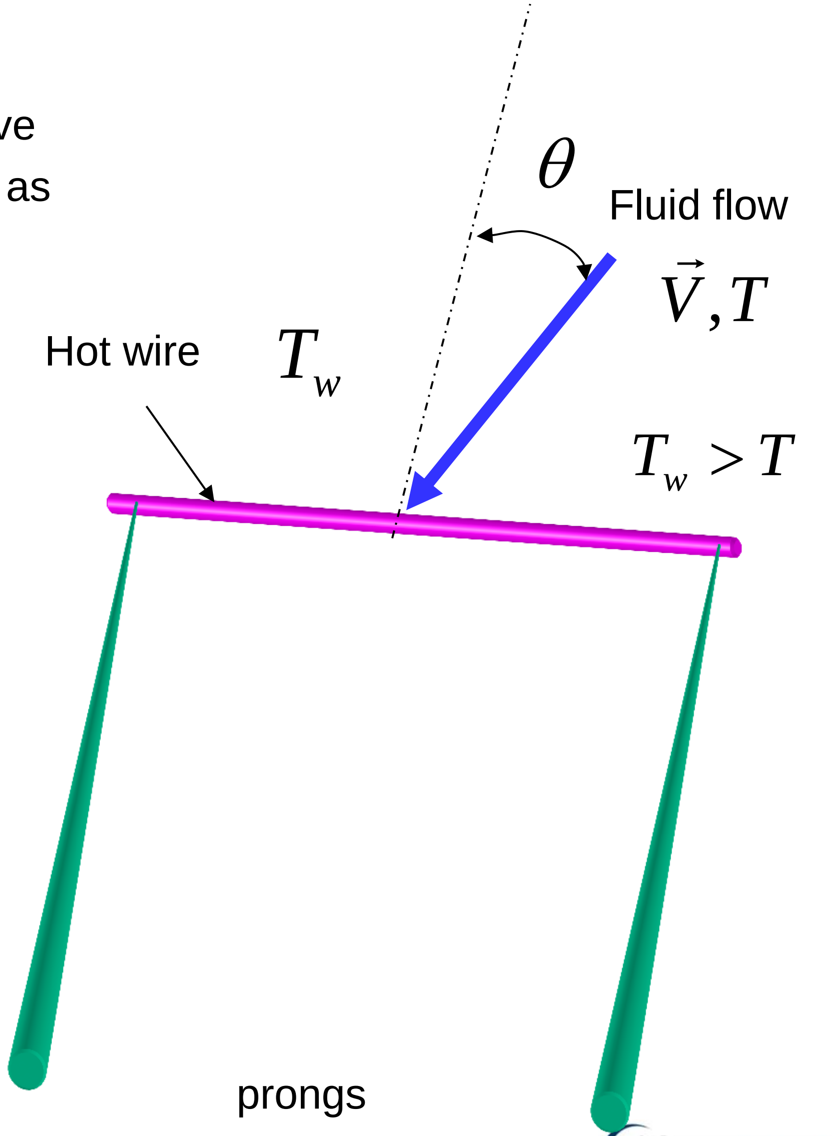
Various effects and error source

- Temperature variation effects:
  - Calibration at Temperature T1.
  - Correlation is needed if real measurements will be conducted at Temperature T2.
  - When the flow temperature varies from position to position or contain turbulent fluctuations, corrections is much more complicated.
  - It requires simultaneous flow temperature measurements.
  - S_V is increasing with overheat ratio a_T.
  - At extremely low a_T, a thermal anemometer is totally insensitive to velocity variations, and becomes a resistance thermometer. The sensor is called cold wire.



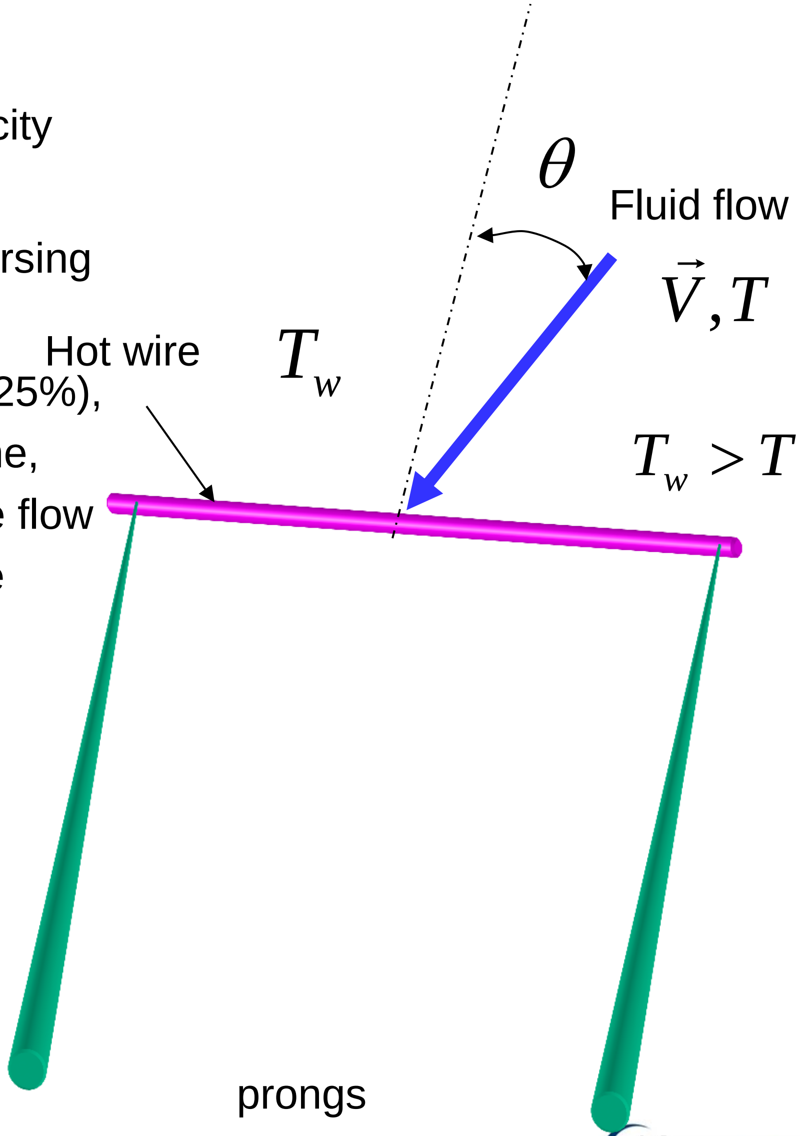
Various effects and error source

- Composition effects:
  - Composition of flow may affect the convective heat transfer from a thermal anemometer in as much as it affect the heat conductivity of surrounding fluid.
  - It requires simultaneous measurements of fluid species concentration.



Various effects and error source

- Reverse flow and high-turbulence effects:
  - thermal anemometer could not resolve velocity orientation.
  - Forward flow can not be identified from reversing flow
  - In highly turbulent flow (turbulent intensity >25%), reverse flow will occurr statistically some time, therefore, using thermal anemometer for the flow velocity measurement may result quite large measurement uncertainty.
  - Pulsed Hot –wire concept



Multi-sensor probes

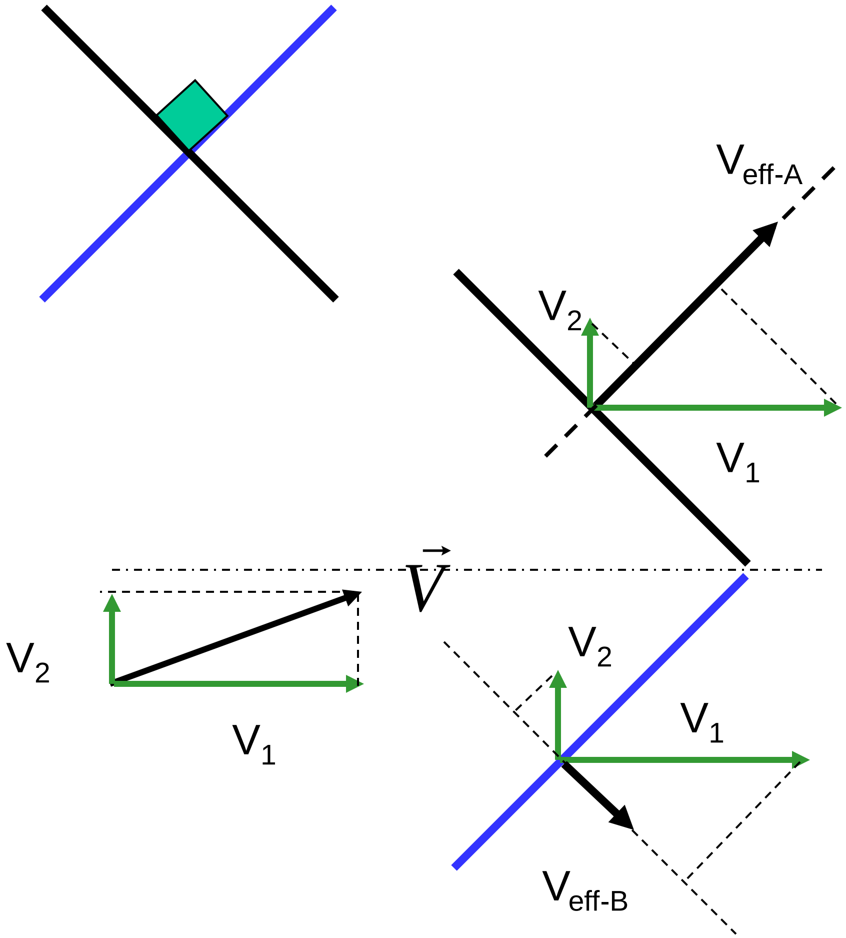
- Cross-wire (X-wire) design:

$$V_{eff-A} = \frac{\sqrt{2}}{2}(V_1 + V_2)$$

$$V_{eff-B} = \frac{\sqrt{2}}{2}(V_1 - V_2)$$

$$V_1 = \frac{\sqrt{2}}{2}(V_{eff-A} + V_{eff-B})$$

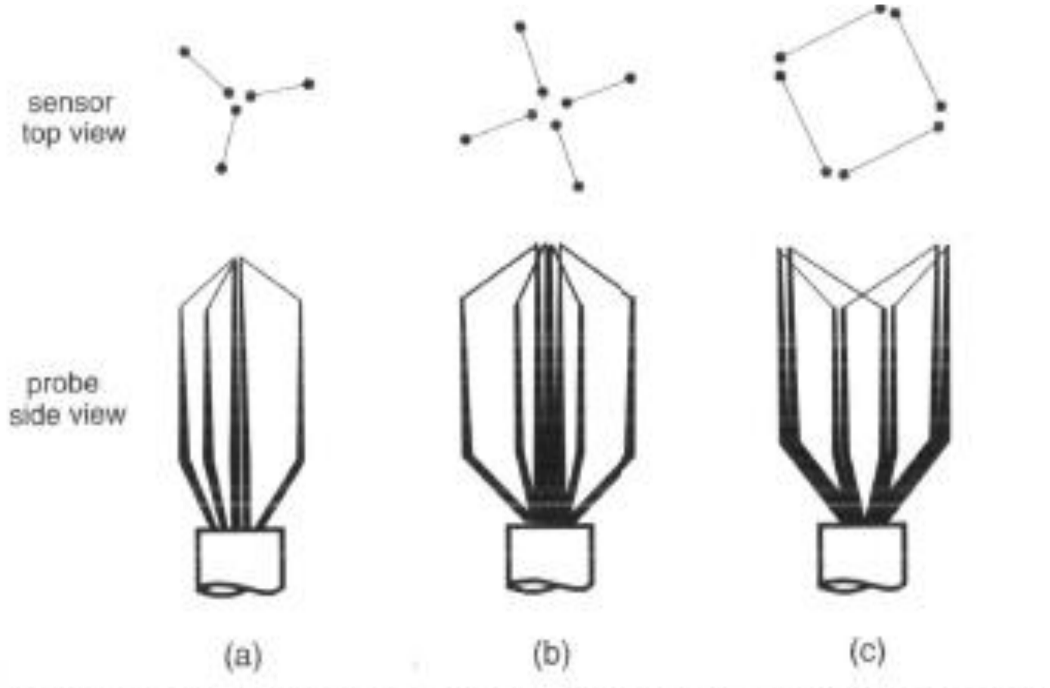
$$V_2 = \frac{\sqrt{2}}{2}(V_{eff-A} - V_{eff-B})$$



Multi-sensor probes

- Three sensor design
- Four sensor design

Use of these probes requires extensive calibration procedure!



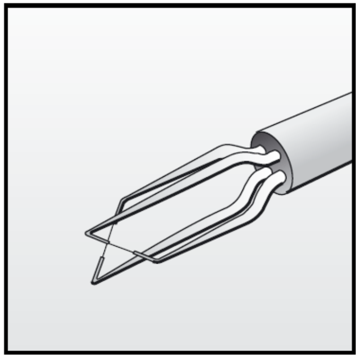


Fig. 7. Sensor arrangement of X-probe.

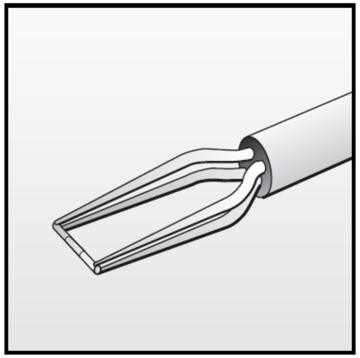


Fig. 8. Tip of split-fiber probe.

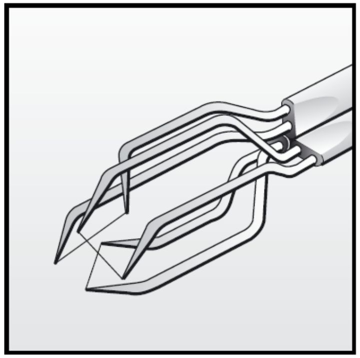
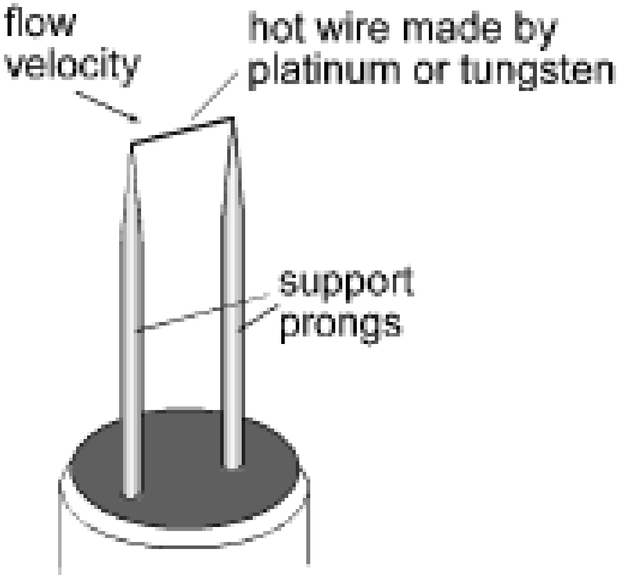


Fig. 9. Tip of triple-sensor probe.

Diameter of hot wires

- L = 0.8 ~ 1.5 mm
- D = ~ 5 μm for conventional applications
- D = ~ 10 μm for high-speed applications
- D = ~ 2 μm for low speed applications
- Prongs: usually tapered to be d≤ 1mm



Lab #05: Determination of the Aerodynamic Performance of a Low Speed Airfoil based on Pressure Distribution Measurements

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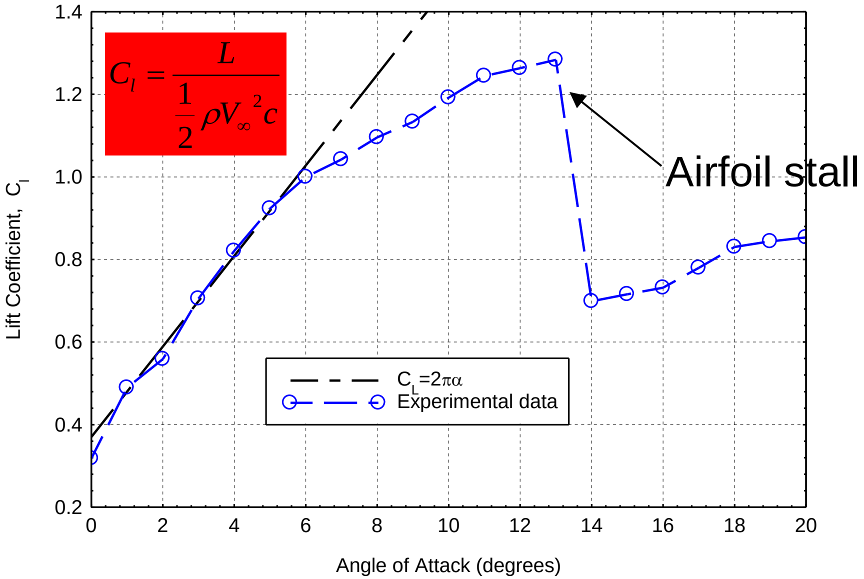
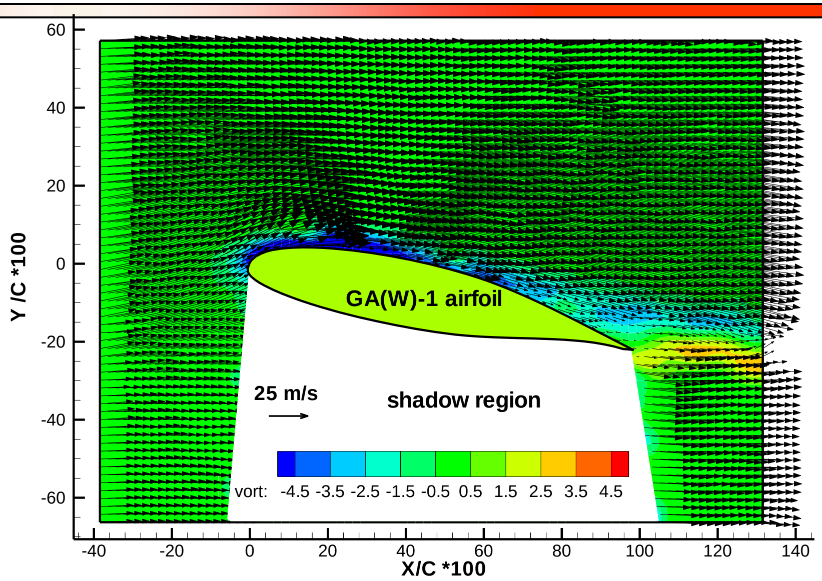
Aerodynamic Performance of An Airfoil





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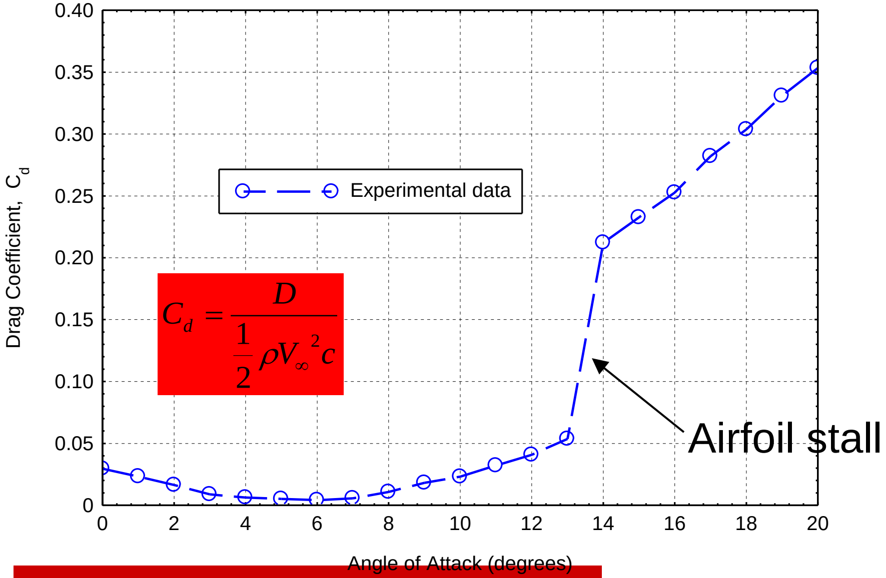
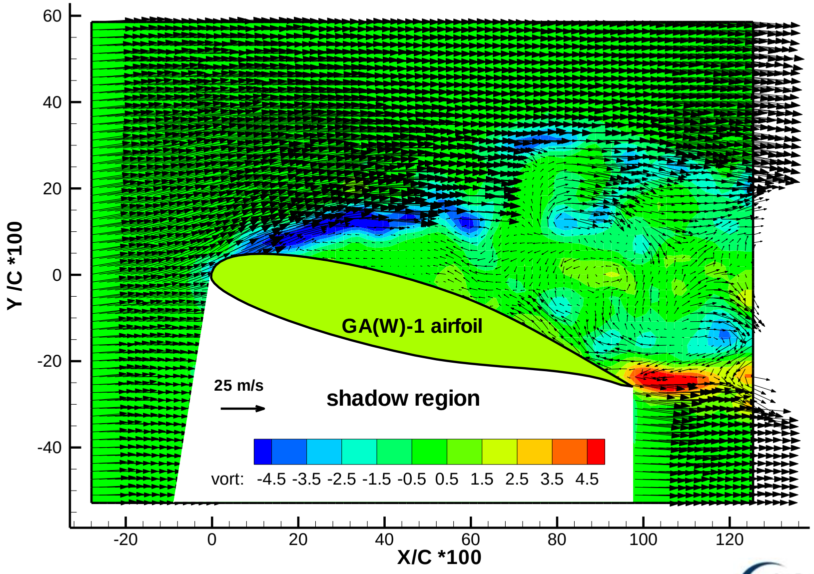
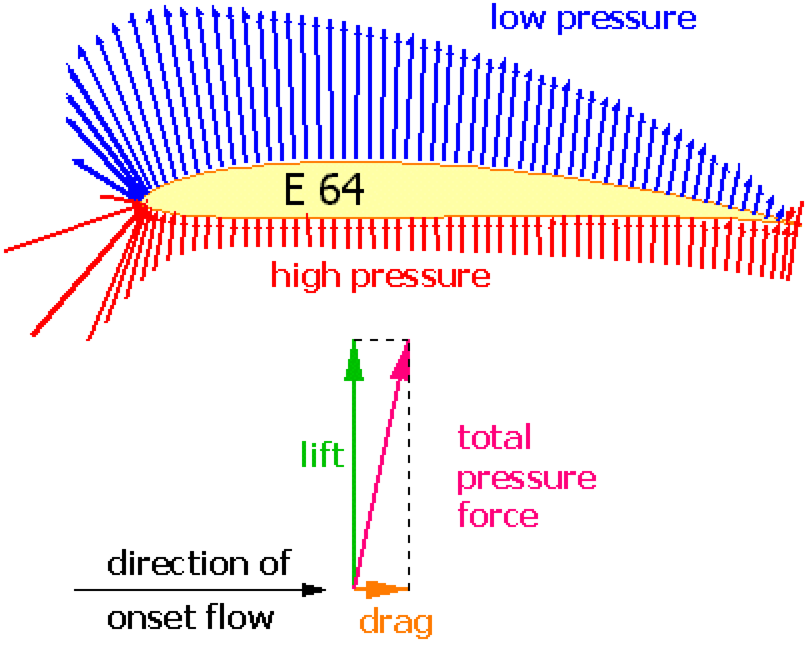
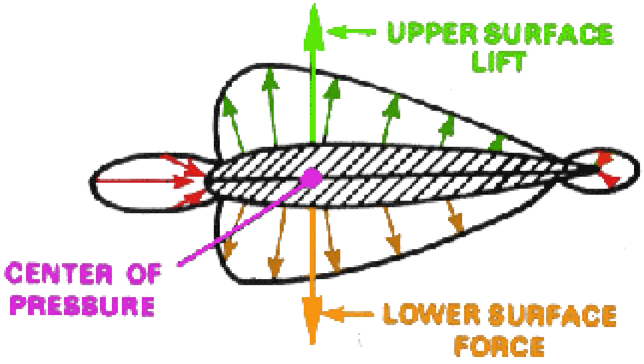




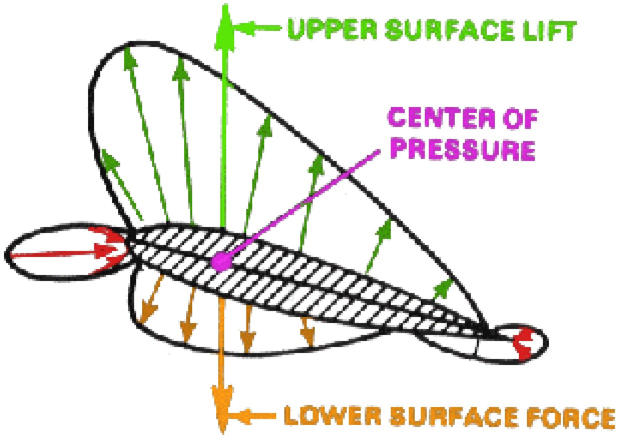
After stall

Determination of the Aerodynamic Performance of a Low Speed Airfoil based on Pressure Distribution Measurements



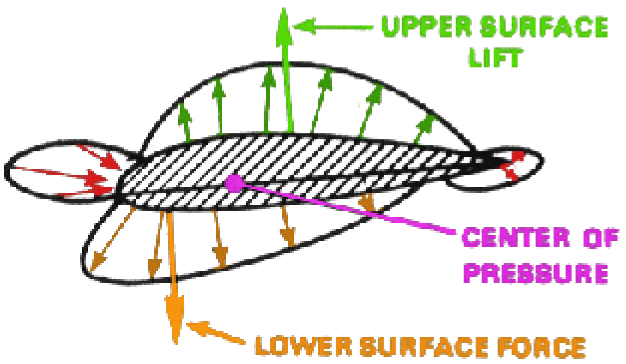


SYMMETRICAL AIRFOIL AT ZERO LIFT

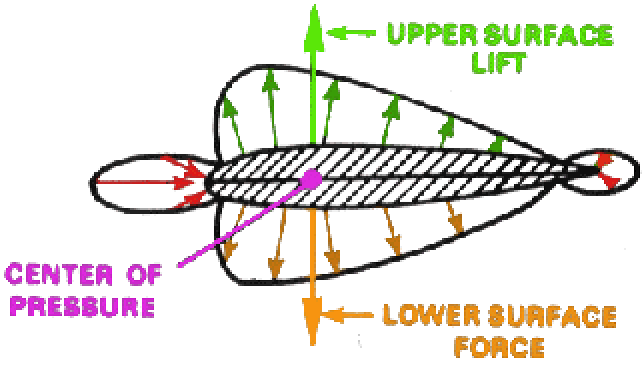


SYMMETRICAL AIRFOIL AT POSITIVE LIFT

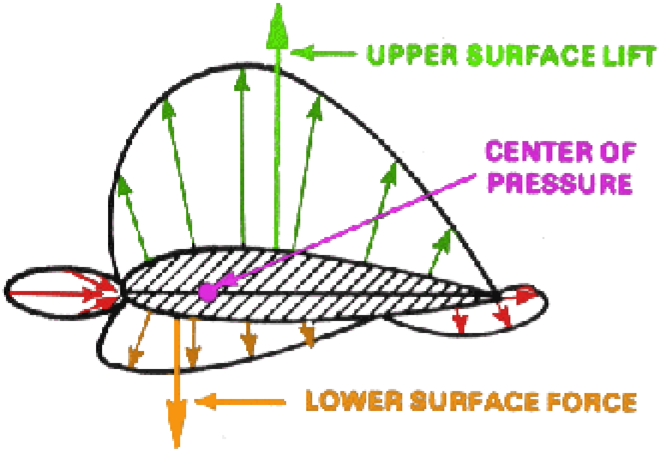
Determination of the Aerodynamic Performance of a Low Speed Airfoil based on Pressure Distribution Measurements



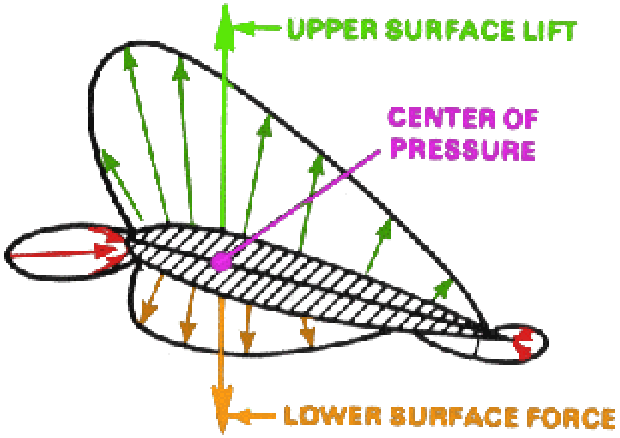
CAMBERED AIRFOIL AT ZERO LIFT



SYMMETRICAL AIRFOIL AT ZERO LIFT



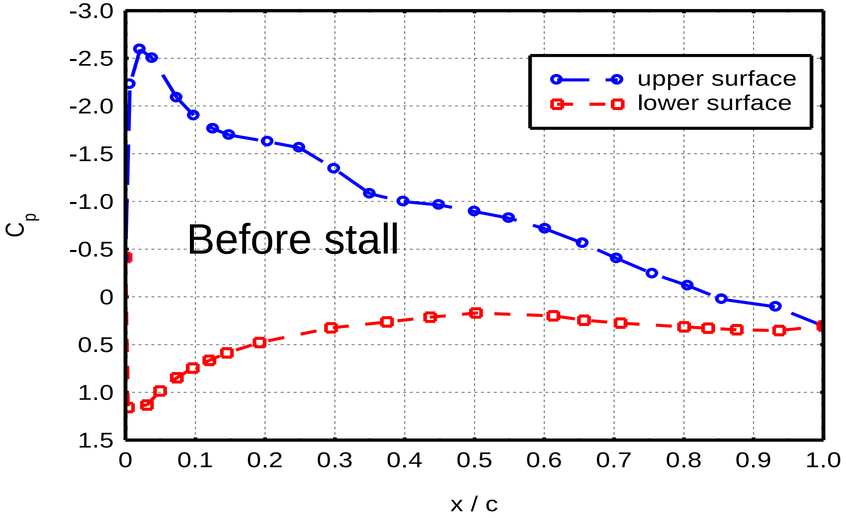
CAMBERED AIRFOIL AT POSITIVE LIFT

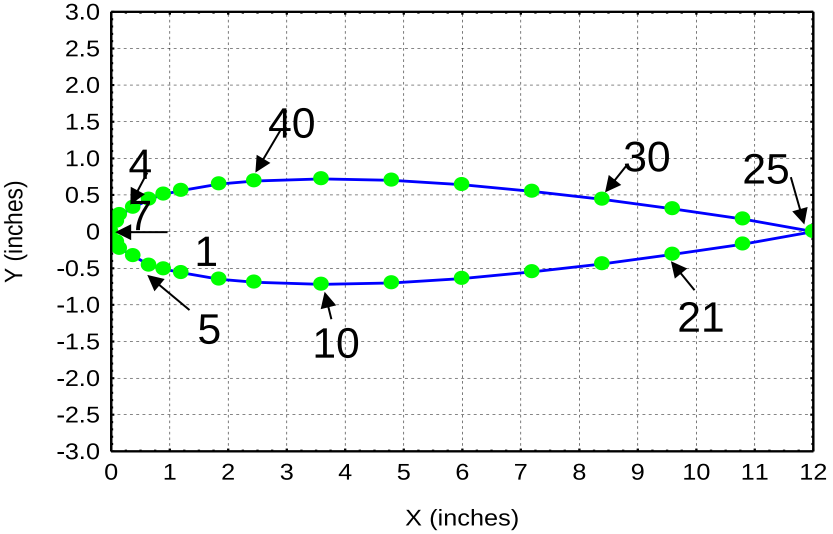


SYMMETRICAL AIRFOIL AT POSITIVE LIFT

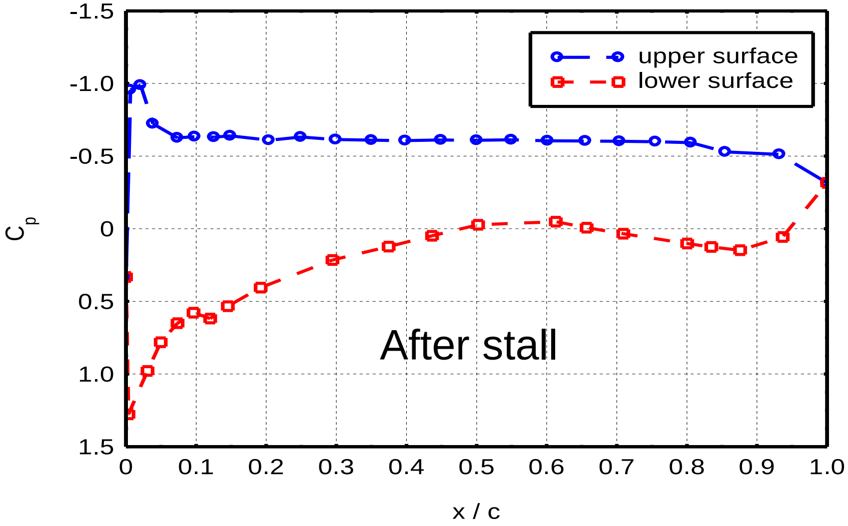
Determination of the Aerodynamic Performance of a Low Speed Airfoil based on Pressure Distribution Measurements

$$C_p = \frac{P - P_\infty}{\frac{1}{2}\rho V_\infty^{\ 2}}$$





NACA0012 airfoil with 49 pressure tabs



Determination of the Aerodynamic Performance of a Low Speed Airfoil based on Pressure Distribution Measurements

What you will have available to you for this portion of the lab:

- A Pitot probe already mounted to the floor of the wind tunnel for acquiring dynamic pressure throughout your tests.
- A Setra manometer to be used with the Pitot tube to measure the incoming flow velocity.
- A thermometer and barometer for observing ambient lab conditions (for calculating atmospheric density).
- A computer with a data acquisition system capable of measuring the voltage from your manometer.
- The pressure sensor you calibrated last week
- A GA(W)-1 airfoil that can be mounted at any angle of attack up to 16.0 degrees.
- Two 16-channel Scanivalve DSA electronic pressure scanners.

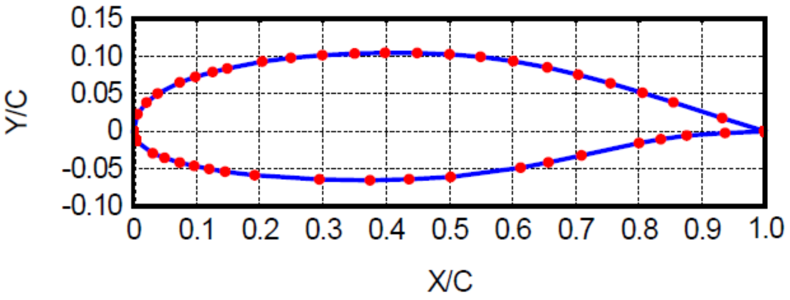
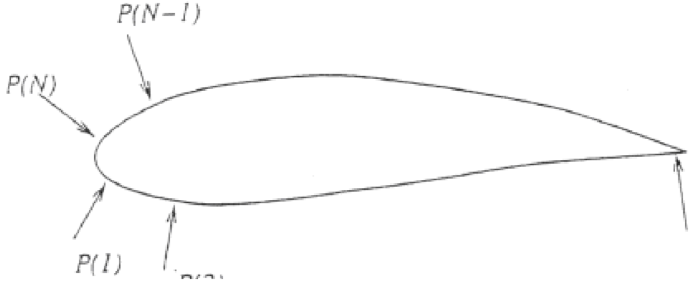


Figure 2. GA(W)-1 airfoil and pressure tap locations.

DSA3217 (Shown)

Determination of the Aerodynamic Performance of a Low Speed Airfoil based on Pressure Distribution Measurements

- Calculating airfoil lift coefficient and drag coefficient by numerically integrating the surface pressure distribution around the airfoil:



$$\begin{cases} p_{i+1/2} = \frac{1}{2}(p_i + p_{i+1}) \\ p_{N+1/2} = \frac{1}{2}(p_N + p_1) \end{cases}$$

$$\begin{cases} \Delta x_i = x_{i+1} - x_i, & \Delta \mathrm{y}_\mathrm{i} = y_{i+1} - y_i \\ \Delta x_N = x_1 - x_N, & \Delta \mathrm{y}_\mathrm{N} = y_1 - y_N \end{cases}$$

$$\delta A'_i = -p_{i+1/2}\Delta y_i$$

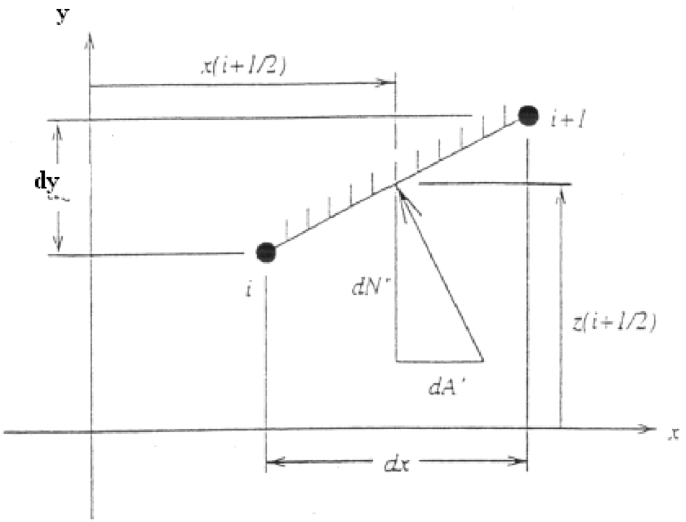
$$\delta N'_i = p_{i+1/2}\Delta x_i$$

$$N' = \sum_{i=1}^{N} \delta N'_i = \sum_{i=1}^{N} p_{i+1/2}\Delta x_i$$

$$A' = \sum_{i=1}^{N} \delta A'_i = -\sum_{i=1}^{N} p_{i+1/2}\Delta y_i$$

$$M'_{LE} = \sum_{i=1}^{N} \delta M'_{LE}$$

$$= -\sum_{i=1}^{N} (p_{i+1/2}\Delta x_i) x_{i+1/2} - \sum_{i=1}^{N} (p_{i+1/2}\Delta y_i) y_{i+1/2}$$



$$L' = N'\cos\alpha - A'\sin\alpha$$

$$D' = N'\sin\alpha + A'\cos\alpha$$

Required Plots for the Lab Report

Required Plots:

- Plots of C_L, C_D and C_M vs. angle of attack for the GA(W)-1 airfoil.
- Plot of C_P at angle of attack $AOA = -4°, 0°, 4°, 6°, 8°, 10°, 12°, 14°, 16°$ for the GA(W)-1 airfoil.
- Plot of dynamic pressure vs. the pressure drop between the inlet and out let of the wind tunnel contraction for the small calibration wind tunnel (including a curve fit).

Your report must provide details on:

- The flow speed you used for the airfoil pressure distribution measurements.
- Discussion of the plots of the pressure coefficient (C_P) distributions of the airfoil.
- Discussion of C_L, C_D and C_M calculated from your C_P distributions—and how you calculated them.
- Estimates of the location of the stagnation point for each angle of attack you consider.
- Estimate of the stall angle (if possible) from your measurements.
- Tunnel velocity, Reynolds number of tests (with respect to the airfoil chord length of 12 inches).
- Discussion about the results of the small wind tunnel calibration tests.