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Direct Measurement of Skin Friction in a Turbine Cascade

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This research was carried out to design and utilize an instrument to directly measure the skin friction on the suction surface of an advanced turbine blade. A floating head gauge configuration was developed to detect the small shear force created by the flow passing over the nonintrusive sensing element. The floating head was mounted to a cantilever beam arrangement with minute deflection due to the shear force, which allows the balance to be a nonnulling type without introducing misalignment errors. This results in a simpler, more reliable design. Measurements were conducted in cold flow in the Cascade Tunnel at Virginia Tech for exit Mach numbers from 0.84 to 1.37. The cascade was representative of a modern turbine stage. The output from the gauge was found to be repeatable for the same nominal input conditions. The measured values of skin friction coefficient ranged from 0.002 to 0.004 over the conditions tested. No other values can be found in the literature for comparison. Finally, a full Navier–Stokes computational fluid dynamics code with a modern turbulence model was used to predict the flow and skin friction coefficient for an exit Mach number of 1.2. The observations compared reasonably well with the numerically predicted value for C_f.

Nomenclature

A = sensing head area
C_f = skin friction coefficient
M = Mach number
P = pressure
P_0 = total pressure
q = dynamic pressure
T_w = wall temperature
T_0 = total temperature
U = velocity
γ = ratio of specific heats
ρ = density
τ_w = wall shear stress

Introduction

IMPROVEMENTS to high-pressure turbines have been researched extensively. For low size-to-power and weight-to-power ratios, turbine stages operate with high stage load. This can be achieved with a significant flow turning in the rotor and with high exit flow velocity. However, the losses due to the trailing-edge shock waves increase rapidly with the increasing supersonic exit flow Mach number. As a result, the high-pressure turbines in modern engines have a 60–70-deg exit flow angle and transonic throughflow.

The main goals in the development of the turbine blades are now known. The aerodynamic loss is one of the most important factors. Control over this loss would certainly be desirable, since this could lead to higher efficiency while maintaining the same stage load, or to higher stage load with the same efficiency. The flow is three dimensional, highly unsteady, turbulent, and significant heat transfer occurs between the blade and the flow. There is also a high level of turbulence in the "freestream" flow. These factors make computations, and especially turbulence modeling, difficult. One of the attempts that could be made in order to better understand the flow is to measure the skin friction on the blade surface. It would also serve to validate computational fluid dynamics (CFD) codes. Last, the skin friction contributes directly to the loss, and so this information aids in improved design. We were unable to find any prior direct measurements of skin friction in a turbine cascade.

Current techniques for the measurement of skin friction fall in two general categories: 1) indirect or 2) direct methods.[1] Indirect methods involve measurements of the velocity gradient or heat transfer at the wall. This is feasible for simple incompressible and compressible laminar flows, but these techniques are much less reliable in turbulent and/or complex flows. Uncertainties with these methods can be quite large, especially in a compressible, three-dimensional, turbulent boundary layer, because a mathematical model or Reynolds analogy type of relation is required to deduce skin friction. For these reasons, a direct wall shear force measurement technique is strongly preferred for a complex flow, and that approach was adopted here.

The basic configuration of the skin friction gauge used in this work consists of a cantilevered floating surface that fits into a cutout in the turbine blade surface. A history of early direct measurement designs that includes a floating element design was presented by Winter.[2] The present gauge is a variation of the gauges used at Virginia Tech for a number of different applications.[3,4] The frictional force must be measured over a small area; therefore, the measured shear force values are small and the skin friction gauge must be very sensitive. The current design can measure the forces from a thousandth of a Newton to a tenth of a Newton accurately. The device employs piezoresistive crystal strain gauges that sense the strain in the cantilever beam. This type of strain gauge is exceedingly sensitive with gauge factors in the area of 150, compared to a gauge factor of near 2 for common foil strain gauges. This kind of sensitivity enabled the adoption of so-called nonnulling type design. Since the piezoresistive strain gauges have such a high gauge factor, the cantilevered floating element undergoes extremely small deflections during a measurement. This renders insignificant any misalignment effects that could cause an errant measurement as a result of tilting the floating head into the flow. The nonnulling design is preferred because it is less complex in that it does not require a series of mechanical linkages that can introduce

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mechanical problems and substantial error in the measurement.

The following sections present the design of the floating head skin friction balance, the facilities and cascade used, and a discussion of the results obtained. This is followed by a comparison with the predictions of a modern CFD code for the case of an exit Mach number of 1.2.

General Description of the Gauge

The configuration chosen was a floating element gauge that has been specifically developed for directly measuring the skin friction on the surface of the turbine blade. The general configuration is shown in Fig. 1. Figure 1a shows how the unit fits into a blade. Figure 1b shows the unit mounted into a calibration fixture. The sensing head has an oval shape with the long axis of 20 mm and a short axis of 5 mm with the short axis aligned in streamwise direction. Since the flow in this cascade experiment is two dimensional, an oval shape allows for a larger head area, and thus, a larger signal, while maintaining a reasonable measurement space in the flow direction. The head was machined together with the blade to make sure that it had the same shape. Also, it was made of the same material as the blade to simulate the blade conditions and match the heat flow pattern. A gap of 0.01 cm around the head was chosen because of its practicality in terms of tolerances and minimizing errors caused by the gap around the floating element. The sensing head was mounted to the tip of the sensing unit. The cantilever beam is arranged parallel to the blade surface to fit the strain gauge sensor inside the blade.

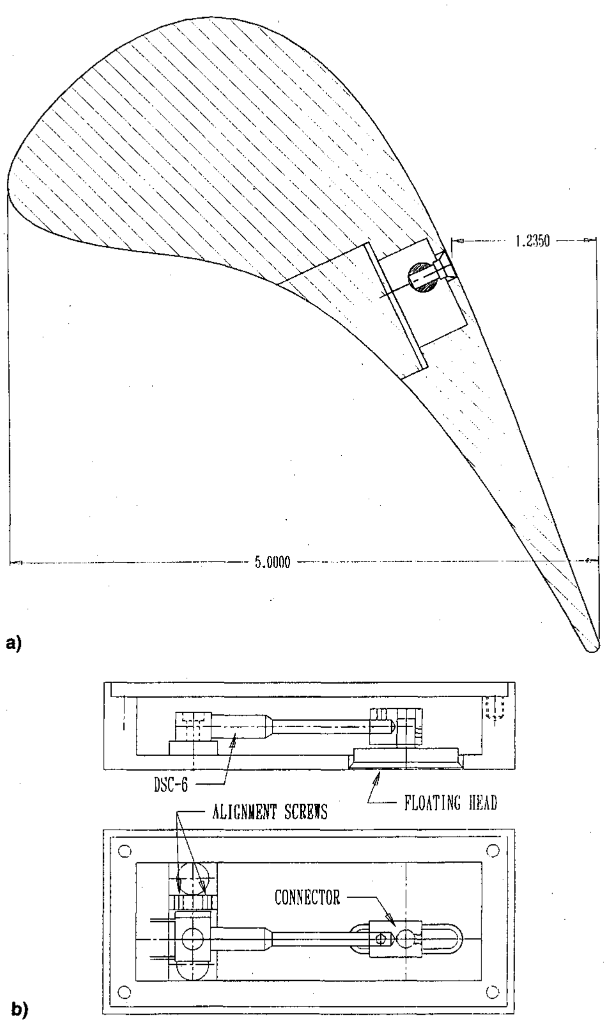

Fig. 1 General arrangement of the skin friction gauge: a) mounted in turbine blade and b) in fixture.

The cavity of the sensor bay inside the blade is filled with liquid, Dow–Corning 200 fluid with 10,000 cSt viscosity. The oil plays two important roles. First, the presence of a liquid in the cavity minimizes pressure gradient effects by providing a more continuous surface to the flow and eliminating pockets of air underneath the sensing head. The fluid is also incompressible, which minimizes any pressure differences in the gauge cavity. Second, the viscous liquid provides damping that alleviates the effects of facility vibrations.

Shadowgraphs were used to make sure that the sensing head was located in the turbulent boundary-layer region. A typical shadowgraph is shown in Fig. 2.

The floating element skin friction balance is a nonintrusive element, meaning that it does not alter the flow from which the measurements are being taken. Ideally, the floating element would be aligned perfectly with the blade surface. Also, the effect of the gap between the floating element and the surrounding wall is important. A relevant investigation was conducted by Allen[5,6] with a large version of a nonintrusive, direct force measuring balance. In that parametric study, the effects of each individual misalignment were investigated as well as the effect of gap size on each misalignment error. Allen based his criteria for minimizing the effects of misalignment on knowledge of the boundary-layer thickness. For instance, specific ratios of lip-to-diameter and gap-to-diameter will produce negligible effects on shear measurements for a given boundary-layer thickness-to-diameter ratio at a specified amount of protrusion or recession of the floating head. In studies such as those discussed here, the boundary-layer thickness is basically an unknown quantity, so that the safest procedure is to hold the protrusion or recession of the sensing head to within reasonable limits (on the order of 0.0005 in.). Small ratios of protrusion may result in forces larger than the shear force.[7] Intuitively, it would seem that the error would depend on the characteristics of the boundary layer, and it might be more significant the thinner the boundary layer. One common assumption about gap size is that having as small gap size as possible is beneficial. In fact, Allen observed that as the gap size is increased, protrusion errors become less significant. Also, a common misconception is that a small amount of floating head recession is preferable to protrusion. Allen showed that either protrusion or recession is equally damaging to the measurement. The general conclusion drawn from Allen's study is that for a small protrusion or recession of the floating head, lip and normal forces can be large enough to thwart any attempt to determine the shear force. Therefore, in the construction of the gauge in this study, great care was taken to ensure that the floating head was aligned with the surrounding wall. Allen found that a small gap size is not necessarily preferable to a relatively large gap

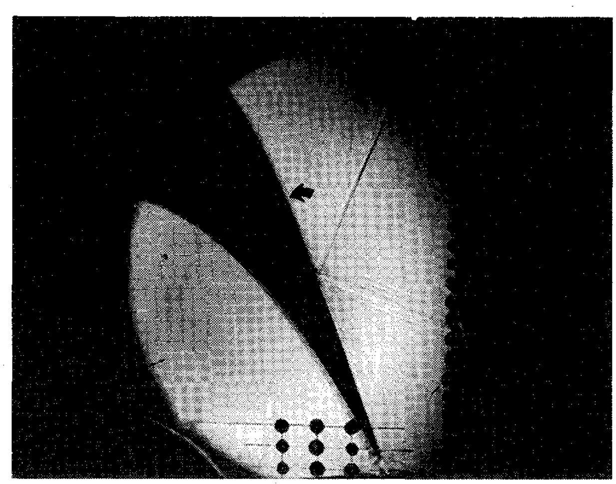

Fig. 2 Typical shadowgraph of the flow (arrow shows the location of the skin friction gauge).

size. However, the gauge in this study is liquid filled, and the surface tension forces at the free liquid surface are important to keep the liquid inside the balance in the presence of pressure gradients across the heads, and so a small gap was used.

Another consideration of design is the effect of pressure gradient on the floating head. One of the principle reasons for filling the gauge with an incompressible liquid is to make the balance appear in the view of a pressure gradient in the main flow as a wall, thus eliminating any effect it could have. This technique was shown effectively in the study of Refs. 8 and 9. One might think that the streamwise pressure gradients may cause liquid spillage out of the gap. However, due to the high viscosity of the liquid used and small gap size, no liquid expelled to the blade surface was noticed. A nonuniform pressure gradient would tend to put a moment on the cantilever as well as cause the cantilever torsion. This type of applied forces is canceled in the configuration of the Wheatstone bridge.

Sensor Element and Instrumentation

The strain sensing element utilized here is a deflection sensor cartridge (DSC) from Kistler Morse, a complete multipurpose displacement transducer that has the capability of being very sensitive while remaining stiff. The particular model DSC-6 sensor used is dual-axis sensitive and it measures minute deflections in two directions simultaneously. For the two-dimensional flow here, only a single axis was needed. The sensor is made of piezoresistive strain gauges of 1000-Ω resistance. As the force is applied to the cartridge, the crystals deflect, which causes a resistance change. The DSC senses from 0 to 0.0381 cm (0.015 in.) with a linearity of 0.05% full scale. Note that the forces being measured in this application move the tip of the sensor on the order of 0.0001 in., which is at the lower end of the range of the transducer. The experimental setup consists of the sensor inside the gauge being wired directly to a bridge completion box, which converts the signal to an output voltage. The resistors making up the strain gauges inside the DSC-6 sensor form two half bridges perpendicular to one another. The bridge completion box contains two completing half bridges and a potentiometer for zeroing the signal from each axis. The gauge was powered by a +5-V power supply.

The unamplified output from the bridge completion box was read either from a digital voltmeter or a personal computer-based data acquisition system. The computer system was comprised of a DAS-20, 12-bit A/D conversion board installed in a Zenith AT computer. The MetraByte STA-20 screw terminal adapter connected to DAS-20 received the unamplified signals. The data was collected and processed by LabTech Notebook data acquisition software. The gauge output was filtered with a simple Butterworth filter.

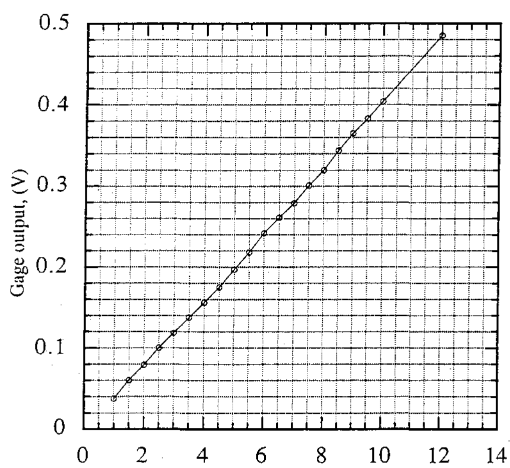

Fig. 3 Sample calibration curve.

Calibration Procedures

A direct force method was chosen for calibrating the skin friction gauge, using standard weights and a digital voltmeter. The gauge was clamped nearly vertical, so that by hanging small weights directly on the sensor head, the sensor was pulled in the streamwise direction. Output in millivolts was read on the voltmeter. The applied weights range from 1 to 12 g. It was very important that the signal return to the same zero after each of the weights was removed. In this respect, the gauge response was repeatable within the drift tolerances. The drift was studied carefully and it was found that the signal drifted 0.5 mV in 3 h, which was approximately 3% of the total expected output signal. A sample calibration curve is shown in Fig. 3.

Cascade

A cascade of four blades was used. The cross section of the blades that was used is shown in Fig. 1a. The tangent of the camber line near the trailing edge was 67 deg. The radius of the trailing edge was 0.125 in., the axial chord was 5.0 in., and the span was 6.0 in. The blades were manufactured of aluminum. The sidewalls of the cascade were two Plexiglas® plates, and the blades were mounted between them with a screw and pin on both sides.

The cascade was placed in the test section of the cascade tunnel at Virginia Tech, a blowdown-type tunnel. The flow conditions in the cascade were set by the upstream total pressure and the exit pressure. The scheme of the tunnel is shown in Fig. 4. This facility is described in more detail in Ref. 10. The tunnel is equipped with a feedback control system for the opening of the main valve in order to achieve a constant upstream total pressure. In this way, the upstream total pressure could be maintained level within 1% for about 20 s, which determined the maximum time for data acquisition.

The two dimensionality of the flow may be questioned for this span-to-chord ratio, but earlier studies, conducted in the same cascade[10] showed that it was acceptable.

Data Reduction

The skin friction balance actually measures a shear force over the exposed part of the sensing head. It has to be nor-

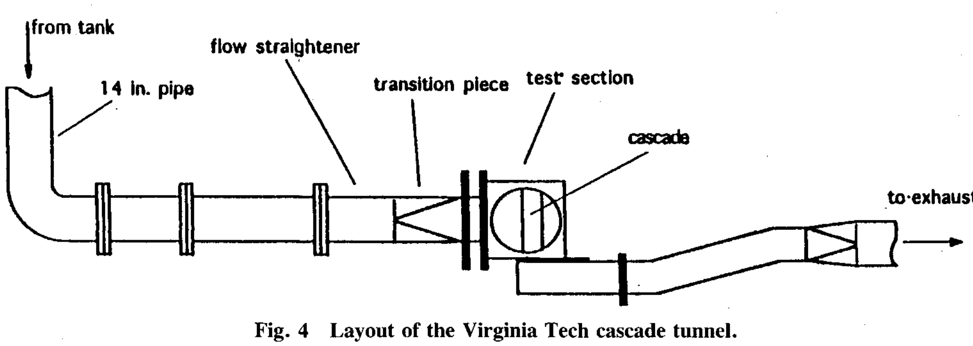

Fig. 4 Layout of the Virginia Tech cascade tunnel.

Table 1 Run conditions and skin friction results

Run no.	M_{exit}	P_0, kPa	P, kPa	M_e	q, N/m^2	τ_w, N/m^2	C_f
1	1.20	159.7	68.1	1.18	68,788	234.8	0.0035
2	1.20	159.7	68.1	1.18	65,788	177.6	0.0027
3	1.20	159.7	68.1	1.18	65,788	192.1	0.0029
4	1.20	159.7	68.1	1.18	65,788	234.8	0.0035
5	0.93	142.5	75.0	1.01	53,000	256.1	0.0047
6	1.03	139.0	66.7	1.09	55,344	298.8	0.0054
7	1.26	159.7	68.5	1.17	61,066	192.1	0.0031
8	1.37	156.2	31.6	1.67	64,008	234.8	0.0036
9	0.84	138.8	81.9	0.90	46,598	85.4	0.0018
10	0.93	142.2	74.5	1.01	52,901	87.5	0.0017
11	1.04	145.7	69.2	1.09	57,401	187.9	0.0033
12	1.10	152.6	68.7	1.14	62,731	256.2	0.0040
13	1.10	154.0	69.3	1.14	63,306	256.2	0.0040
14	1.10	154.0	69.3	1.14	63,306	256.2	0.0040
15	1.10	154.0	69.3	1.14	63,306	213.5	0.0034
16	1.10	152.6	68.7	1.14	62,730	213.5	0.0034

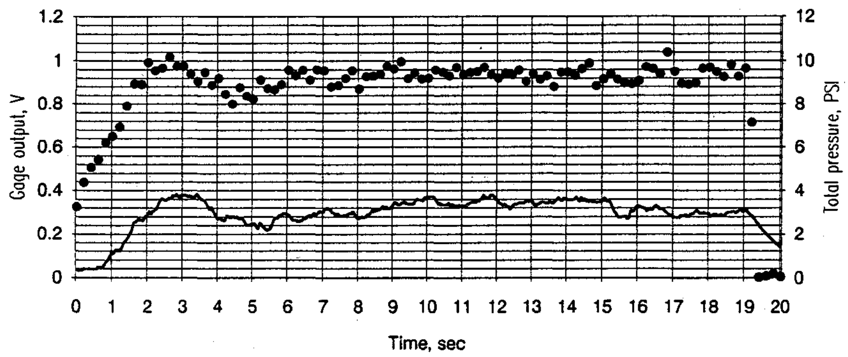

Fig. 5 Sample skin friction and total pressure curves. Run no. 12, M = 1.20. —— = gauge output and • = total pressure.

malized by the area of the sensing head A, that is equal to 1.148 cm^2, to obtain the shear force. In order to calculate the skin friction coefficient

$$C_f = \tau_w / \tfrac{1}{2}\rho U_e^2$$

a value of dynamic pressure at the boundary-layer edge, $q = \frac{1}{2}\rho U_e^2$, is required. Extending this to variables usually measured in compressible flow, $q = \gamma P M^2/2$. In the previous relation, the static pressure P was taken from the measurements of Walls,[11] conducted in the same blade cascade with the same flow conditions, and the Mach number at the sensing head location was calculated from the total and static pressure using isentropic relations.

A sample trace of the skin friction gauge output is shown in Fig. 5 along with the corresponding total pressure trace. The skin friction trace follows the total pressure trace quite well. After the flow is started and stabilized at about 8–9 s, an average value of skin friction output for about 5–6 s can be read before the tunnel flow breaks down.

Experimental Results

A number of tests were conducted with different cascade exit Mach numbers. During the runs, the upstream total temperature and total pressure were measured as the downstream static pressure to determine the exit Mach number. Table 1 presents a summary of the data collected during the test series. Relevant flow conditions including total pressure, total temperature, and Mach number are listed.

Looking at the results, one can see the repeatability of the tests and the skin friction data. For example, the last five runs were with an exit Mach number of 1.100, which resulted in an edge Mach number of 1.14 at the gauge location. The five skin friction results range from a low of 0.0034 to a high of 0.0040 with an average value of 0.0038. This indicates an uncertainty of ±9%. Under the simplest and cleanest test conditions, one can hope to measure C_f to within about ±3–5% at best, and so the 9% figure in this complex geometry and flow appears reasonable. The worst behavior occurred for the Mach numbers very near to unity and rather large uncertainties are indicated in that regime. Also, the shock impinging on the surface near the gauge at the Mach 1.20 exit condition caused larger uncertainties in the results.

The absolute level of the skin friction coefficient measured seems reasonable for a turbulent boundary layer at these conditions. In an attempt to validate our CFD tools, a calculation for the exit Mach number of 1.2 conditions was made for comparison. The calculations were made using the methods described in Ref. 10. The CFD code ANSERS[13] was employed, which is a two-dimensional, finite volume treatment of the full Navier–Stokes equations with an upwind scheme and Roe's flux difference method. Flux limiting was accomplished with the Min–Mod method. Spatial differencing is third order for the inviscid terms and second order for the viscous terms. The whole formulation was solved with time relaxation using a spatially split approximate factorization method. The turbulence model employed was the compressible Clauser eddy viscosity model presented in Ref. 12. Transition was fixed from experimental observation using shadowgraphs. A C-type grid with 219 × 23 points was utilized. Comparison with results from coarser and finer grids indicated grid convergence.

A plot of predicted Mach number contours is given in Fig. 6. Note the shock impinging near the gauge location. Some calculations were made moving the transition point, but the results for the skin friction at the gauge location changed only about 2–3% for the reasonable changes in the transition location. The predicted variation along the surface for different assumed locations for the start of transition and also for calculations assuming a transition zone with various start and

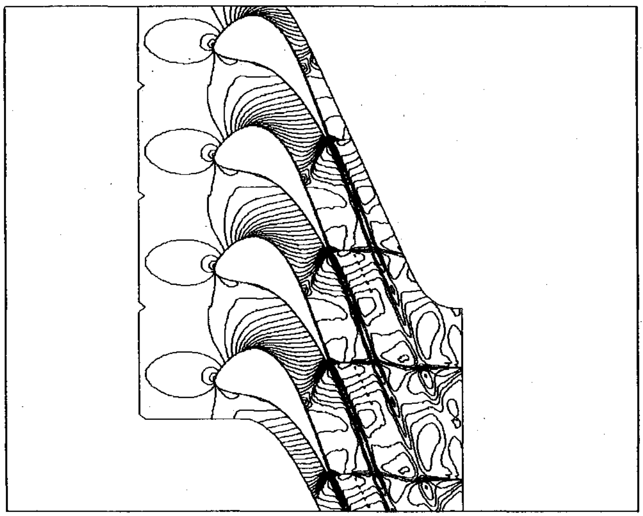

Fig. 6 Predicted Mach number contours for $M_{exit} = 1.2$.

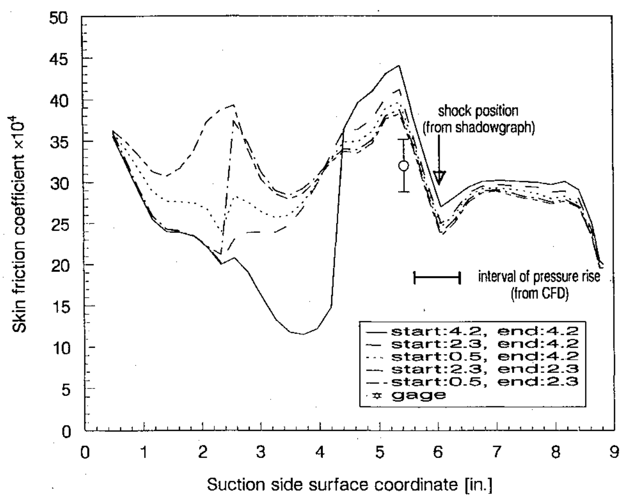

Fig. 7 Predicted skin friction variation with different assumed transition locations.

end locations is shown in Fig. 7. All of the predictions show rapidly decreasing values of C_f near the gauge. The predicted values of C_f varied from 0.0043 at the upstream edge of the gauge to 0.0045 in the center and 0.0040 at the downstream edge. All of the predictions are somewhat above the average value. However, this is a complex region of a complex flow and we view the agreement reasonable in such a situation.

Conclusions

The major goal of designing, constructing, and implementing an instrument to directly measure skin friction on the surface of a turbine blade in a cascade was achieved. The results of the tests showed that repeatable measurements can be obtained with a nonnulling cantilever skin friction balance with a floating head. The results obtained from the cold-flow tests agreed reasonably well with the predictions of a modern CFD code. The gauge location was in a complex regime, because a shock impinged nearby downstream and transition was not far upstream. The shock was also observed to be somewhat unsteady in the experiments. The uncertainty in the transition location determined from a shadowgraph was relatively large. Also, transition was modeled as an abrupt process going from laminar to fully turbulent at the transition station. Altogether, we view the agreement between calculation and experiment as reasonable for such a complex flow.

The value of C_f is only as accurate as the value of q used to nondimensionalize the shear force. A more complete analysis of the cascade flowfield including instream measurements at the gauge location would add to the accuracy of the skin friction coefficient determination.

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