Pressure Measurements

Data Acquisition Procedures:

Pressure data were acquired throughout the entire experimental testing period from 2017 to 2019 via two different Scanivalve pressure transducers. The finalized archival data, reported here, were taken in July and August of 2019. This data was acquired via the Scanivalve SSS-48C9 pneumatic scanner housing a PDCR23D pressure transducer and a SCSG2 signal conditioner. This system has 48 pressure ports that can be measured sequentially using the internal pressure transducer with a differential range of 10 in of H_2O with an accuracy of 0.30% of full scale. Due to the large number of pressure taps along the ramp and boundary layer development plate (89 total), pressure measurements were taken in three sequential groups using the Scanivalve's 31-port circular quick connectors. Each channel was sampled sequentially at either 1 - 2 kHz for 15 seconds which was found sufficient to provide converged mean values. The reference pressure for each measurement was the freestream static pressure collected via a pitot tube located at: X = -0.97 m, Y = 0.58 m, and Z = 0.19 m.

This Scanivalve device was calibrated in the wind tunnel against the Setra pressure transducers used for setting the wind tunnel freestream speed. A sample calibration curve for this device is shown in Figure 1 below. The Mach 0.6 wind tunnel uses two Setra Model 270 absolute pressure transducers, to measure pitot static and total pressures respectively, with a range of 600-1100 HPa and an accuracy of 0.05% of full scale. The calibration was done by connecting the Scanivalve and each of the Setra's pressure lines to the freestream pitot tube. The freestream Mach number was then varied between 0 - 0.217, using the Setra's output, and the Scanivalve voltage was recorded. The difference in the Setra outputs, the pitot dynamic pressure, was used as the known pressure to calibrate the Scanivalve.

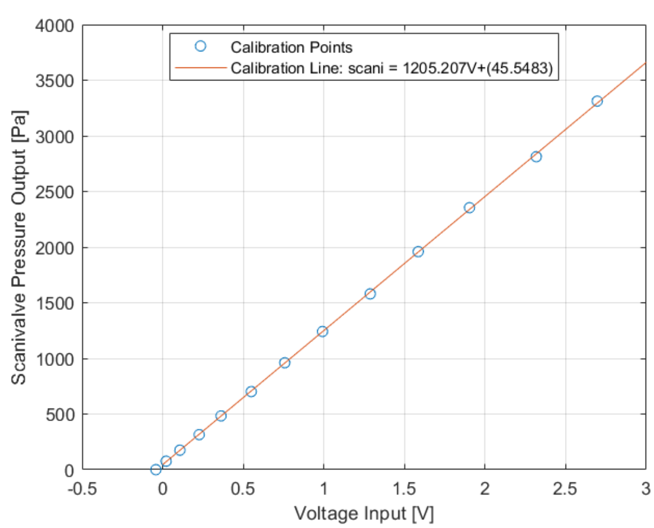

Figure 1 Sample calibration curve for the Scanivalve SSS-48C pneumatic scanner using an NI USB-6343 DAQ.

Processing of Pressure Data:

The individual data files for each group were loaded into and processed in MATLAB. Pressure data are reported in terms of a pressure coefficient defined as follows:

$$C_p \equiv \frac{(P_i - P_\infty)}{(P_T - P_\infty)} = \frac{\Delta P_i}{q} \tag{1}$$

where P_i is the local static pressure, P_∞ is the freestream static pressure, P_T is the freestream total pressure and q is the freestream dynamic pressure. Figure 2 shows the centerline pressure coefficient and pressure coefficient spatial derivative for each of the separation cases. This centerline pressure data, as well as the spanwise pressure measurements, are provided in the accompanying data files.

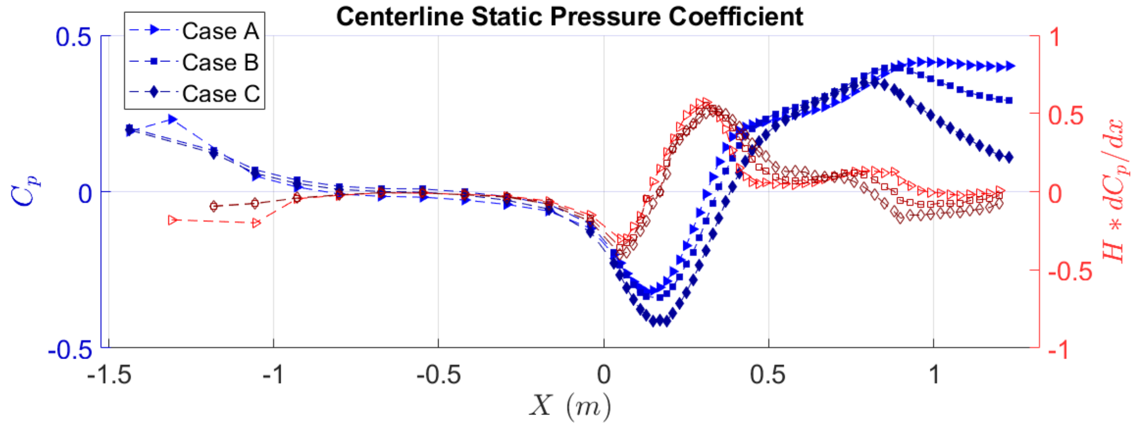

Figure 2 Streamwise pressure coefficient distribution and pressure coefficient gradient distribution for each flow case. Note that for the pressure coefficient spatial gradient, the ramp height H = 0.2 is used to non-dimensional the term.

Uncertainty Analysis:

The uncertainty analysis procedure followed the general guidelines laid out in the ASME PTC 19.1-2005 Test Uncertainty manual [1]. This section will outline the procedure used to calculate the uncertainty for the C_p measurements, both of which are reported in data files for each separation test case. The combined standard uncertainty of C_p is a combination of the random uncertainty, s_{Cp}, and the systematic standard uncertainty, b_{Cp}.

$$u_{C_p} = \left[b_{C_p}^2 + s_{C_p}^2 \right]^{\frac{1}{2}} \tag{2}$$

The functional dependence of the pressure coefficient on the measured gauge pressure and dynamic pressure is as follows:

$$C_p = f(\Delta P_i, q) \tag{3}$$

The sensitivities of C_p with respect to each of these dependent values were obtained by partial differentiation.

$$\frac{\partial C_p}{\partial \Delta P_i} = \frac{1}{q} \tag{4}$$

$$\frac{\partial C_p}{\partial q} = -\frac{\Delta P_i}{q^2} \tag{5}$$

The random uncertainty, s_{Cp}, is a function of the random uncertainties $s_{\Delta P_i}$ and s_q, and were obtained from equations (3) and (4) as follows:

$$s_{C_p} = \left[\left(\frac{\partial C_p}{\partial \Delta P_i} s_{\Delta P_i}\right)^2 + \left(\frac{\partial C_p}{\partial q} s_q\right)^2 \right]^{\frac{1}{2}} \tag{6}$$

or equivalently,

$$s_{C_p} = \frac{1}{|q|} \left[s_{\Delta P_i}^2 + C_p^2 s_q^2 \right]^{\frac{1}{2}} \tag{7}$$

The random standard uncertainties $s_{\Delta P_i}$ and s_q are related to the estimator variances as follows:

$$s_{\Delta P_i} = \sqrt{\frac{var_{\Delta P_i}}{N}} \tag{8}$$

$$s_q = \sqrt{\frac{var_q}{N}} \tag{9}$$

where N is the number of samples.

Propagation of the systematic uncertainties was done in a similar manner to that of the random uncertainties.

$$b_{C_p} = \left[\left(\frac{\partial C_p}{\partial \Delta P_i} b_{\Delta P_i}\right)^2 + \left(\frac{\partial C_p}{\partial q} b_q\right)^2 \right]^{\frac{1}{2}} \tag{10}$$

or equivalently,

$$b_{C_p} = \frac{1}{|q|} \left[b_{\Delta P_i}^2 + C_p^2 b_q^2 \right]^{\frac{1}{2}} = \frac{b_p}{|q|} \left[1 + C_p^2 \right]^{\frac{1}{2}} \tag{10}$$

Here the fact that the systematic uncertainty for the measured gauge pressure and dynamic pressure are the same, b_p, was used to simplify the equation. This fact is due to all pressure measurements being made with the same pressure transducer. The systematic uncertainty of the Scanivalve pressure transducer was divided into two components, the calibration uncertainty, b_{cal}, and the instrument uncertainty, b_{inst}.

$$b_p = \left[b_{cal}^2 + b_{inst}^2 \right]^{\frac{1}{2}} \tag{11}$$

The instrument uncertainty is that given with the pressure transducer, 0.3% of full-scale with the full-scale range being 10 inches of water. Once converted to the metric system, this yields b_{inst} = ±7.47 [Pa]. The calibration uncertainty is based off the linear regression used to convert the Scanivalve transducer output voltage to pressure. The calibration curve is shown in Figure 1 and the linear fit equation is:

$$P = 1205.207V + 45.5483 \quad (12)$$

where V is the transducer output in Volts and P is the respective pressure in Pascals. From this regression curve fit the uncertainty was calculated using the procedure outlined in section 8-6 of the ASME PTC 19.1-2005 Test Uncertainty manual [1]. The calibration uncertainty is dependent on the voltage and hence varies for each point. In general, b_{cal} is about 60-85% of b_{inst}.

The combined standard uncertainty was given in equation (2) and is a combination of the random uncertainty and the systematic standard uncertainty. Here it is repeated utilizing equations (6) and (10).

$$u_{C_p} = \frac{1}{|q|}\left[\, b_p^2(1 + C_p^2) + (s_{\Delta P_i}^2 + C_p^2 s_q^2)\right]^{\frac{1}{2}} \quad (13)$$

The expanded uncertainty is the combined standard uncertainty multiplied by the Student's t-table value, $t_{\nu,p}$ where ν is N – 1 and p is the selected confidence interval. At 20:1 odds or p = 95% confidence and assuming a large sample size, $t_{\nu,p}$ = 1.96. Using this analysis, the true value is expected to lie within:

$$C_p \pm t_{\nu,p} u_{C_p} \quad (14)$$

where $t_{\nu,p}\, u_U$ is the expanded uncertainty or simply the uncertainty of the quantity.

References:

[1] *ASME PTC 19.1 - 2005 Test Uncertainty*. ASME, 2005.