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AFIT/GAE/ENY/93D-6

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THESIS

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THESIS

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Symbol	Definition	
Cp	Specific Heat at Constant Pressure	kJ/kg K
C_{pt}	Total Pressure Loss Coefficient	
$\overline{C_{pt}}$	Mass Averaged Total Pressure Loss Coefficient	
f	Frequency	bars/sec
h_t	Total Enthalpy	kJ/kg
M	Molecular Weight	kg/kmol
P_t	Total Pressure	kPa
$P_{t\infty}$	Upstream Total Pressure	kPa
R	Universal Gas Constant	J/kg K
r	Recovery Factor	
Re	Reynolds Number	
T_t	Total Temperature	K
T	Static Temperature	K
U	Velocity	m/s
U_x	Velocity in X Direction	m/s
U_m	Mean velocity through the cascade	m/s
W_t	Work of Turbine	kJ/kg
x,y,z	Cartesian Coordinates	m
α	Flow Angle	degrees
ρ	Density	kg/m^3
ρ_∞	Upstream Density	kg/m^3
γ	Ratio of Specific Heats	

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Abstract

A linear turbine cascade was used to investigate the effects of wake passage due to stator-rotor interaction. The wakes were modeled by passing 1.98 mm (0.078 in) diameter bars upstream of a linear cascade blade row. Total pressure loss coefficients, mass averaged total pressure loss coefficients and velocities were used to characterize the effects of wake passage.

Bar passing frequencies of 80, 160, 320 bars/sec were tested. These frequencies were tested with the bars at 6.35 mm (0.25 in) intervals and at two Reynolds numbers, 3.41×10^5 and 4.55×10^5.

Bar spacings of 12.7 mm (0.5 in), and 89 mm (3.5 in) were also examined. For a bar spacing of 12.7 mm these tests were made at a Reynolds number of 4.55×10^5 and bar passing frequencies of 80 bars/sec, 160 bars/sec, and with the bars stopped. For a bar spacing of 89 mm these tests were made at a Reynolds number of 4.55×10^5 and bar passing frequency of 40 bars/sec.

The varying Reynolds numbers did not affect the results nor was there appreciable differences for the range of wake passing frequencies. However, for the same bar passing frequency, losses were effectively halved by doubling the

spacing. The lack of influence of frequency and the effect of spacing was consistent with the time scale used. Since the maximum time scale reached was 0.95 any influence due to changes in frequency were not felt in the blade passage. Whereas, for the same frequency, with half the bars, there were half the losses in the passage at any given time.

I. Introduction

Wake Passage Effect

Background An axial flow turbine has alternating sets of rotors and stators. The stator acts as a nozzle and accelerates the flow to the rotor. The rotor is rotating relative to the stator, extracting work from the flow. The flow from the stator, however, is not perfectly uniform. The trailing edge of the stator will produce wakes that travel into the rotor passage. Since there is a relative motion of rotor and stator, these wakes also translate across the inlet of the rotor.

These wakes passing into the rotor may influence the performance of the turbine stage. They may affect the heat transfer, the losses, or the blade boundary layer. How these passing wakes influence the total pressure losses in the rotor is examined here.

Cascade A linear turbine cascade is a model of an axial flow turbine. A cascade (Fig. 1.1 a,b) is essentially a cross section of the turbine blades attached to a hub of infinite radius. When the spacing and geometry of the tip and root of the blade are the same, a cascade is considered linear.

The cascade model has been used since the 1919 (7:21), and has contributed to the improvement of turbomachinery.

The cascade model, however, does not normally take into account the effects of wakes due to the relative motion of the stator and rotor.

Models of Wake Passage A method of introducing wakes in a turbine passage is described by Doorly (3:4.1-4.12). Doorly uses the proposition that the upstream wakes could be produced with bars protruding from a disk (Fig. 1.2) with infinite radius. The main focus of Doorly's work is the effect of wake passing on the heat transfer and blade boundary layer.

Dring (5:5-6) used a full scale rotating turbine rig to study the effect of periodic turbulence. His focus, like Doorly, was on the effect on heat transfer.

For this thesis, wake passing was modeled by translating a row of bars across the inlet to the cascade blades. Unlike Doorly's model, however, the bars traveled perpendicular to the flow and in a plane parallel to the leading edges of the blades in the cascade. The direction of bar travel represented the relative motion of a stator and rotor.

Objective

The objective of this thesis was to measure total pressure losses and investigate the affect of wake passing on those total pressure losses. Three parameters which

could influence the effects on the losses were varied. The three parameters were: the Reynolds number (velocity), the frequency of wake passing, and the spacing of the wakes.

In the following chapter the theory of the total pressure loss, how wake passing was modeled, and why total pressure loss is important is described. Chapter 3 describes the experimental apparatus used to model the wake passing and measure the total pressure loss. Chapter 4 outlines the procedure followed in making the total pressure loss measurements. Chapter 5 contains the discussion of the total pressure loss measurement results. Chapter 6 is a summary of the results and the work done on this thesis. Chapter 7 lists the recommendations to expand the investigation of wake passing effects.

II. Theory

Turbine Speeds

The premise of this thesis was to model the wake passage of the upstream row of stator vanes into a rotor and determine the effect on total pressure losses. Wake passing was modeled by passing a row of 1.98 mm (0.07813 in) diameter bars across the inlet to the row of blades. The size of the bars was chosen to represent the trailing edge of an upstream stator vane.

However, the frequency of wake passing modeled for this thesis could not hope to approach the frequency of wakes passing in a turbine. A turbine rotor rotates about 15000 RPM. If a turbine stator has 100 vanes a rotor blade experiences 25000 wakes passing every second. The maximum bar passing frequency achieved for this thesis was 320 bars/sec.

Therefore, the speeds and spacings of the bars were chosen in an attempt to model the time scale of an actual turbine. The time scale is the ratio of the time for a particle of air to pass through the rotor passage to the time for a new wake to enter the rotor passage.

$$S = \frac{\frac{C}{U_m}}{\frac{1}{f}} = \frac{f\,C}{U_m} \qquad (2.1)$$

In an actual turbine the time scale is on the order of 1.5. Unfortunately this time scale could not be reached and the maximum time scale achieved was 0.95.

Pressure Loss to Lost Work Relation

The stator or nozzle in an axial flow turbomachine produces no work. Therefore, there is no drop in total temperature across the adiabatic stator. However, when dealing with a row of blades a total pressure drop is observed. This total pressure drop arises (2:65) from the friction of the blades. Total pressure losses in turbomachinery are important because they result in lost potential work.

The work of a stage (stator and rotor) of a turbine is the change in enthalpy across the stage. Since no work is done in the stator there is no change in total temperature across the stator. Ideally the amount of work from the turbine stage then is:

$$W_t = h_{t1} - h'_{t3} = C_p (T_{t1} - T'_{t3}) \qquad (2.2)$$

Exaggerated in Fig. 2.1, it can be seen that for an isentropic expansion in the rotor, a total pressure loss in the nozzle results in a work potential of:

$$W_t = h_{t2} - h_{t3} = C_p (T_{t2} - T_{t3}) \qquad (2.3)$$

Thus there is a net loss of work of:

$$W_t = h_{t3} - h'_{t3} = C_p (T_{t3} - T'_{t3}) \tag{2.4}$$

Attempts to analytically determine the total pressure loss do not deal with the issue of wake passage. Dixon (2:82-87) divides the loss into three parts (i) profile loss, (ii) secondary loss, and (iii) tip clearance loss. This method accounts for friction, complex three dimensional flows, and the gap at the tip of the rotor. He also states there exist methods to predict the performance to within 2% for on-design conditions.

Cohen et al. (1:290-292) discusses the losses in the trailing edge due to the size, and the pitch/chord ratio. Hill and Peterson (8:383) approach the issue of predicting entropy generation due to trailing edge wake. None of these approaches, however, deal with the influence of the trailing edge on the next row of blades.

Characterization of the Tunnel

The performance of a cascade is characterized by the total pressure loss. The total pressure loss is generally given as:

$$C_{pt} = \frac{P_{t\infty} - P_t}{\frac{1}{2}\rho_\infty U_\infty^2} \tag{2.5}$$

for a particular point in the flow. Following the example of Langston et al. (9:22) C_{pt} for this thesis was normalized by the upstream dynamic pressure. Often this same parameter is normalized by the downstream dynamic pressure.

The total pressure loss is then usually averaged (normally on a mass basis) giving the mass averaged total pressure loss.

$$\overline{C_{pt}} = \frac{\iint \rho U_x C_{pt}\, dxdy}{\iint \rho U_x\, dxdy} \qquad (2.6)$$

Total pressure loss coefficient and mass averaged total pressure loss coefficient were the two figures of merit that were quantified for this thesis.

III Experimental Apparatus

Turbine Cascade Test Facility

The tests for this thesis were done on AFIT's linear Turbine Cascade Test Facility (TCTF). The linear turbine cascade is located in Building 19, at Wright-Patterson AFB, Area B. The tunnel has been used for a number of theses, including Gallasi(1989), Acree(1990), and Meschwitz(1991). The cascade is adaptable to many types of experiments and extensive modifications were made for this thesis.

The tunnel (Fig. 3.1) has a bell mouthed inlet. Because the inlet is open to the atmosphere, the air is screened and filtered before entering the tunnel. The cascade then contracts at a 7:1 area ratio where the air flow enters a rectangular passage leading to the test section. The inlet to the test section is 11.43 cm (4.5 in) from the top to bottom and is 30.5 cm (12 in) wide. It is constructed of clear 1.27 cm (0.5 in) thick Plexiglass. The flow is guided by two internal clear Plexiglass sidewalls. These sidewalls are adjustable in order to vary the inlet angle. For this thesis the inlet side walls were fixed to give a constant inlet angle of 45 degrees.

The test section is a 60.96 cm (24 in) diameter chamber that can be rotated to vary the inlet angles. In the test section are four blades mounted on a removable platform.

This is to allow easy access for any blade modifications. On the bottom of this platform, static pressure ports are tapped at the leading and trailing edge of the second blade. The test section is covered by a removable clear Plexiglass top. The exit flow is channeled down two more internal clear Plexiglass side walls into a draw-down fan.

The fan is a 20 hp 45.72 cm (18 in) diameter centrifugal blower. The speed can be varied by adjusting a variable vane at the blower inlet. The fan is normally able to provide an exit Reynolds number of 6.83×10^5 (90 m/s). A Reynolds number of 4.55×10^5 (60 m/s) was the limit of the fan for this thesis due to blockage of the wake passing mechanism.

The test section has four blades, two of which are shown in Fig. 3.2 a. The blades were modeled after those used by Langston et al. (9:21). The span of the blades is 11.43 cm (4.5 in), they have a chord of 11.43 m (4.5 in), a spacing (pitch) of 8.89 cm (3.5 in), and an aspect ratio of 1.

The two end blades are constructed of aluminum. The blades in the center are made of urethane foam. Blade #2 (Fig. 3.2 b) is instrumented with static pressure taps and thermocouples. The static pressure taps and thermocouples on the instrumented blade were not used for this thesis.

Wake Passing Mechanism

Modifications to TCTF Extensive modifications were made to the test section. A triangular piece of Plexiglass was removed from the center of the circular test section cover, directly above the blades. The edges of the triangular piece were milled down and it was placed (Fig. 3.3) back in its own hole. Held in place by three brackets, this left a triangular slot in the top of the cascade. The slot created a perimeter around the blades for bar passage.

Five additional slots were cut in the triangular top to allow access to the flow. The slots were cut perpendicular to the x axis at 2.54 cm (1 in) intervals and spanned the center two blades (Fig. 3.4 a). Pressure and velocity measuring instruments were introduced through these slots. This distributed the measurements for the performance of the tunnel into five planes. Slots that were not being used for measuring were sealed.

The inlet and exit side walls also had to be modified to allow the bars to pass through them. Therefore, a passage for the bars was cut (Fig. 3.4 b) into the two inlet and one exit side walls, essentially cutting each side wall into two pieces.

The belt in which the bars were mounted was a neoprene rubber, double sided V-belt (Dayco, BB43), normally used for

power transmission. 183 holes were drilled in the belt and small 1.98 mm (0.07813 in) diameter bars made of drill rod were force fit into the holes. Most of the bars were held in place by friction although some bars were modified to keep them from coming loose.

To increase the friction to hold the bars in the belt, the end of a bar was knurled and a drop of solder placed on it. When the solder solidified, but while it was still quite hot, the soldered end of the bar was then reinserted into the hole. Concerns about the ability of the belt to take the extra stress, however, forced this method to be used on a limited number of bars. Approximately one third of the bars were treated in this manner.

The belt was mounted on three sheaves (pulleys), one at each corner of the triangular piece of Plexiglass. The pulleys were mounted to the Plexiglass with a screw flush with the inside wall. One of the pulleys was a double pulley. Attached to the double pulley was the driver belt.

The driver belt was a V-belt (Dayco, L524), also normally used for power transmission. It was attached to a Power Matched/RPM Reliance Electric DC Motor. The motor was mounted to the frame of the linear turbine cascade. The speed of the motor was adjustable and was controlled by a Reliance Electric (DC1-70V) DC Electric Motor Controller.

The bars traversed in a continuous loop. First, they

passed through a slot in an entrance sidewall. Then, they translated parallel to the leading edge of the blades, where they were held perpendicular to the flow by a guide (Fig. 3.5 a) on the bottom wall of the cascade. The direction of the bars representing the relative motion of a row of stator vanes. Next, the bars passed through another slot in a sidewall. Finally, they looped back behind the blades downstream, through the two exit sidewalls, to come around for another pass. The path of the belt/bars can be seen in Fig 3.5 b.

A secondary cover (not shown) was fashioned to reseal the tunnel after the triangular slot was made. The purpose of the second cover was to stop any transfer of air into the tunnel through the triangular slot. This cover enclosed all the pulleys and the whole belt path. The seal was not complete, however, because holes had to remain in the secondary cover to allow the driver belt to engage the double pulley.

Limitations The parameters of the data being measured were influenced by the capability and limitation of the equipment. The bars in the passage upstream of the blade basically created a blockage which restricted the air flow capability. The draw-down fan, then, could only provide a Reynolds number of 4.55×10^5 compared to 6.83×10^5 without the bars in the flow path.

The bar speed was limited by the construction of the belt, the motor, and safety concerns. A minimum setting on the motor control prohibited low speeds. At high speeds, vibration of the motor, physical contact with side walls or bottom, and/or the centrifugal effect would cause the bars to slip out of the belt. A bar slipping out of the belt was potentially dangerous and needed to be monitored. A safety issue arises if a bar were to be ingested into the fan. Therefore, the bars were stopped after every test run to make any needed adjustments.

Instrumentation

HP3852A All pressure and temperature data measurements that were taken for this thesis were channeled through a Hewlett Packard HP3852A Data Acquisition and Control Unit. The HP3852A was equipped with three 24 Channel High-Speed FET Multiplexers, a 8 Channel Relay module, a High-Speed Voltmeter and an Integrating Voltmeter. The HP3852A acquired all analog transducer signals and performed the analog to digital conversion. The HP3852A was remotely programmed and controlled by a Zenith 386 PC via a National Instruments General Purpose Interface Bus (GPIB).

Temperature Temperature measurements were taken with J-type thermocouples. The thermocouples were attached to the HP3852A directly. The HP3852A was already configured

for these thermocouples so no calibration was necessary. These J-type thermocouples were iron/constantan and suited for the temperature ranges used.

Pressure An important tool used for this thesis was a 36 port Scanivalve. The Scanivalve was used to take all the pressure measurements. The Scanivalve was equipped with a pressure transducer and referenced to atmosphere. The Scanivalve pressure transducer received signal amplification from an Endevco Model 109 Power Supply Conditioner unit. A Scanivalve CTRL2P/S2 solenoid controller controlled the stepping procedure to access different ports.

Total pressure measurements were made with a Kiel probe, and a pitot-static probe. A Kiel (Fig. 3.6) probe is less sensitive (Fig. 3.7) to the incoming angle of the flow (6:249). It was used for total pressure measurements just behind the bars where the angle of the flow was unknown. A pitot-static tube was used to measure the total pressure at points inside the passage between blades 2 and 3.

Velocity and Angle Two different methods for measuring the velocity were available. A single hot wire placed in the flow was one method. An IFA-100 Intelligent flow analyzer was used to measure the voltage to determine the velocity.

The second method for measuring the velocity, and the method used for the data presented in this thesis, was with

the pitot-static tube. The tube was zeroed in yaw into the flow by maximizing the total pressure. A protractor mounted to the top of a brass holder (Fig. 3.8) allowed angle measurement to within ± 2.5 degrees. The pitot static tube, along with the total temperature measurement and angle of the flow provided all the necessary information to determine the velocity.

Either method for determining total pressure loss and velocity would have worked. Different measuring methods and instrumentation (7:32) do not greatly affect the integrated values of velocities and loss. Problems with the fragility of the hot wire and short supplies forced the decision to use the pitot-static tube measurements exclusively.

<u>Bar Passing Frequency</u> The frequency of wake passing was measured with a ISSC-1262 Motion Detector. Attached to the motion detector was a magnetic flux device. When the lines of magnetic flux were broken by a conducting metal, a current was induced. The metal used to trigger the motion detector was a steel bolt threaded into the top of the pulley on the driver motor (Fig. 3.9). The motion detector amplified the signal and sent it to a Racal-Dana Nanosecond Universal Counter. The counter was set to measure the period between trigger signals. The period was then converted to bar passing frequency.

The motor was steady and could maintain the period

±0.01 seconds for low speeds and control improved with higher speeds. This translates to a frequency range of approximately ±2 bars/sec.

Software

The software for this thesis was written in BASIC using Microsoft QuickBasic 45. The purpose of the software was mainly to control the HP3852A. However, the computer also collected and stored all the data.

Several calibration, data reduction, and data collection programs existed for other theses which used the TCTF. The programs used to collect data for this thesis were either modifications of those same programs or were written using modules from those programs. A listing of programs with flow charts is located in Appendix A.

The programs that were used to calibrate the pressure measuring devices and the hot wire were PRESSCAL.BAS and XWIRCAL.BAS respectively. These programs were written by Gallasi (1989), with modifications by several other students. No major modifications were needed to utilize these same programs.

The programs that were used to control the HP3852A for the pressure measurements were ISOBAR3.BAS and ISOBAR6.BAS. ISOBAR3.BAS acquired total pressure measurements only. ISOBAR6.BAS performed the same measurements as ISOBAR3.BAS

with additional subroutines to acquire angle measurements. ISOBAR6.BAS also had a continuous loop for the purpose of pointing the pitot-static probe into the flow. The two ISOBAR programs used were essentially two different versions of the same program and were written exclusively for this thesis. Since all measurements were made manually, both programs used graphics to help the user find the point in the tunnel where measurements were to be taken. ISOBAR6.BAS could also acquire the angle of the flow via manual input by the user. These were necessary measurements to determine to total pressures loss as well as the mass averaged total pressure loss.

VELAQ3.BAS acquired the velocity from the hot wire. This program was also a modification of 1SOBAR3.BAS. It used the same graphic features to help the user locate the point to be measured. The programs let the user acquire angle and velocity at any point in the flow.

As a time saving step VELAQ3.BAS, ISOBAR3.BAS and ISOBAR6.BAS did any data reduction internally. However, all raw data was saved as a precautionary measure.

Table 3.1 shows the programs used to acquire data for this thesis. The table also give a brief description of what each program does.

Table 3.1 Programs Used and Description

Programs Used	Purpose and Description	Output
XWRECAL.BAS	Calibrate hot wire	Calibration Curve
PRESSCAL.BAS	Calibrate pressure transducer	Calibration Curve
VELAQ3.BAS	Velocity measurements with hot wire	Velocity and Angle
ISOBAR3.BAS	Total pressure measurements	C_{pt}
ISOBAR6.BAS	Total and static pressure measurements, velocity, and angle	C_{pt}, Angle, Velocity, U_x

IV. Procedures

Calibration

The main data taking devices were the pressure transducer in the Scanivalve and J type thermocouples. The pressure transducer required calibration. The calibration of the pressure transducer as discussed by Meschwitz (10:4.2) required applying a known pressure to the transducer and recording the associated voltage. The relationship between the pressure and voltage was linear. A detailed calibration procedure can be found in Appendix B.

Pre-Test

Instrumentation Warm Up Before a test was run the instrumentation was warmed up. Meschwitz (10:4.6) states that he allowed approximately two hours for the Scanivalve to stabilize. The two hour wait for the Scanivalve was the controlling factor on the start time for any measurements. However, this time also allowed any other equipment to warm up.

Tunnel Velocity The rough tunnel velocity was determined by a pitot-static tube directly behind the bars. The pitot-static tube was connected to a U-type manometer. The height of the water in the U-type manometer could be converted to velocity. In order to make a good

determination of the tunnel velocity the bars had to be set in motion. If the bars were not set in motion the pitot or static port of the probe might sit in a wake of a bar, giving erroneous results on the manometer.

Total Pressure and Velocity

Location The measurements for planes 1-4 were all made in the passage between the second and third blades of the cascade (Fig. 3.4 a). The placement of the probe was limited by physical interference with the blades. A traverse of a plane went from the pressure side of blade 3, with the vertical stem of the probe in physical contact with the blade, to suction side of blade 2. Towards the suction side of blade 2 enough room was provided between the vertical stem of the probe and the blade to allow the tip of the pitot-static probe to rotate. This room was allowed so probe could rotate to point into the direction of the flow. A full span of plane 5 could be made because there was no interference. The measurements of plane 5 started with the probe at the trailing edge of blade 3 and went to just beyond the trailing edge of blade 2.

Scope The original test plan included two Reynolds numbers, four different bar passing frequencies, and a test with no bars in the flow. Four additional tests were later included. These additional tests were done to examine the

influence of bar spacing on the losses. Table 4.1 is a list of the tests conducted. The Reynolds number referred to in Table 4.1 is the Reynolds number based on chord length and exit velocity.

Table 4.1 Tests conducted in TCTF with bar passing mechanism

Bar Frequency (bars/sec)	Low Reynolds	Medium Reynolds
No Bars	3.41×10^5	4.55×10^5
Bars Stopped - 6.35 mm spacing	3.41×10^5	4.55×10^5
80 -6.35 mm spacing	3.41×10^5	4.55×10^5
160-6.35 mm spacing	3.41×10^5	4.55×10^5
320-6.35 mm spacing	3.41×10^5	4.55×10^5
Bars Stopped - 12.7 mm spacing	-	4.55×10^5
80 -12.7 mm spacing	-	4.55×10^5
160-12.7 mm spacing	-	4.55×10^5
40 -88.9 mm spacing	-	4.55×10^5

<u>Pressure Loss Measurements</u> A typical test run consisted of making total pressure and velocity measurements for all five planes at a single Reynolds number and a single bar passing frequency. The velocity and pressure

measurements were taken at the same time with a pitot-static probe.

With the tunnel running at the desired velocity, the desired bar speed was set and a probe was introduced to the flow through the slots in the top. A set screw on the pitot-static tube allowed precise placement of the probe in the mid-span of the cascade passage. All other slots not being used for measurements were sealed. A movable seal allowed the probe to be placed in different locations in slot for the plane being measured. All measurements were taken with y=0 to be with the vertical stem of the probe in physical contact with the pressure side of blade 3. Marks scribed into the top cover of the cascade and an index on the brass probe holder permitted precise y placement each time that plane was measured.

Problems arose while trying to find the reference (ie upstream total and dynamic pressure). The normal procedure is to fix a probe far upstream of the cascade test section and use the data from this probe for normalization. However, at a far upstream location the bars had not yet influenced the flow. Therefore, using far upstream condition was not a fair representation on which to base the total pressure loss. Also, since the bars were only located one half chord upstream of the blades, the flow has already come under the influence of the blades and has begun to turn and

and accelerate. A dynamic pressure determined from a pitot static tube in this location could be made to give a range of dynamic pressure by changing the angle of the upstream probe.

Therefore, as a reference state the upstream conditions were characterized as follows: Total pressure measurements were made with a Kiel probe just behind the bars (The Kiel probe is less sensitive to variations in the incoming angle of the flow). The upstream static pressure used for normalization was a pneumatic average of several static pressure measurements. Four static pressure ports (Fig. 4.1) on the bottom of the tunnel and the static pressure from a pitot-static probe located in the center of the inlet of the adjoining passage were averaged. This averaged value was used for the dynamic pressure.

When the upstream measurements were made for the bars stopped tests, a slightly different method was used to determine the upstream condition. First, the steps were followed to find the rough tunnel velocity. The height of the manometer was then noted and the bars were stopped. As mentioned before, with the bars stopped the manometer might give erroneous results, so the bars were turned by hand to give the same manometer reading as with the bars in motion. This procedure then gave the same reference point to all the test cases whether the bars were moving or not.

Fig. 4.2 shows three important details about the TCTF and the wake producing mechanism. First it shows that the total pressure inside the tunnel is less than the atmospheric pressure. This is due to losses introduced by screening and filtering necessary at the inlet to the TCTF.

Secondly, the data identified with the triangles shows the difficulties in finding a reference point. The total pressure reading varied with changes in the angle of the probe. A higher total pressure was measured at 35 degrees than at 45 degrees, the inlet condition. With the bars at the low frequency, this pressure (measured just behind the plane of the bars) was the maximum that could be achieved. Which leads to the third detail.

The initial expectation was that passing the bars in front of the blades would produce an average pressure between that for the clean flow, when there was no bar directly upstream, and when in a wake of an upstream bar. What the plot shows, however, is that the pitot tube in this location doesn't experience the average pressure drop. When the bars were moved at small increments to different positions upstream of the probe the wakes could be mapped and they always show a higher or equal total pressure than the measurements made with the bars in motion. This means that with the pitot probe behind the plane of the bars, when the bars are spaced at 6.35 mm (0.25 in) and moving, the

pressure drop is not an average but rather represents the minimum total pressure after the bars.

The Scanivalve scanned the five static pressures and the total pressure from the Kiel probe once each plane before the in-plane total pressure measurements were taken. The total pressure measurement inside the plane was made by turning the pitot probe into the direction of the flow. The software had a continuous loop instructing the Scanivalve to continue scanning until a user input stopped it. The probe was zeroed in yaw by monitoring the pressure measurements on the computer monitor. When the pressure measurement maximized, the angle was input into the computer, stopping the scanning and recording the pressure and the angle. With the probe still in that location the Scanivalve next scanned the static pressure port on the probe.

Temperature Measurements The computer also acquired the total upstream temperature once per plane before the in-plane total pressure measurements were taken. A thermocouple was placed upstream of the bars. To measure total temperature the thermocouple was placed just inside the top of the inlet and in the boundary layer. The temperature measured was actually the recovery temperature (where the recovery factor is the percent of kinetic energy recovered) but was taken to be the total temperature.

$$T_t \approx T_r = T + r\frac{U^2}{2Cp} \qquad (4.1)$$

Since the velocities dealt with were small the differences between total and recovery temperature was less than 1 degree.

Using isentropic relations and knowing the total and static pressure at that point, static temperature was calculated by the computer.

$$\frac{T_t}{T} = \left(\frac{P_t}{P}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} \qquad (4.2)$$

The total temperature and the static temperature determined from isentropic relations then went into determining the velocity.

$$U = \sqrt{2\frac{\gamma}{\gamma-1}\frac{R}{M}(T_t-T)} \qquad (4.3)$$

V. Results and Discussion

This chapter contain a discussion of the results of the measurements made for this thesis. Discussed are the effects due to changes in the three parameters: Reynolds number, frequency of wake passing, and spacing. The chapter also includes a discussion of the time scale and its influence on the results.

Results of Measurements at Re = 3.41×10^5

Total Pressure Loss Coefficient Figures 5.1-5.10 are the results of the tests at the lower Reynolds number, Re = 3.41×10^5. Plotted on each figure are the results of two test runs at each frequency. The C_{pt} plots (Fig. 5.1-5.5) have three distinct sets of lines: A thick band of lines in the center, one set that varies over the range of the plot, and one line near zero. The band of data in the center is the C_{pt} for the frequencies of 80, 160, and 320 bars/sec. The total pressure loss for the higher frequency tends to stay to the top of the band while the lower frequency stays near the bottom of the band. This would mean an increase in the losses due to higher frequency. This, however, is inconclusive because all the data was within the margin for error, ± 0.015 C_{pt}.

The set of data for bars stopped varies over the range of the plot. This indicates alternating regions of wakes and clean air. Putting the pitot-static probe in the wake of a bar shows high losses while the probe in clean air shows low losses. In plane 1 the losses become negative. This data is explainable.

For the upstream conditions a Kiel probe was used. The face of the Kiel probe is larger than spacing of the bars so it would always capture part of a wake when the bars were stopped. The pitot probe is much smaller and can be put between wakes. Since plane 1 is near the same plane as the upstream reference point, C_{pt} can be negative if the pitot probe is placed in clean air while the Kiel probe is not.

The bottom single line is the cascade tested with no bars, showing that the bars being in the cascade do indeed affect the results by increasing the total pressure loss.

In plane 5 (Fig. 1.5) the C_{pt} plots show a large variation near the suction side of the blade. This is a result of using the pitot-static probe to measure the total pressure. Flow measurements were made by maximizing the total pressure in the pitot tube. Near the suction side, the flow separates from the blade. Thus there are two maximum total pressures, one inside the separated region and the one just outside the separated region.

The traverse of plane 5 was slightly greater than 8.9 cm (3.5 in). This was to insure at least one complete pass of the span of the blades

Velocities The velocities (Figs. 5.6 - 5.10) followed a consistent pattern. The velocities were lower at the pressure side and increase closer to the suction side. The three bar frequencies and bars stopped results were all in the same band of data. Any differences that show up in the mass averaging, then, are dependent on C_{pt}, not the velocities. The data for the no bars condition is slightly different than the frequency data. For example Fig. 5.7 shows a higher velocity in plane 2 for the no bars condition. When the bars were removed from the test section the characteristics of the tunnel changed and the flow velocity was adjusted, but not to exactly the same velocity.

Angle Figs. 5.11-5.15 are the results of the flow angle measurements. The 0 degree angle is the x-axis of the cascade. Clockwise from that axis is positive (ie flow entering the test section at $\approx 45^{o}$) and counterclockwise is a negative angle (ie flow leaving at $\approx 55^{o}$)

Result of Measurements at Re = 4.55×10^{5}

Total Pressure Loss Coefficient Figures 5.16-5.30 are the results of the test at the higher Reynolds number. For the three frequencies that were also tested at the lower

Reynolds number, the results follow the same pattern. The curve for the 320 bars/sec frequency tends to stay near the top of this band while the curve for the 80 bars/sec frequency stays near the bottom. Again, this is inconclusive because all the data was within the margin for error, ±0.015 C_{pt}.

The spacing of the bars turned out to be the important parameter. For the same bar passing frequencies, losses were effectively halved by doubling the spacing. Consistently, by increasing the bar spacing by a factor of approximately fourteen, the losses went down by the same margin (Although in this latter case, the greatest bar passing frequency that could be achieved was 40 bars/sec.)

Velocities The velocities (Figs. 5.21 - 5.25) followed the same pattern as the velocities at the lower Reynolds number. The velocities were lower at the pressure side and increase closer to the suction side. Again, the results show the velocities for all the cases in the same band of data.

Angle Figs. 5.25-5.30 are the results of the flow angle measurements. The 0 degree angle is the x-axis of the cascade. Clockwise from that axis is positive (ie flow entering the test section at ≈ 45°) and counterclockwise is a negative angle (ie flow leaving at ≈ 55°)

Mass Averaged Total Pressure Loss

The results of the mass averaging (Figs. 5.31 and 5.32) show the three frequencies (80, 160, 320 bars/sec) are on the same line. This is true for both Reynolds numbers. In fact, there is no difference between the $\overline{C_{pt}}$ for the three frequencies at the two Reynolds numbers. This is expected because the Reynolds numbers at which the tests were made were greater than the critical Reynolds number of 2×10^5 (based on inlet velocity and blade chord). Above this the critical Reynolds number Dixon (2:66) show that changes in Reynolds number have no effect on $\overline{C_{pt}}$.

In Figs 5.21 and 5.22 the line for bars stopped, appears to be slightly lower. Statistically, for such a wide variance not enough data was taken to calculate a proper mean, so these points may not be an accurate representation of $\overline{C_{pt}}$. More data points taken per plane in the TCTF would, statistically, make the results cleaner.

The mass averaging also shows the effect (Fig 5.22) of spacing. The results are consistent. For one half the bars, at the same bar passing frequency, the losses were halved. With the bar spacing at 8.89 cm (3.5 in), approximately fourteen time the original spacing, the losses went down proportionally.

Influence of Time Scale

The time scale was always less than, so one changes in frequency could not be felt in the passage. That is, the influence of the wake of any bar not directly in front of the inlet to the blade row passage had left the passage before a new wake had entered the passage. Thus regardless of the frequency, for a time scale less than one, there was always exactly one wake per upstream bar.

Since the wake of each bar represents a loss mechanism, the mass averaged total pressure loss in the passage at any given time was the same for any frequency. This includes the bar stopped condition.

This shows that the bars stopped condition actually is no different than bars passing for a time scale less than one. Thus if one wants to model wake passing, for a time scale less than one, all the moving mechanisms are not needed. All that would be needed is a set of non-translating bars placed in the flow. The complexities in modeling the stator-rotor interactions have then been simplified.

VI Summary

A linear turbine cascade was used to determine the effects of wake passage due to stator-rotor interaction. The wakes were modeled by passing 1.98 mm (0.078 in) diameter bars upstream of the cascade blade row. Total pressure loss coefficients, mass averaged total pressure loss coefficients, and velocities were used to characterize the effects of wake passage.

C_{pt} and $\overline{C_{pt}}$ were both based on upstream conditions. Difficulties with this were addressed by using an upstream total pressure and an average upstream static pressure. This approach led to consistent results.

The losses, due to the introduction of the bars into the passage, was greater than with no bars in the passage. The effects of changing the frequency of bar travel, however, were minimal. Certain trends could be observed but they were within the margin for error, $\pm$ 0.015 C_{pt}. Also, these trends get less pronounced, or become negligible, when the results are mass averaged.

Changing the Reynolds number from 3.41×10^5 to 4.55×10^5 also had little effect on the mass averaged total pressure losses. The two Reynolds numbers chosen to be tested were above the critical Reynolds number, so this result was not unexpected.

The concept that proved to be important was the time scale of wake passage. The time scale was always less than, so one changes in frequency could not be felt in the passage. That is, the influence of the wake of any bar not directly in front of the inlet to the blade row passage had left the passage before a new wake had entered the passage.

Thus, regardless of the frequency, for a time scale less than one, there was always exactly one wake per upstream bar. This leads to the result that the mass averaged value of the pressure loss with the bars moving was no different than the mass averaged value of the pressure loss with the bars stopped.

VII Recommendations

Further Studies

Charts of performance of a turbine cascade are sometimes plotted with total pressure loss vs angle of incidence. The angle of incidence for this thesis was fixed. Another study could be done with variation in incidence using the TCTF.

Heat transfer effects using this wake passing mechanism were studied, concurrently to this thesis, by Capt K. Scott Allen. His research covered the same cases, so the effect of bar spacing on heat transfer has been examined with this set-up.

Wake Producing Mechanism

The wake producing mechanism worked better than was expected. However, it could use some improvements. The shop could manufacture a better second cover to seal the cascade. The new cover could be made of Plexiglass for viewing reasons. Also, it could be made to completely enclose the motor. Thus the seal would be complete.

The bars could be held better in the belt by using the soldering method described in Chapter 3 or some other method. With the bars held more securely the frequency of bar passing could be increased. With an increase in

frequency a time scale that better represents engine conditions might be reached.

An increase in time scale could also be achieved if the Reynolds number is lowered. However, decreasing the Reynolds number to change the time scale might have two effects. First, it would increase the time scale, but secondly if the Reynolds number is dropped below the critical Reynolds number it may influence the characteristics of the tunnel in ways not dependent on the time scale.

Instrumentation

The Scanivalve has a limitation of only being able to scan only one port at a time and can only advance when changing ports. Pressure measuring systems are available with more flexibility. (The measurement of time discrete wake passing effects might be possible.)

A pitot tube which was bent into a 'C' could increase the range of measurement into the back plane. According to Moore (11:1) a large portion of the losses occur there. This probe could also be used to base the total pressure losses on the downstream conditions rather than the upstream conditions.

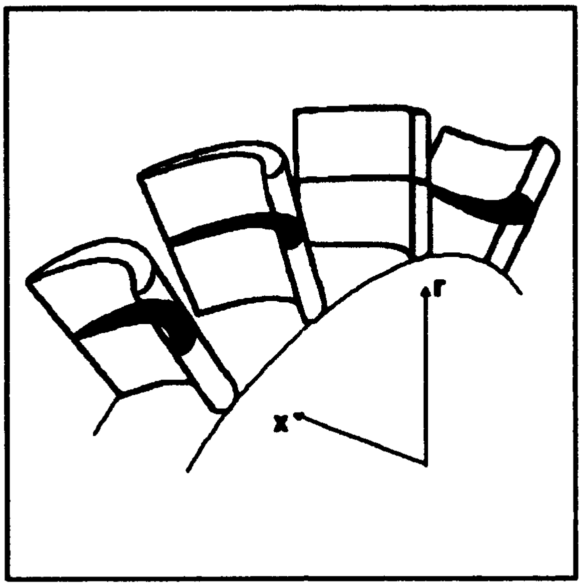


Fig. 1.1 a) Turbine blades

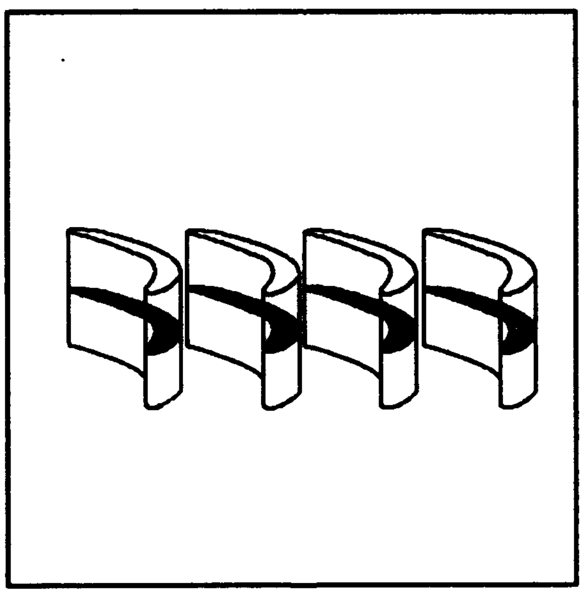


Fig. 1.1 b) Cascade blades

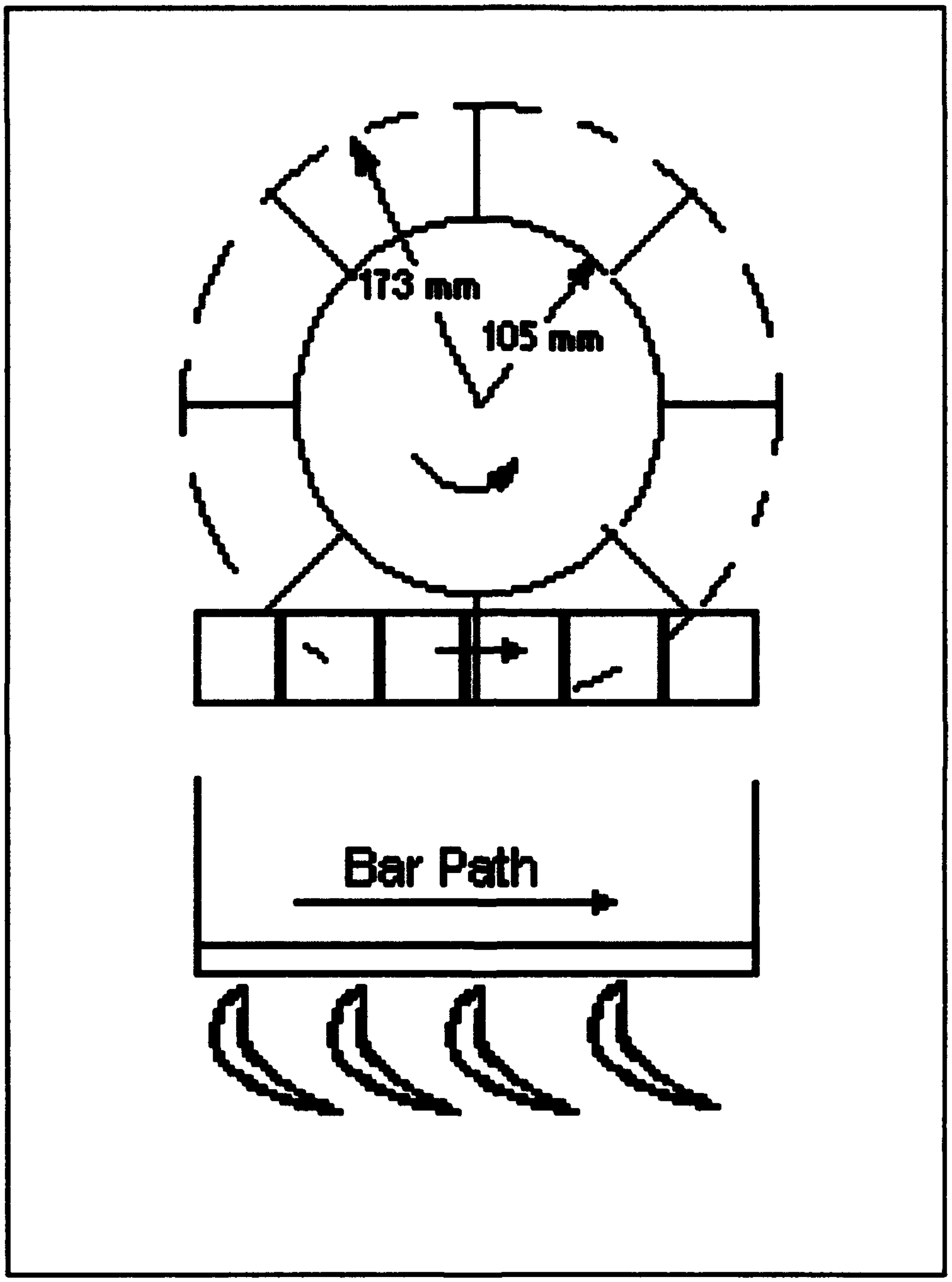


Fig. 1.2 Wake producing system described by Doorly (4:999)

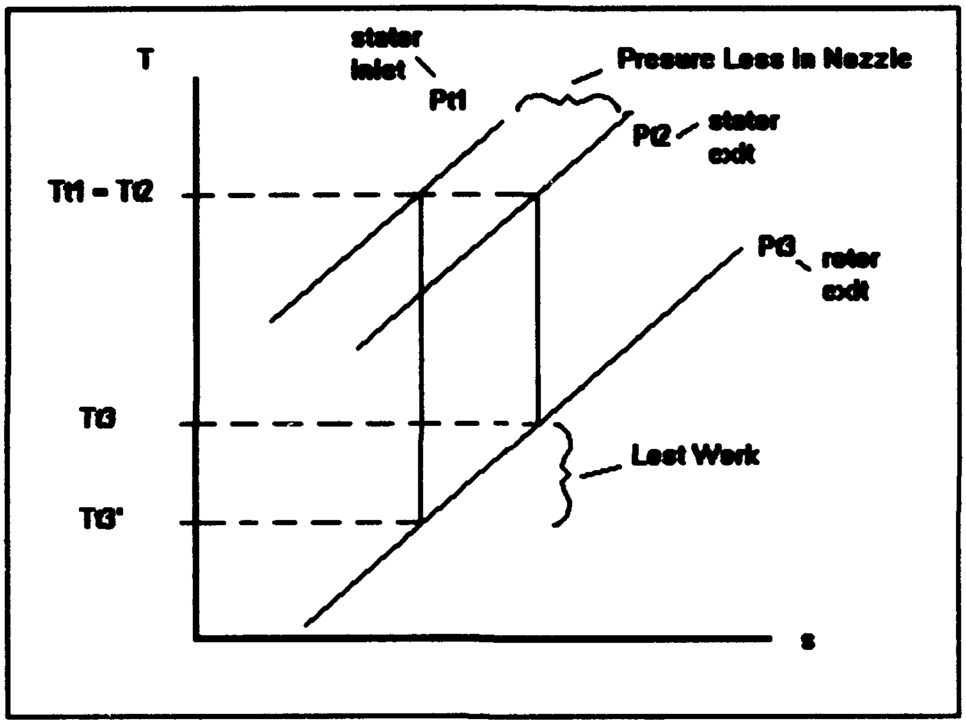


Fig. 2.1 T-S diagram - Lost work due to total pressure loss

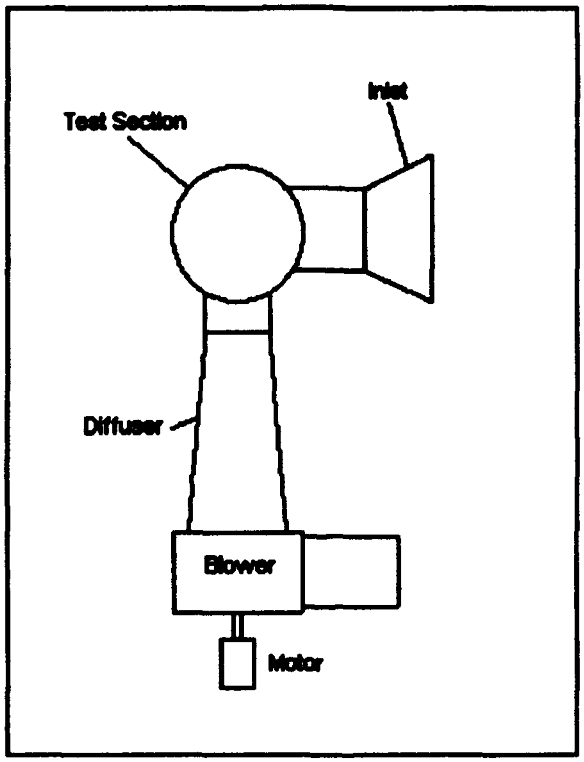


Fig. 3.1 AFIT's Linear turbine cascade

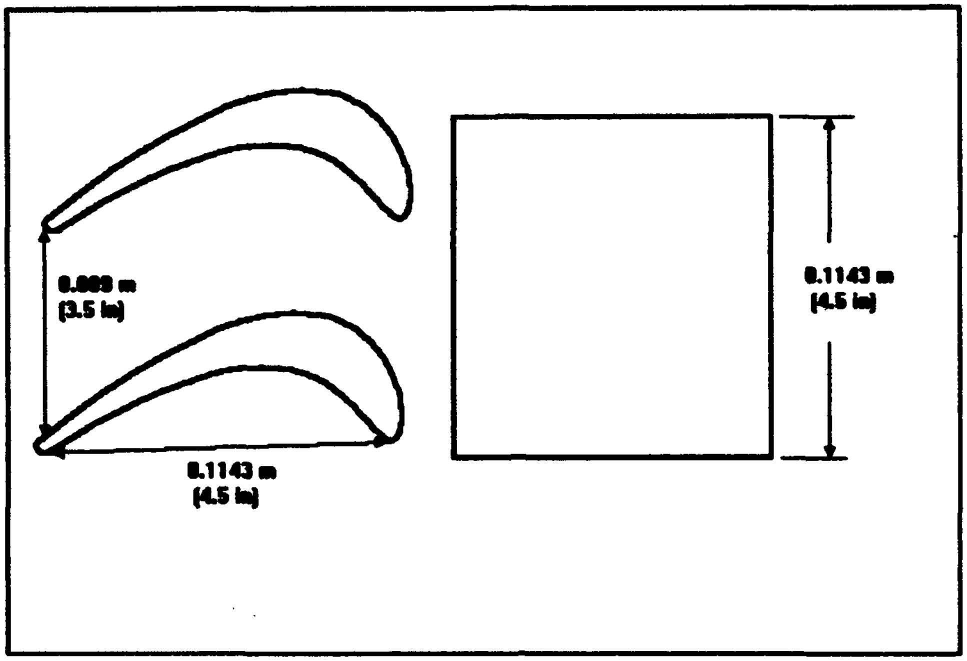
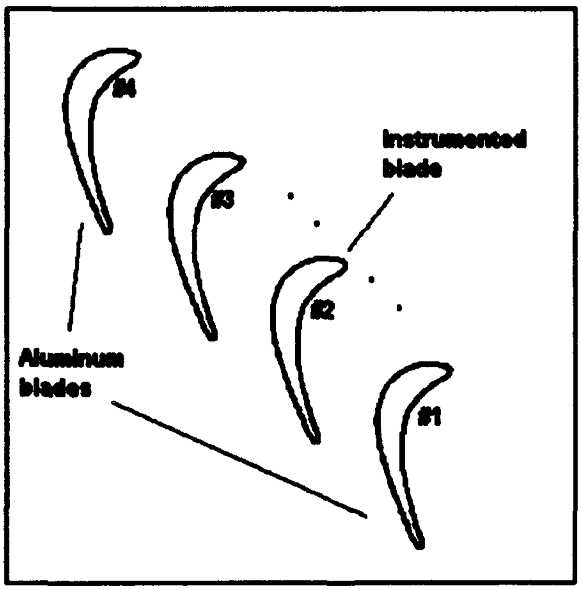


Fig. 3.2 a) Cascade blade geometry



3.2 b) Blade construction and instrumentation

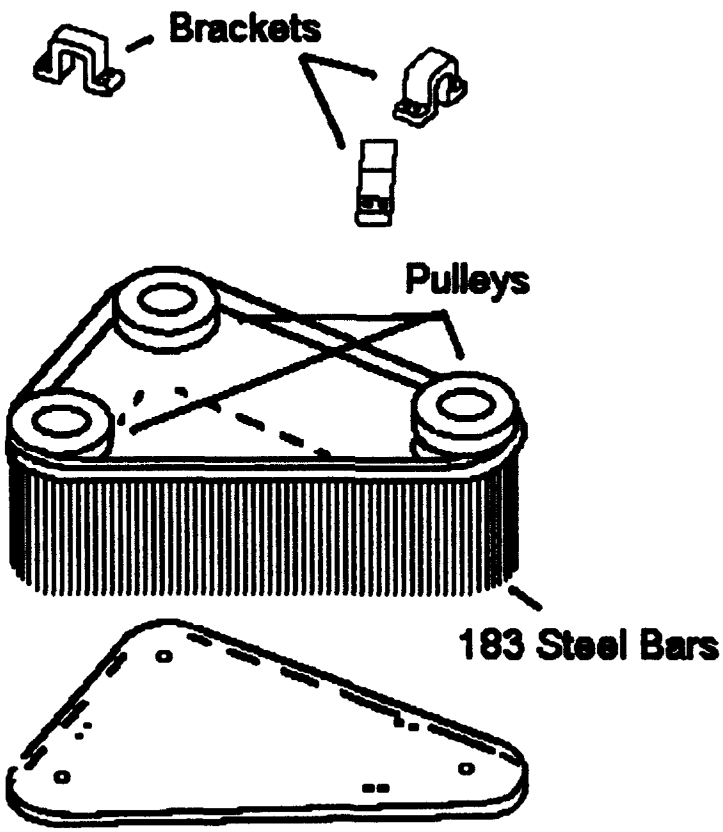


Fig. 3.3 Assembly of wake producing mechanism

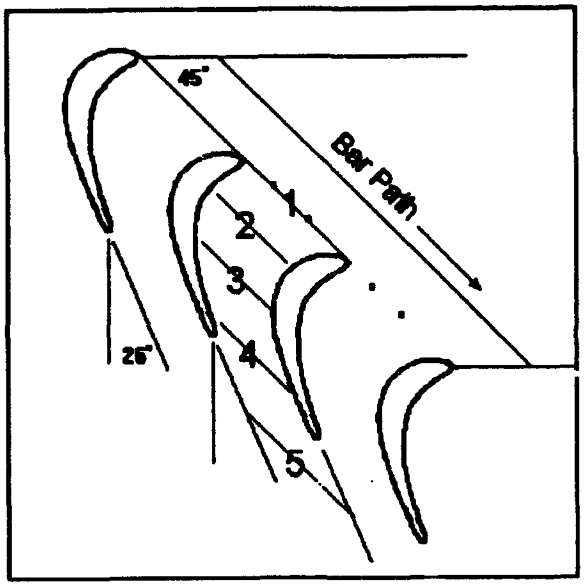


Fig. 3.4 a) Location of five measurement planes

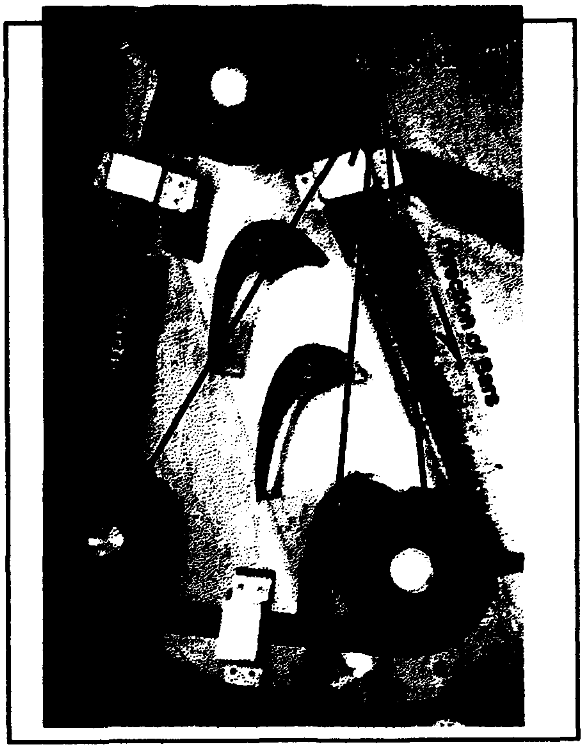


Fig. 3.4 b) Photograph showing cuts in sidewalls

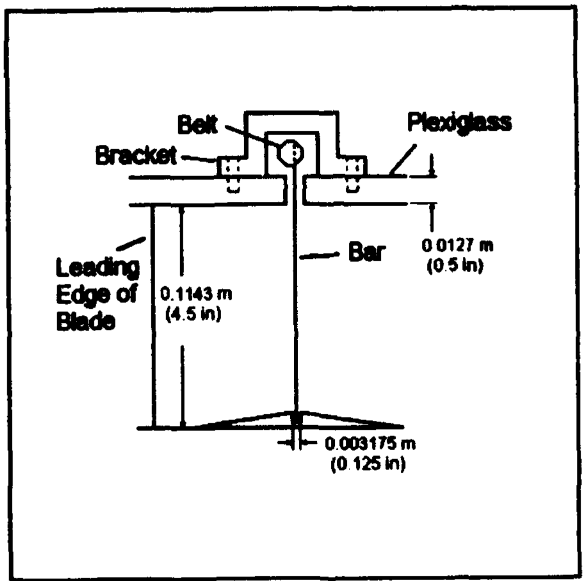


Fig 3.5 a) Schematic diagram of bar guide

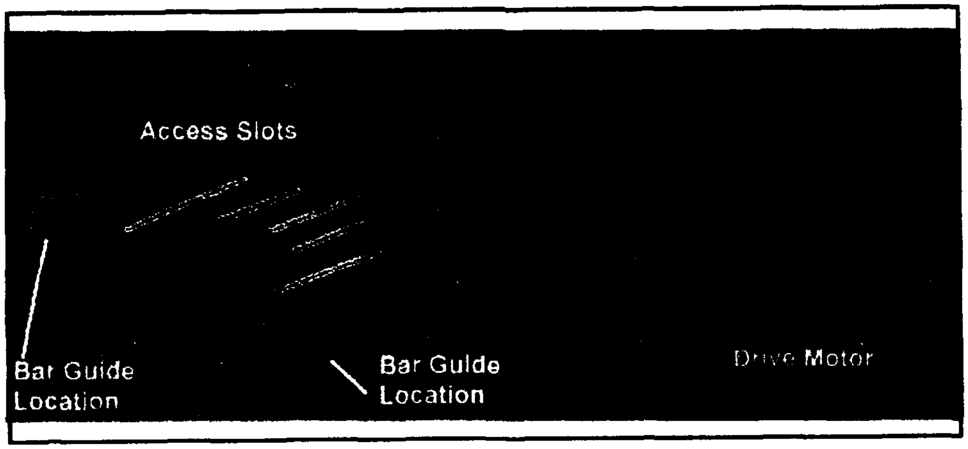


Fig. 3.5 b) Photograph of TCTF

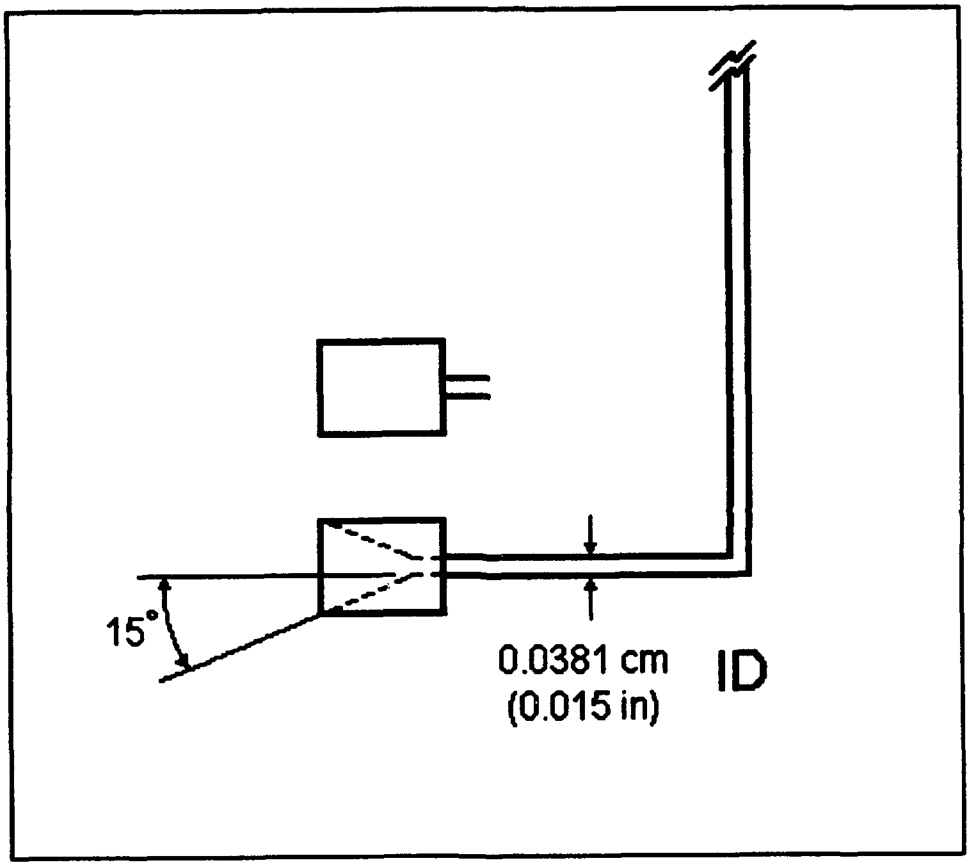


Fig. 3.6 Kiel probe

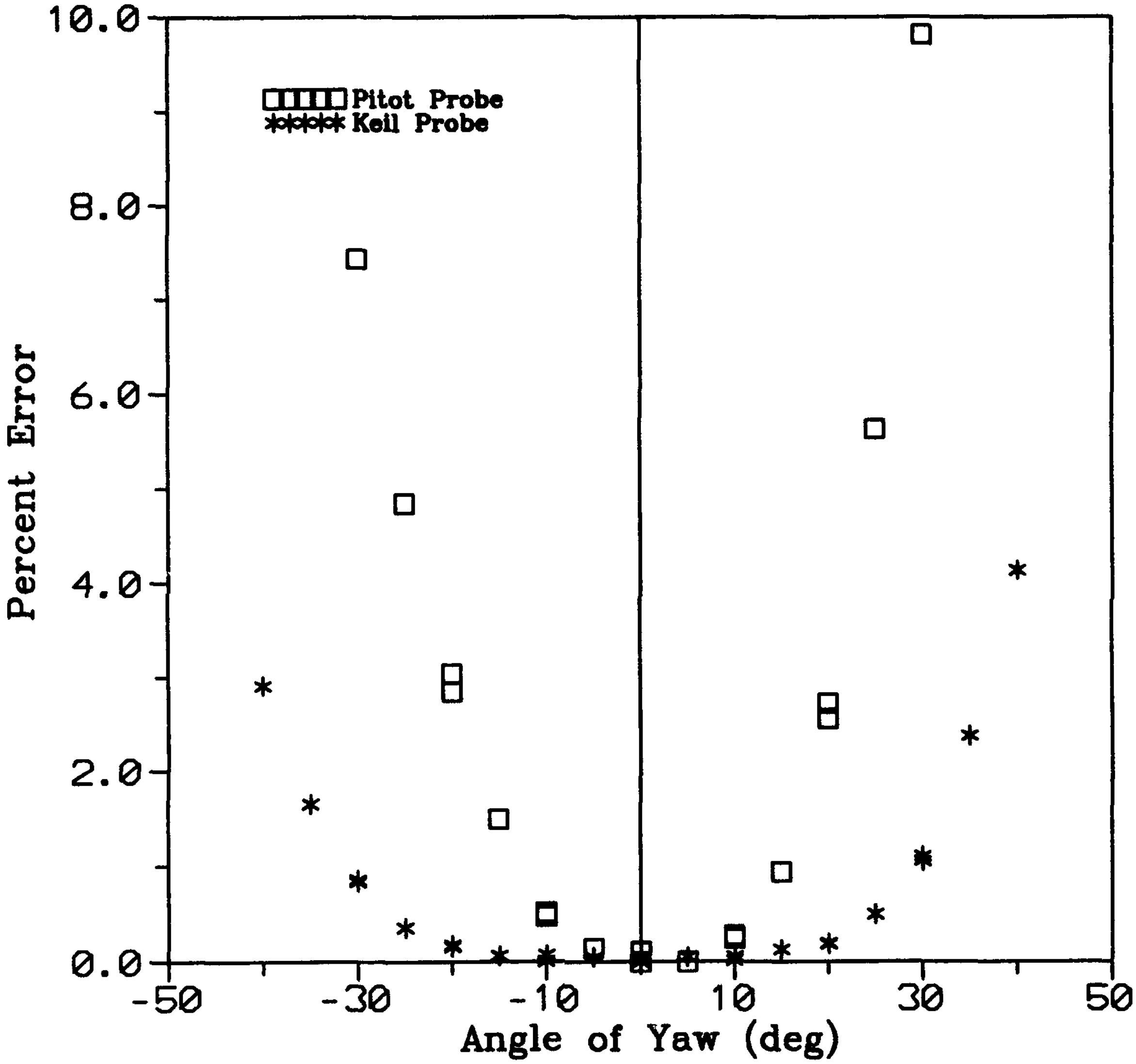


Fig. 3.7 Yaw Characteristics of a Pitot and Keil Probe

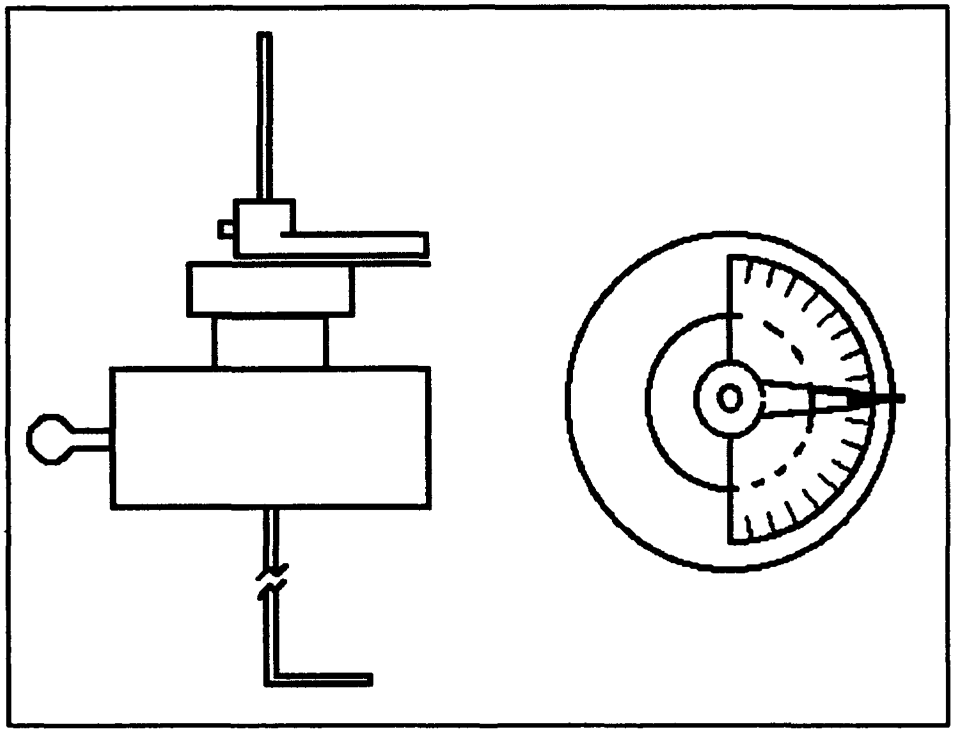


Fig. 3.8 Brass probe holder

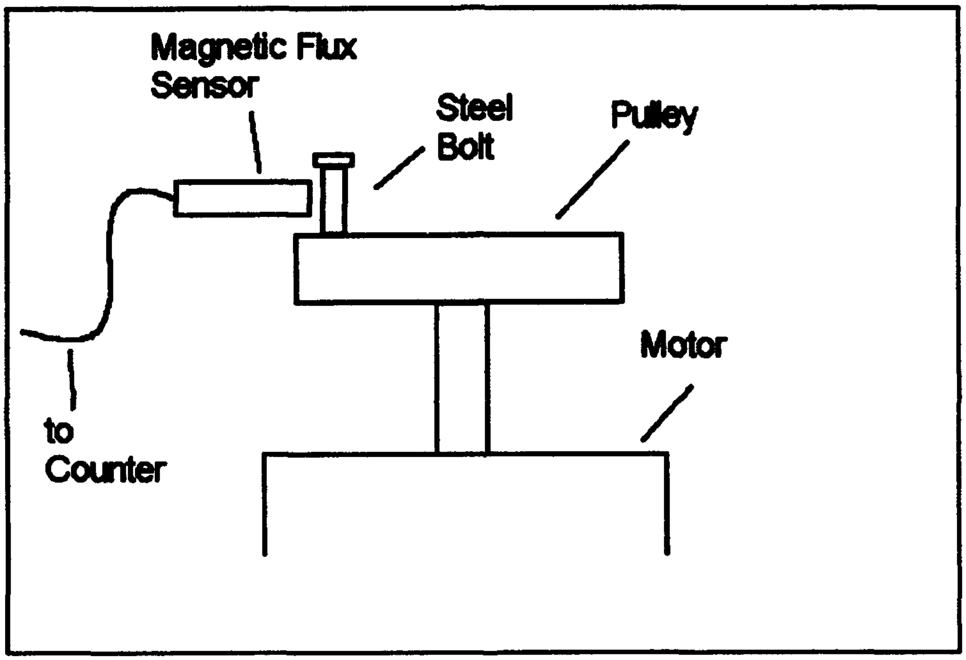


Fig 3.9 Motion detector

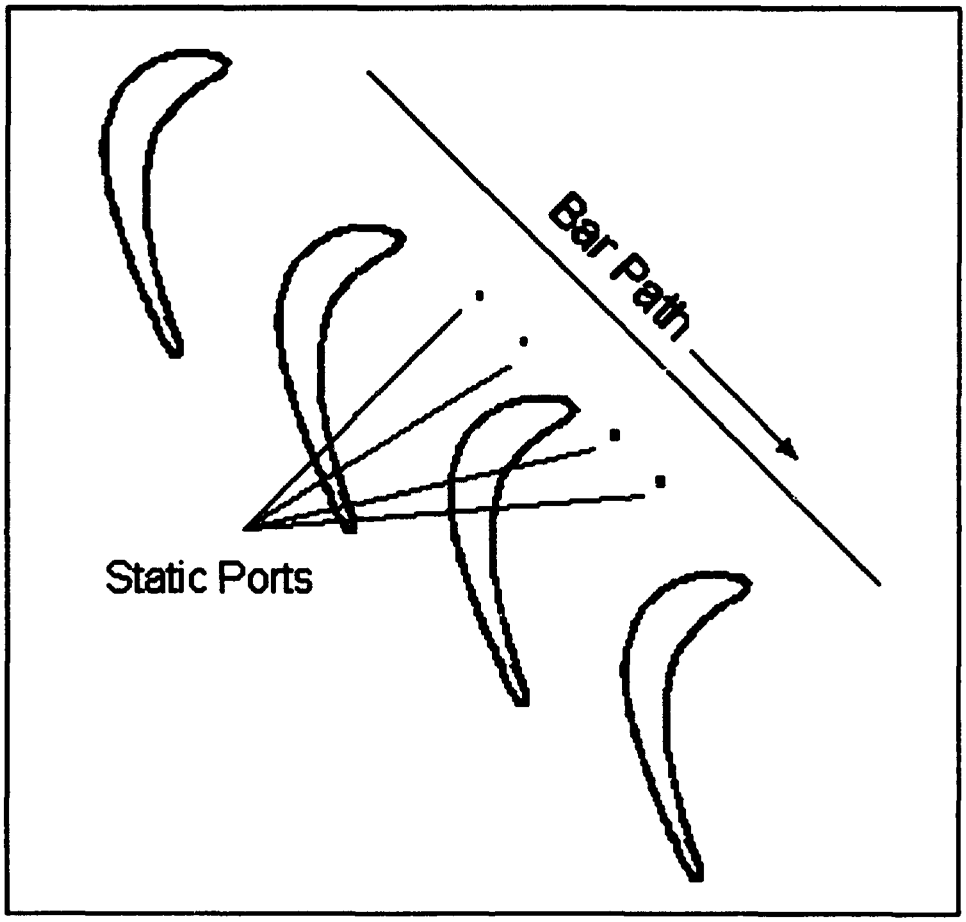


Fig. 4.1 Location of static ports

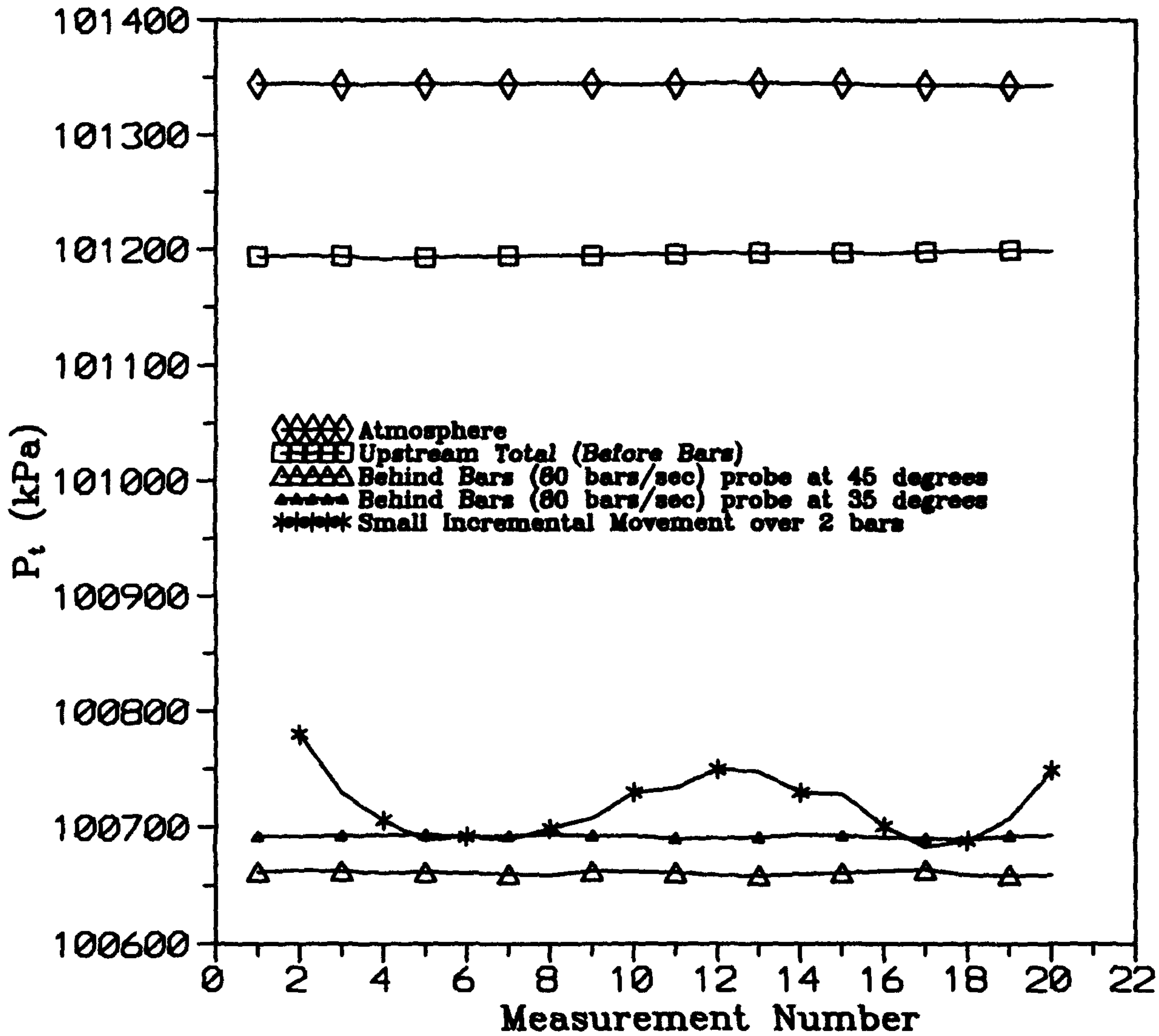


Fig. 4.2 Behavior of Pressure Measurements in TCTF

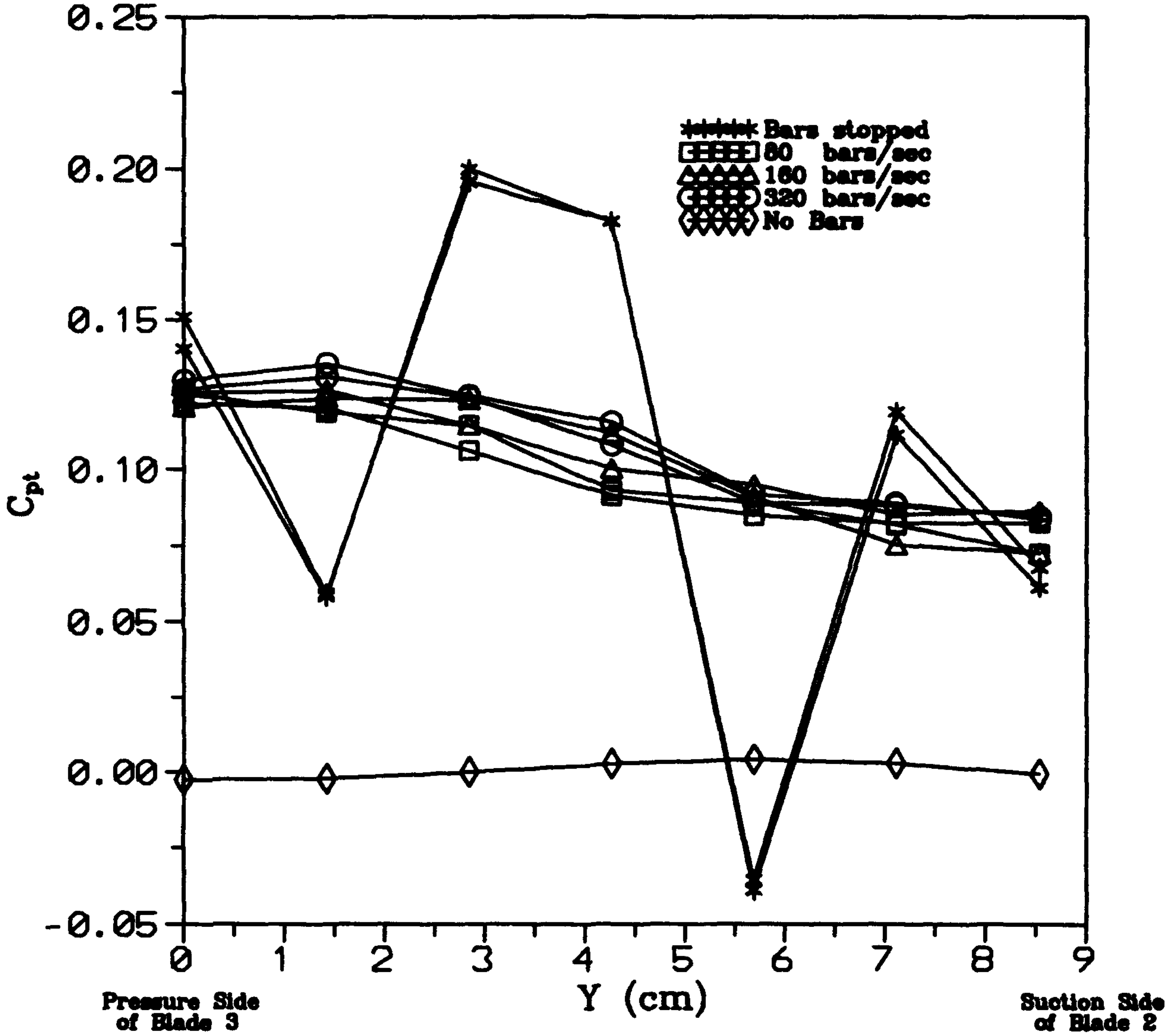


Fig. 5.1 Plane 1 Mid-span C_{pt} at Re 3.41 X 10^5

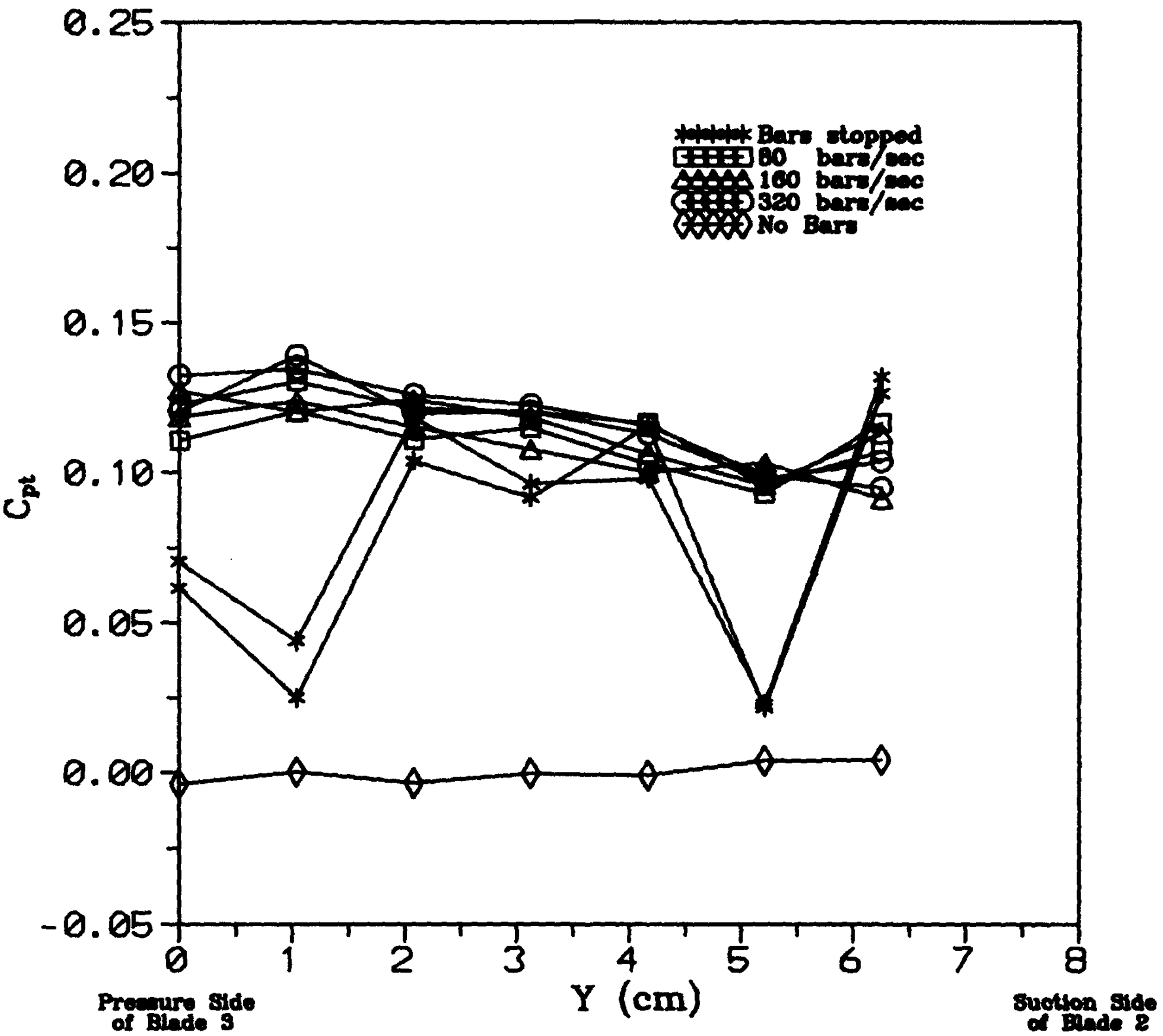


Fig. 5.2 Plane 2 Mid-span C_{pt} at Re 3.41 X 10^5

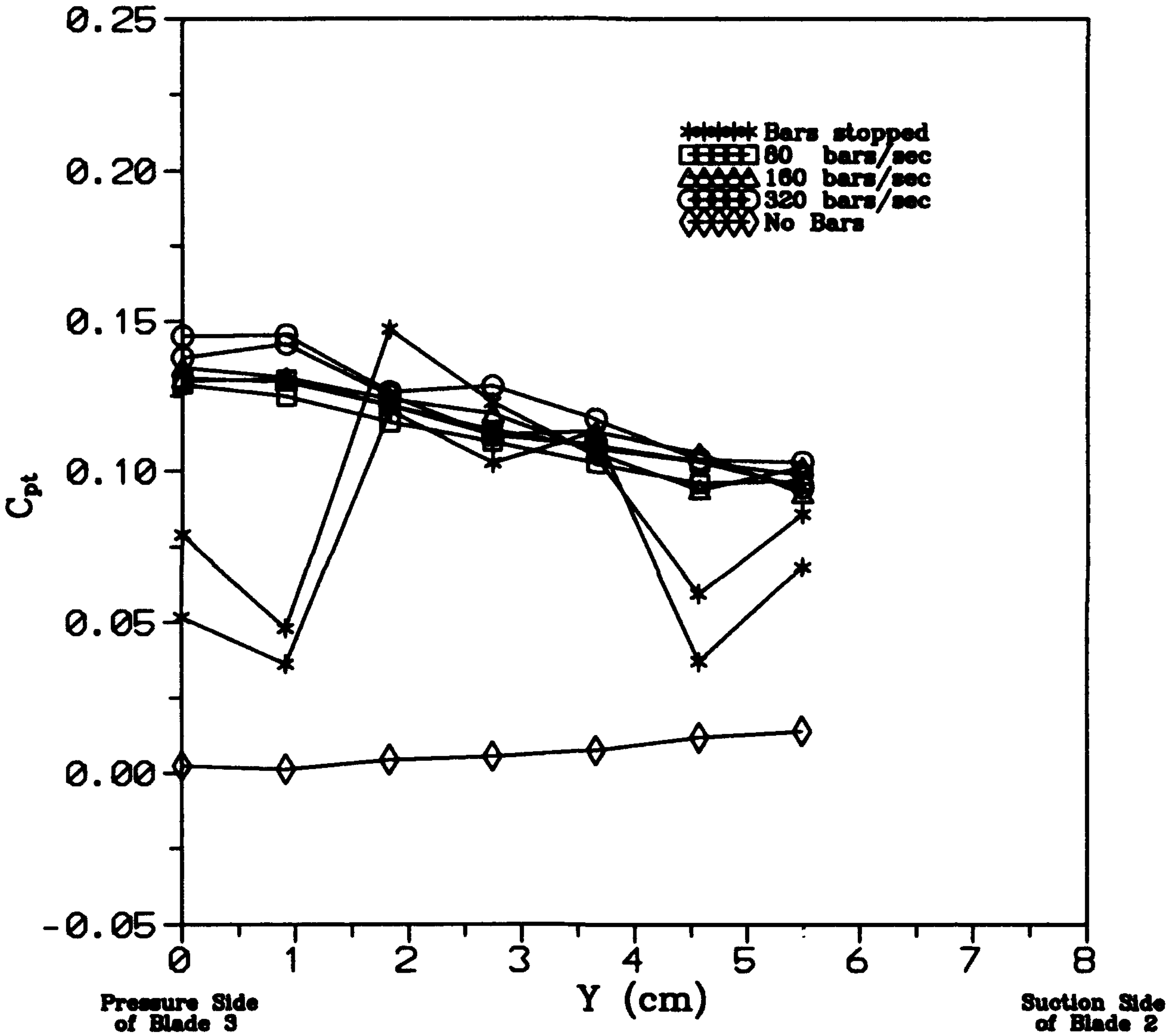


Fig. 5.3 Plane 3 Mid-span C_{pt} at Re 3.41 X 10^5

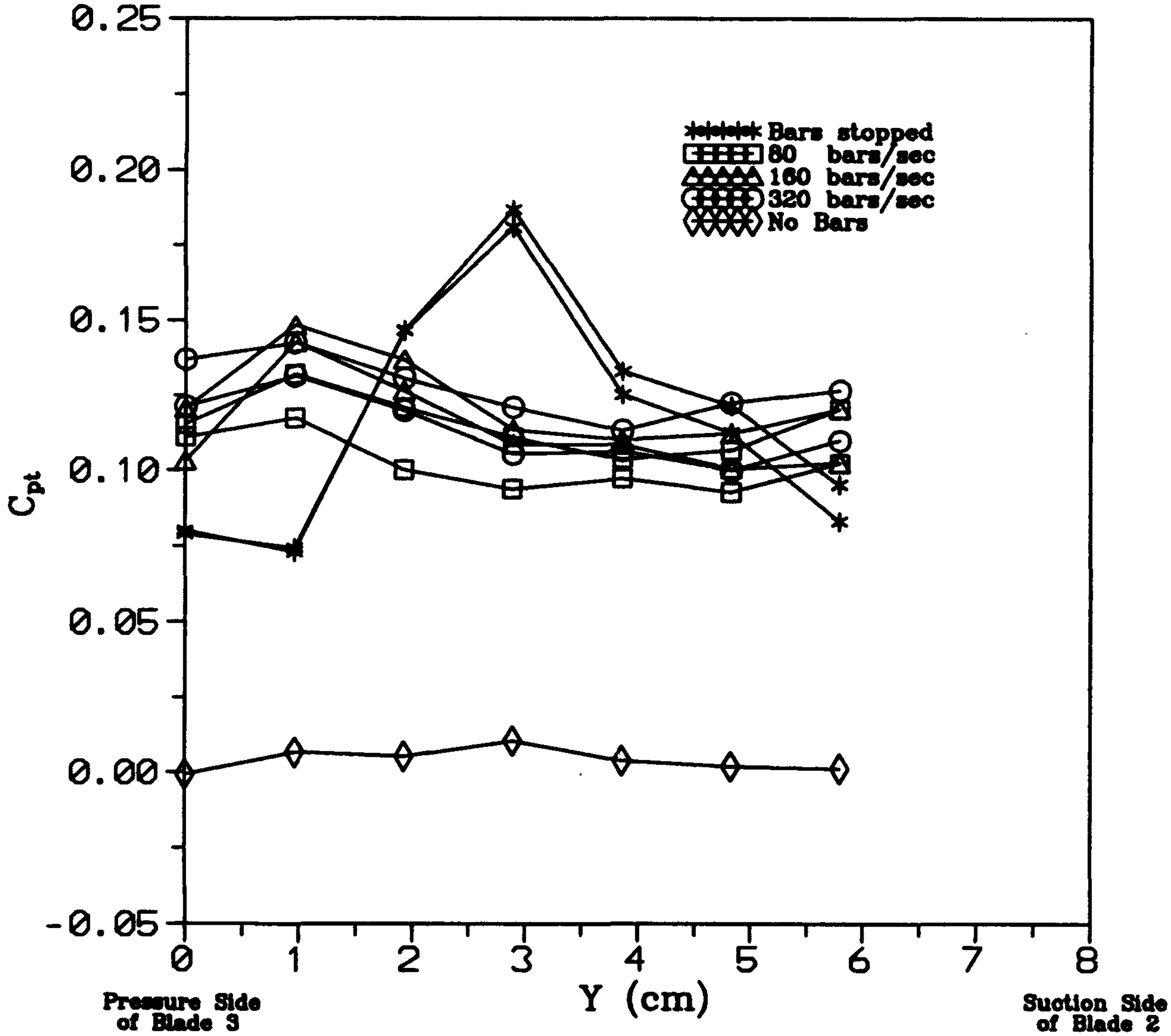


Fig. 5.4 Plane 4 Mid-span C_{pt} at Re 3.41 X 10^6

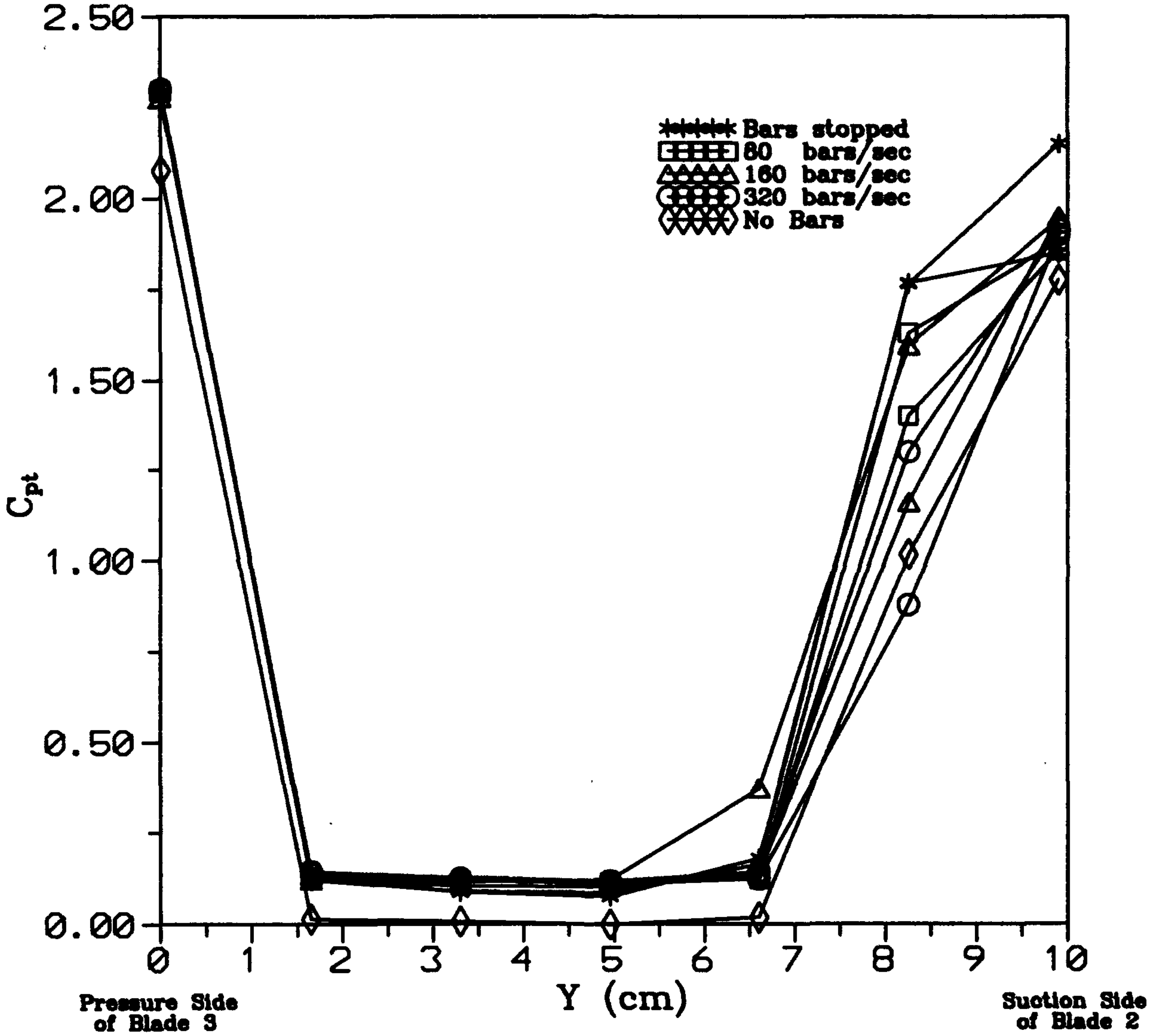


Fig. 5.5 Plane 5 Mid-span C_{pt} at Re 3.41 X 10^6

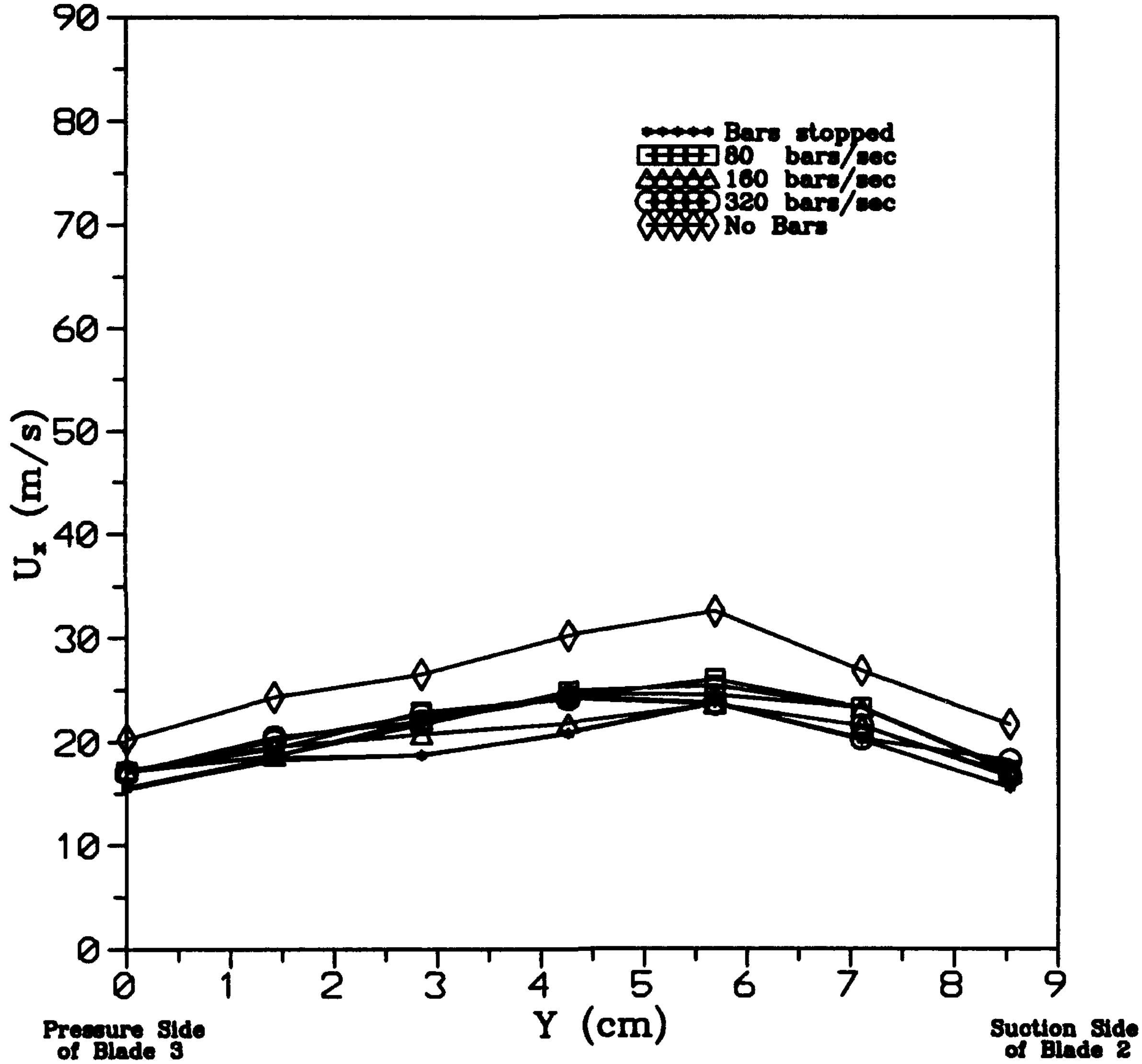


Fig. 5.6 Plane 1 Mid-span U_x at Re 3.41 X 10^5

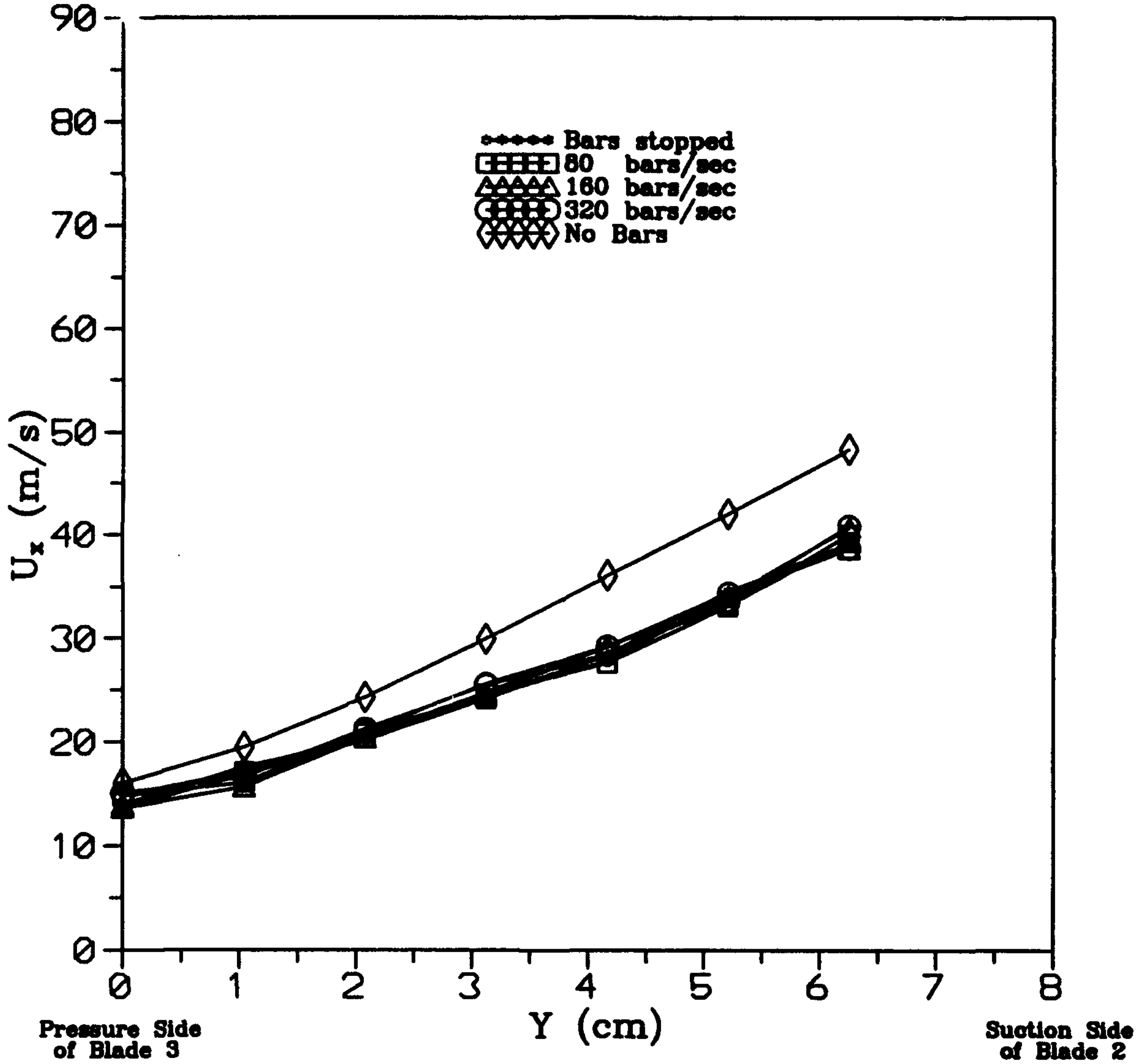


Fig. 5.7 Plane 2 Mid-span U_x at Re 3.41 X 10^5

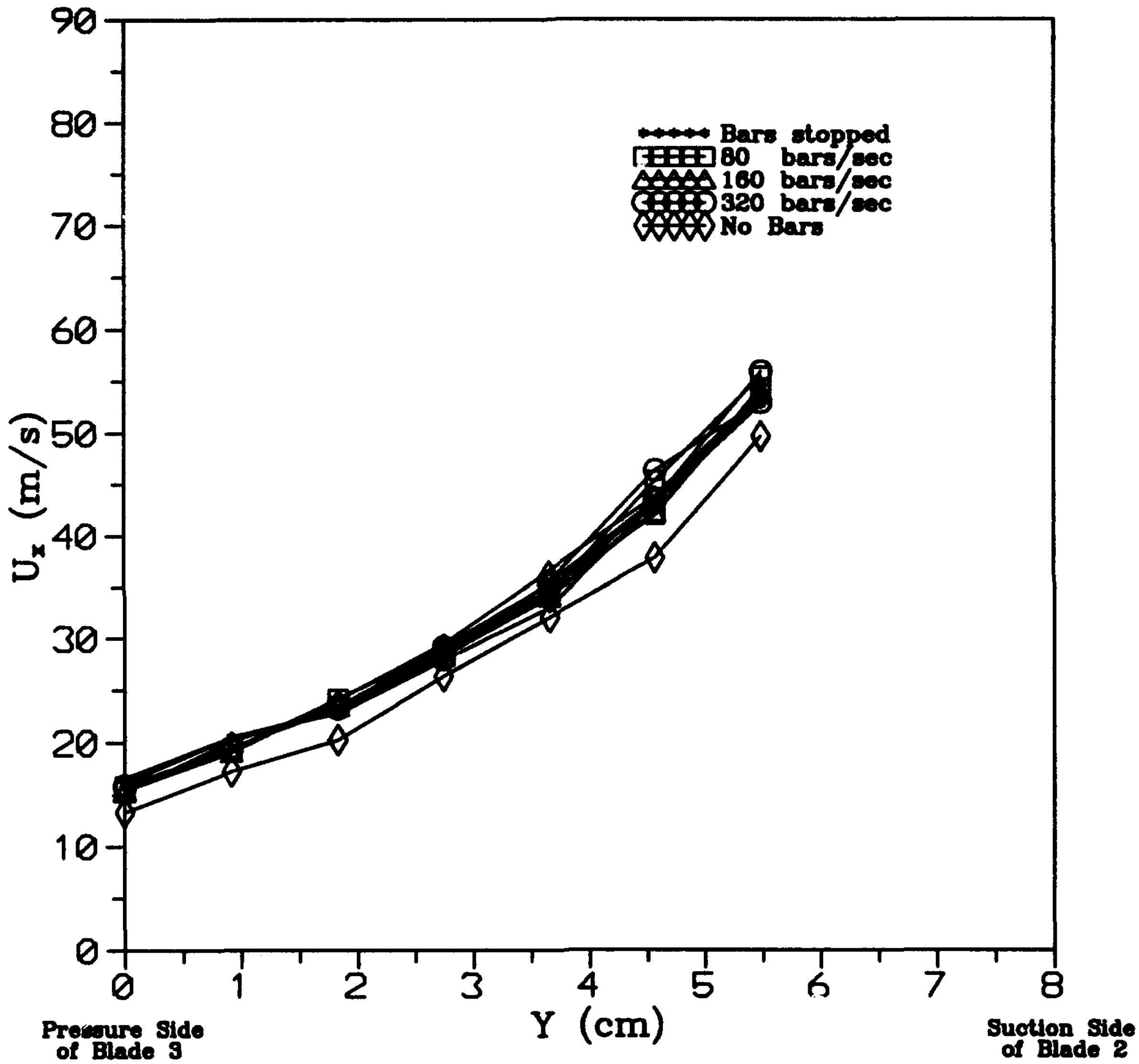


Fig. 5.8 Plane 3 Mid-span U_x at Re 3.41 X 10^5

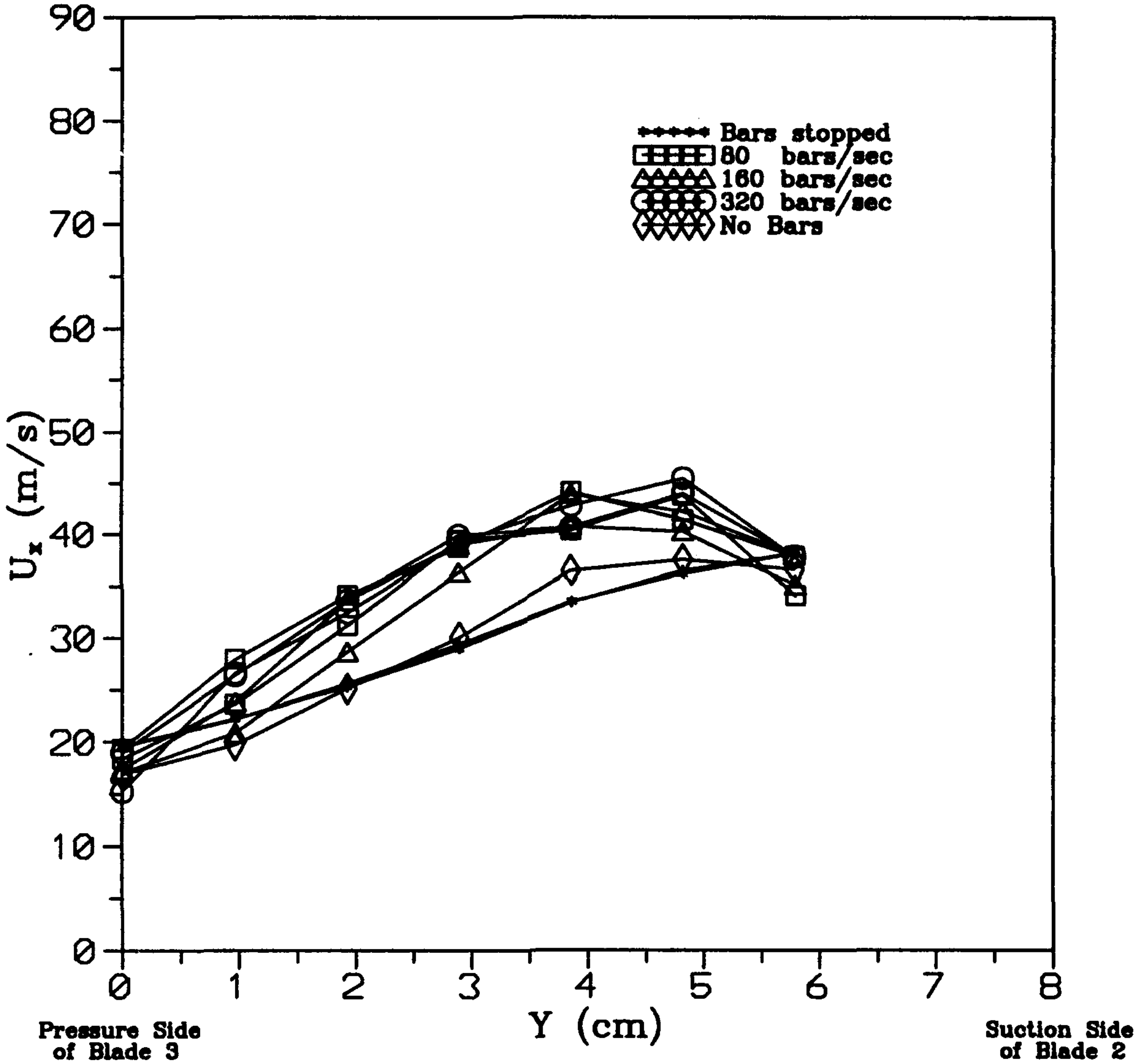


Fig. 5.9 Plane 4 Mid-span U_x at Re 3.41 X 10^5

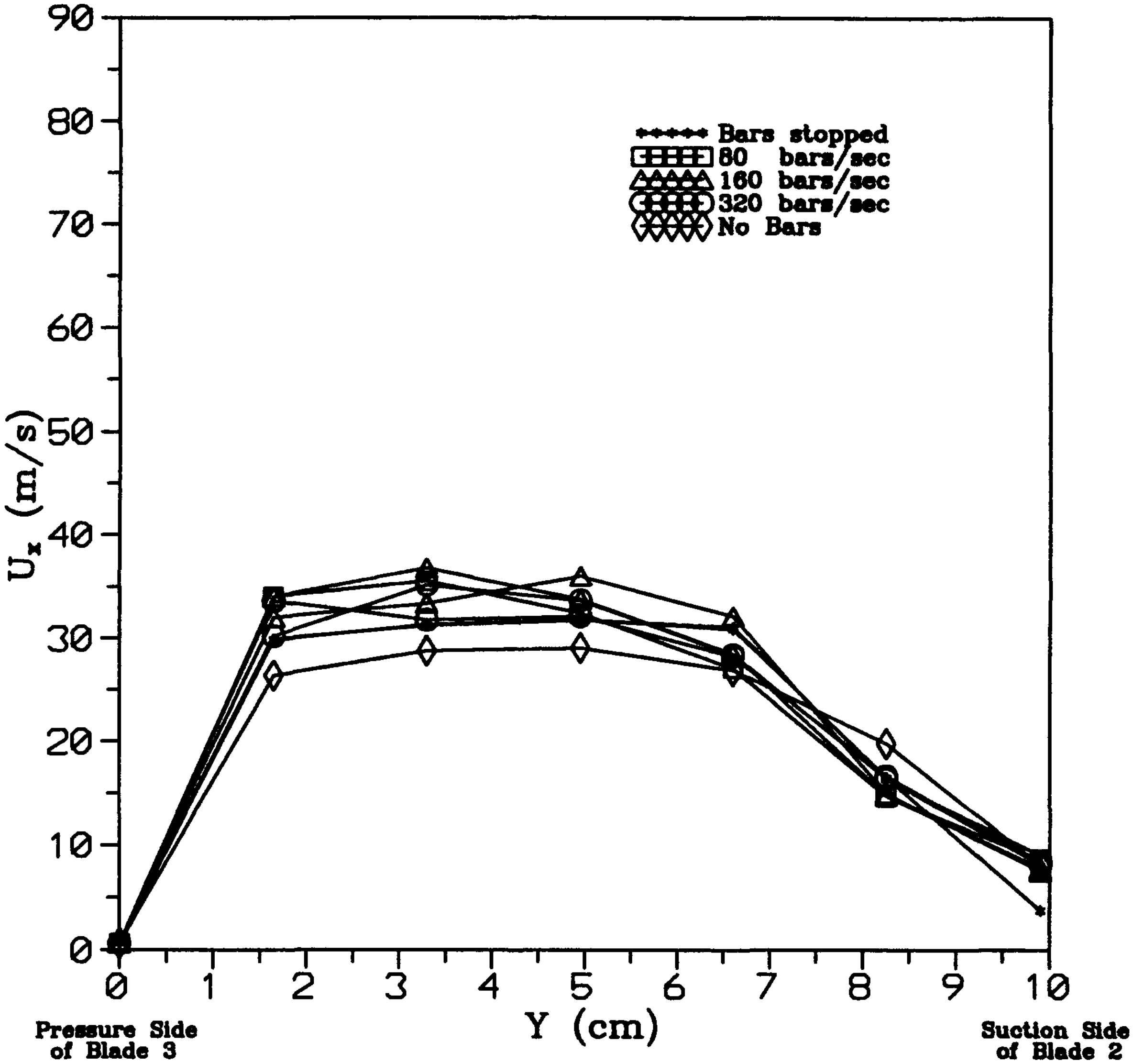


Fig. 5.10 Plane 5 Mid-span U_x at Re 3.41 X 10^6

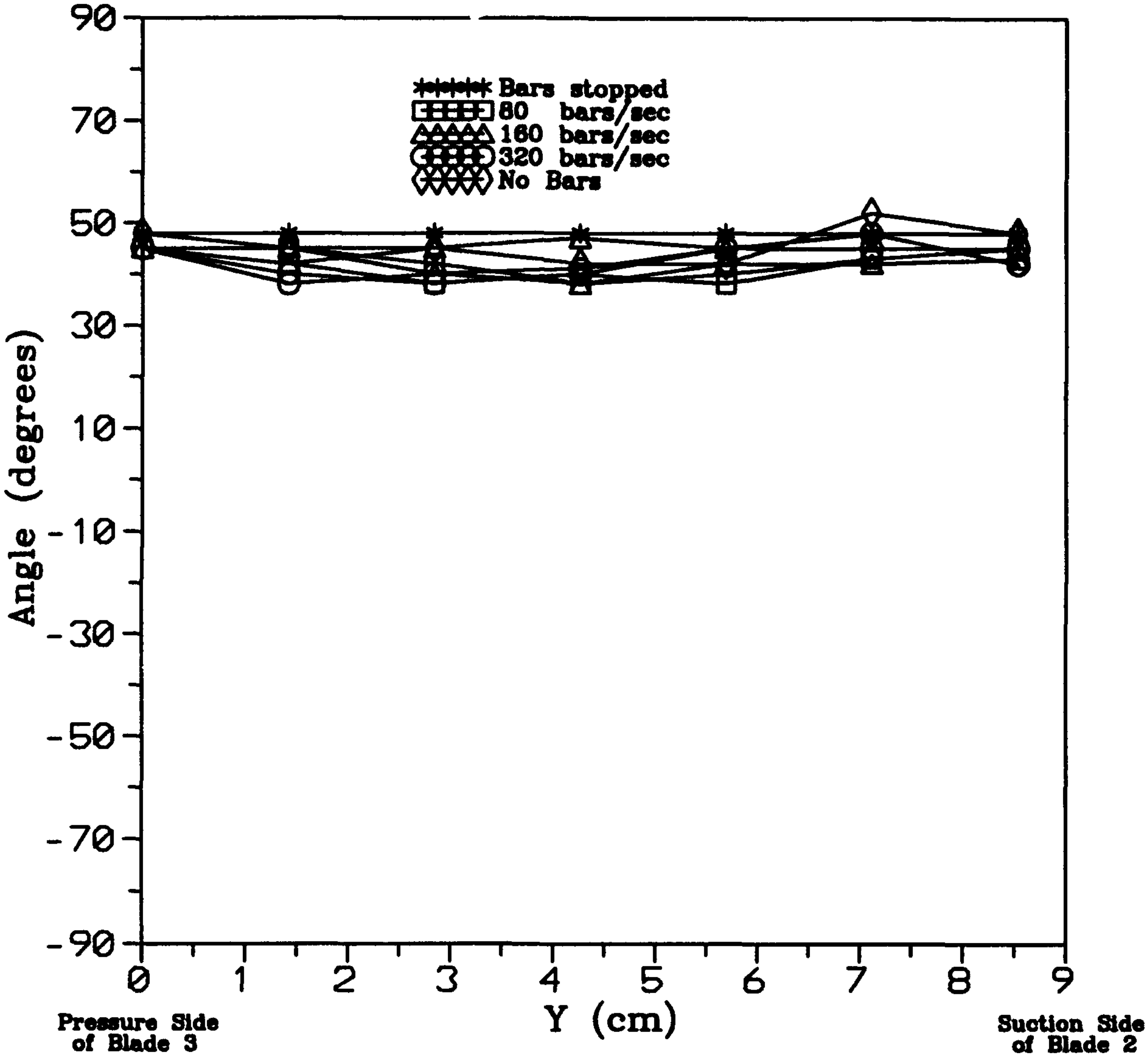


Fig. 5.11 Plane 1 Mid-span flow angle at Re 3.41 X 10^5

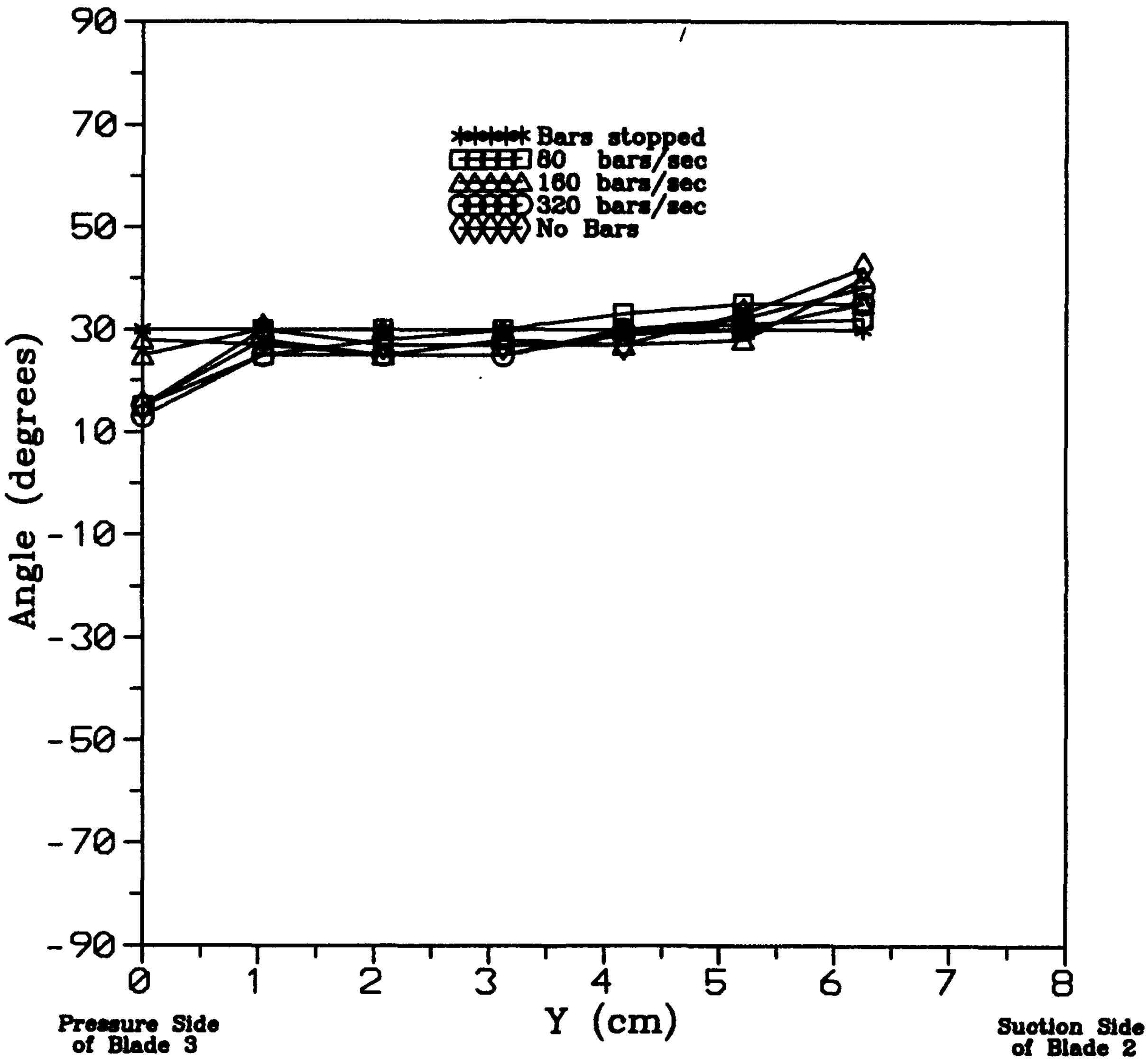


Fig. 5.12 Plane 2 Mid-span flow angle at Re 3.41 X 10^5

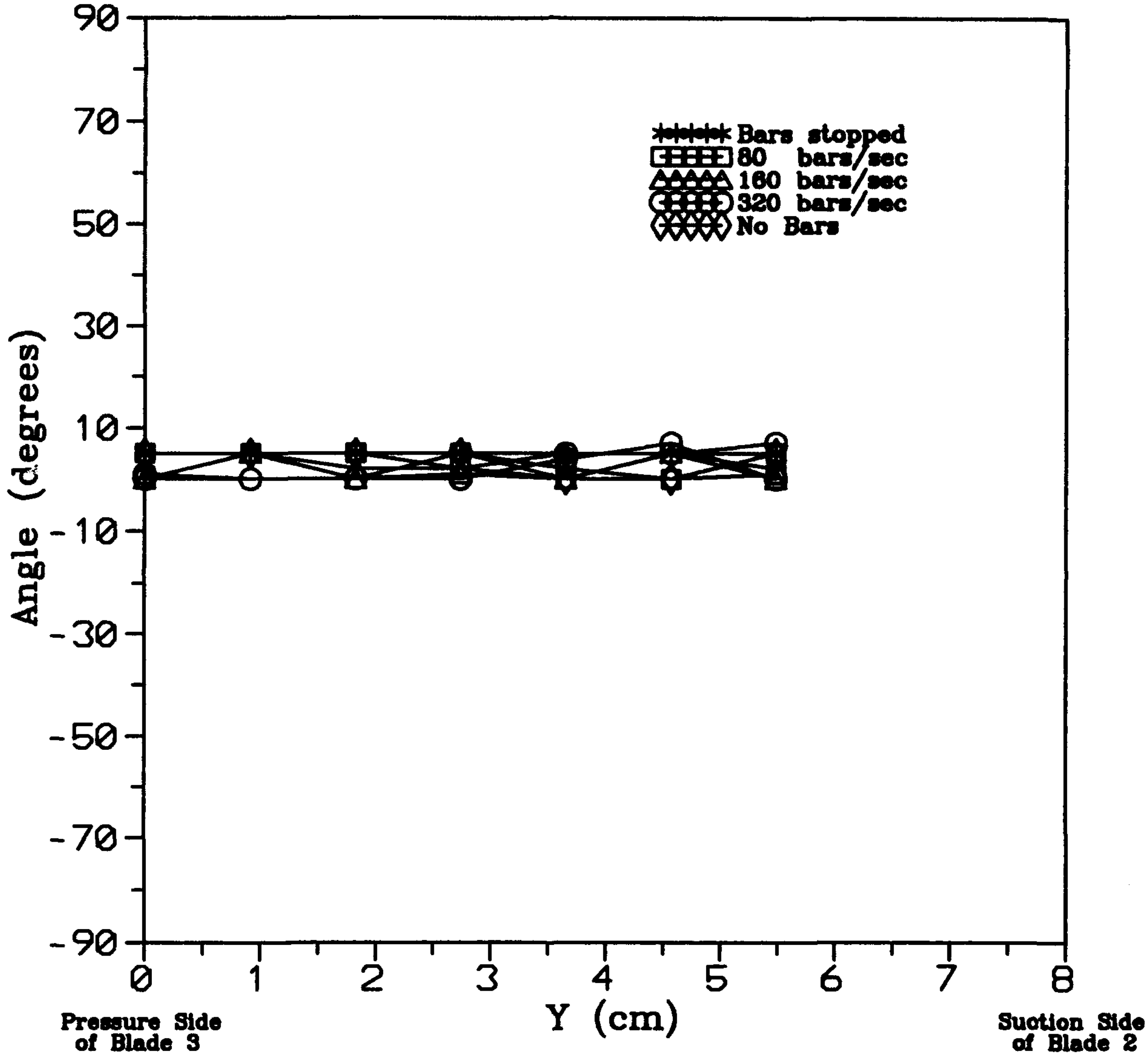


Fig. 5.13 Plane 3 Mid-span flow angle at Re 3.41 X 10^5

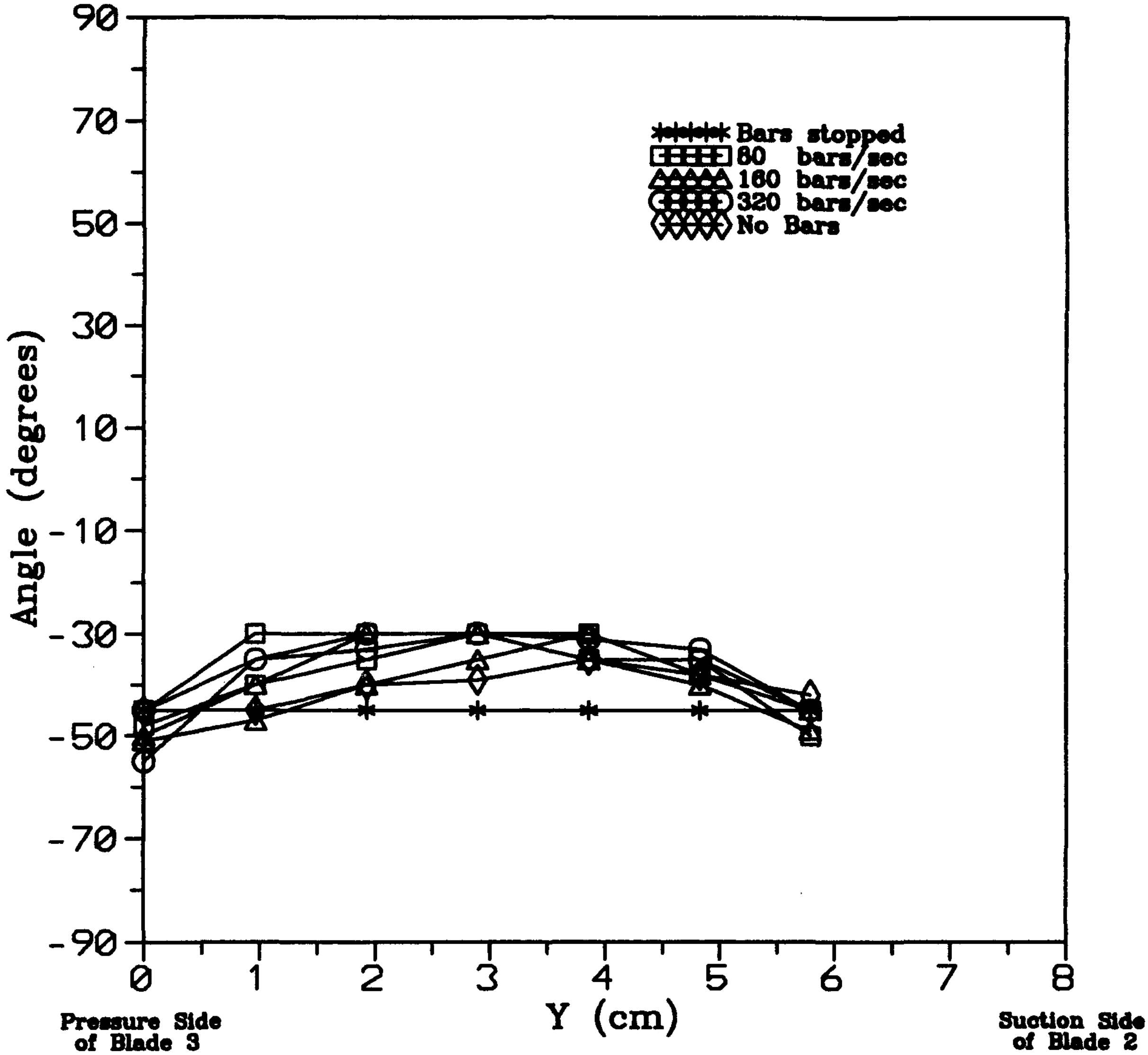


Fig. 5.14 Plane 4 Mid–span flow angle at Re 3.41 X 10^5

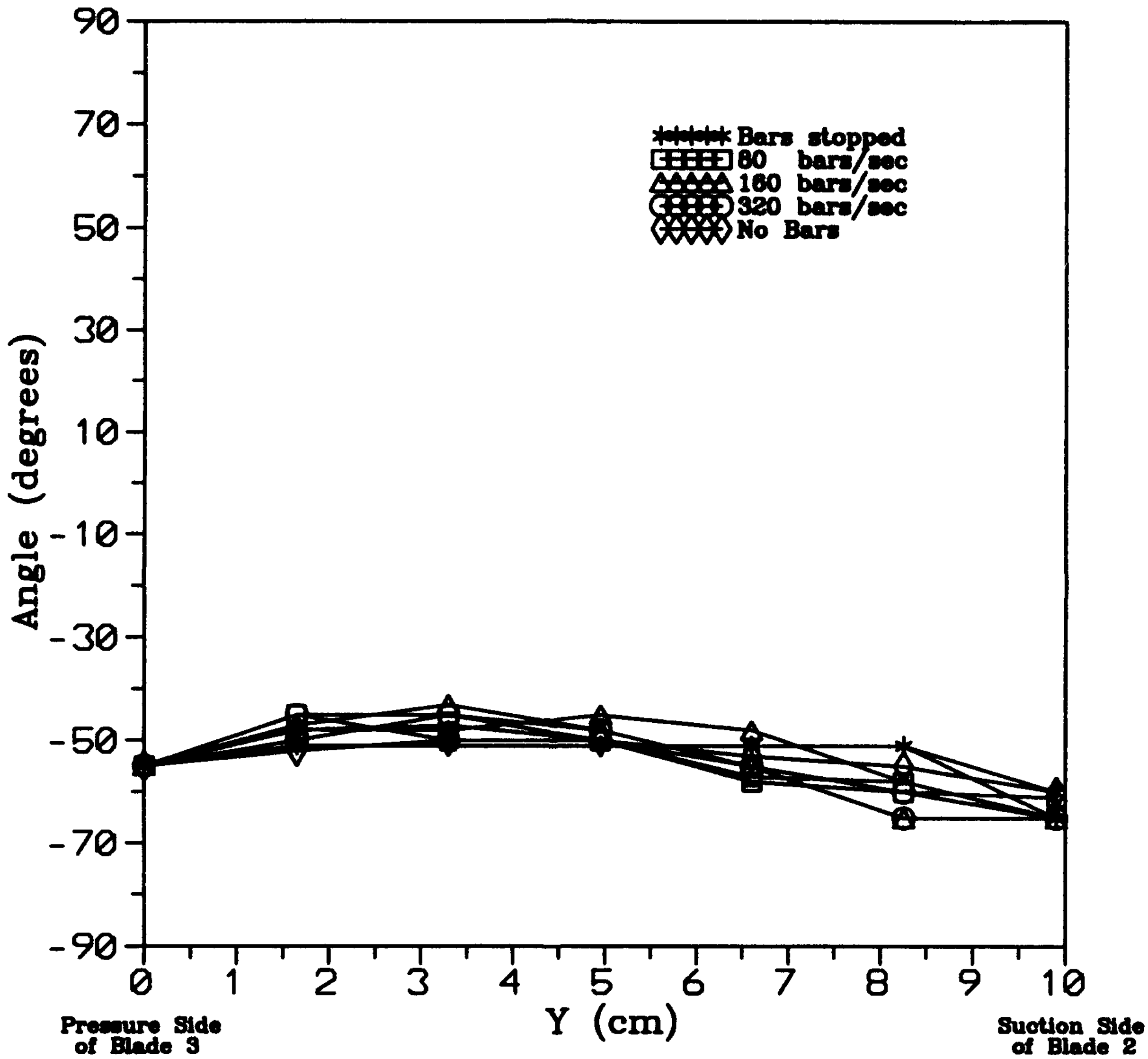


Fig. 5.15 Plane 5 Mid-span flow angle at Re 3.41 X 10^6

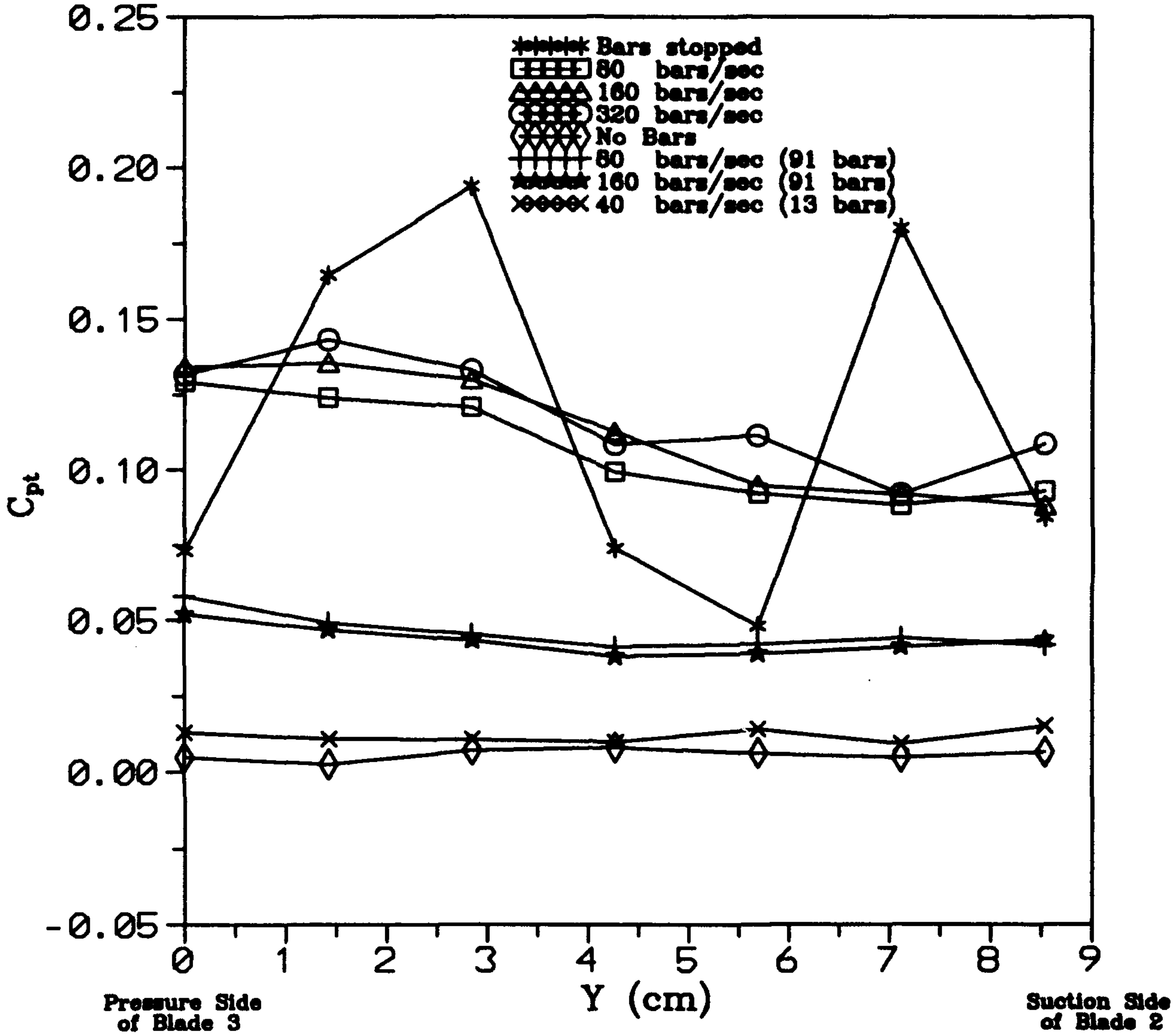


Fig. 5.16 Plane 1 Mid-span C_{pt} at Re 4.55 X 10^5

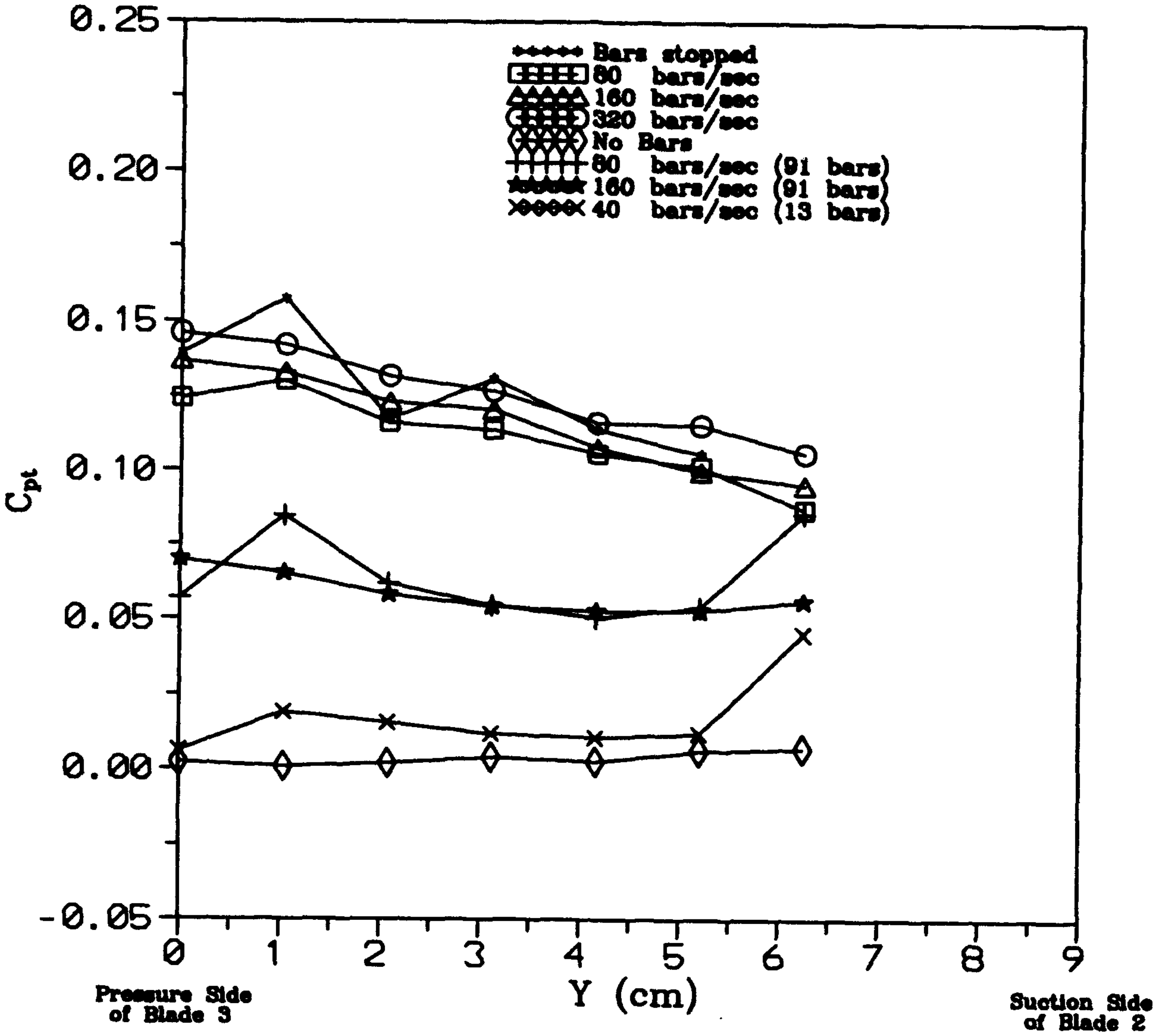


Fig. 5.17 Plane 2 Mid-span C_{pt} at Re 4.55 X 10^6

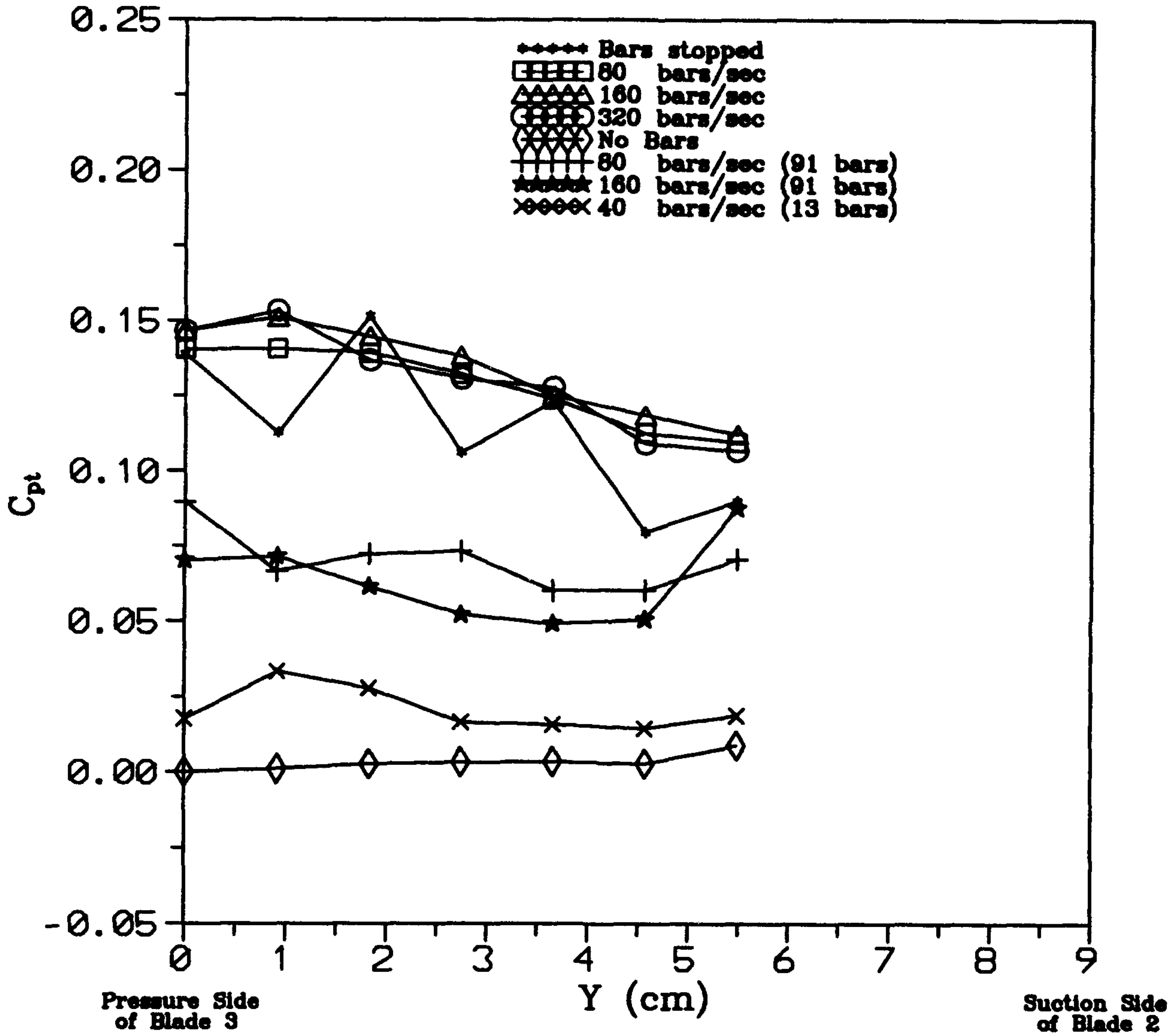


Fig. 5.18 Plane 3 Mid-span C_{pt} at Re 4.55 X 10^{5}

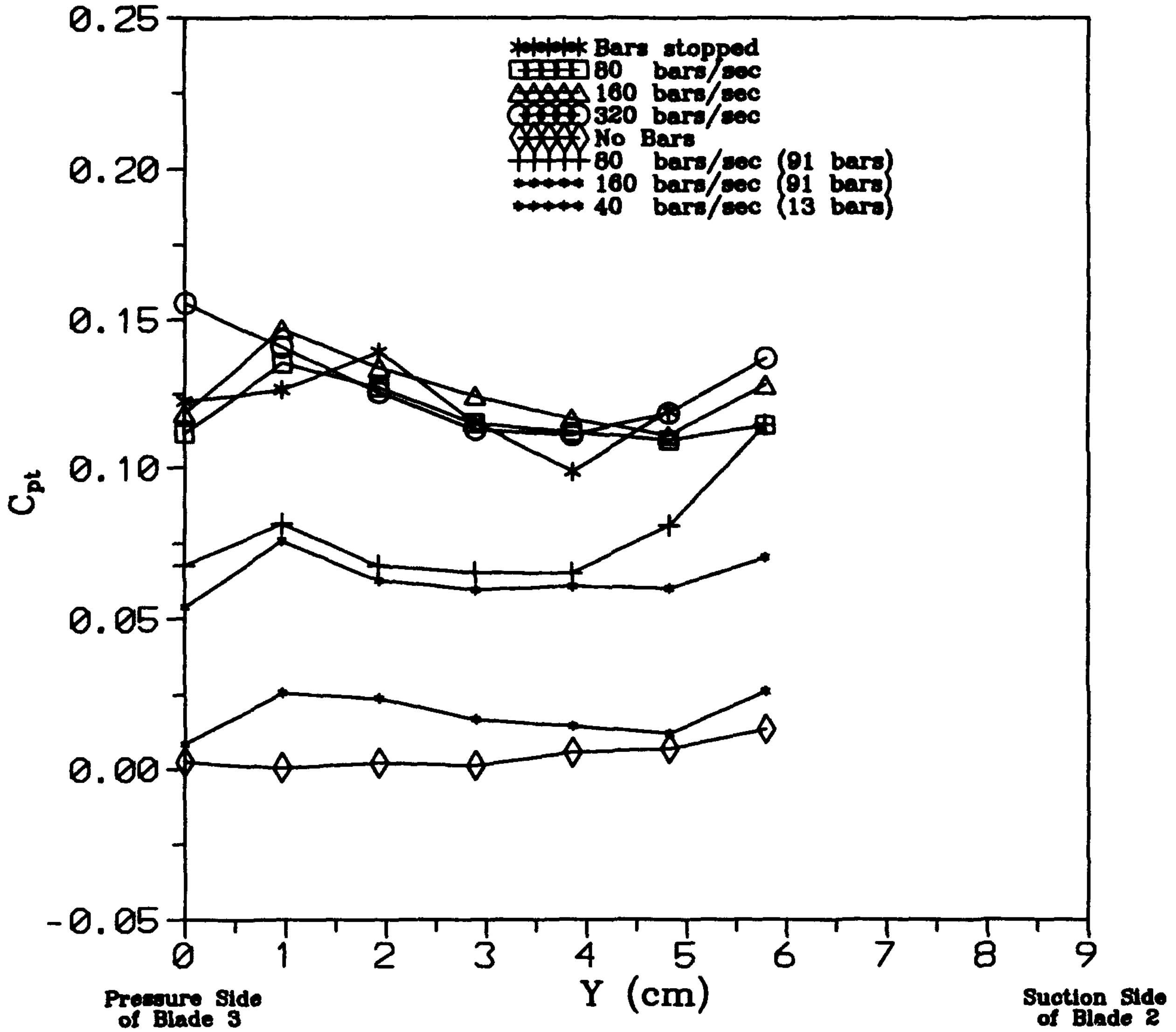


Fig. 5.19 Plane 4 Mid-span C_{pt} at Re 4.55 X 10^6

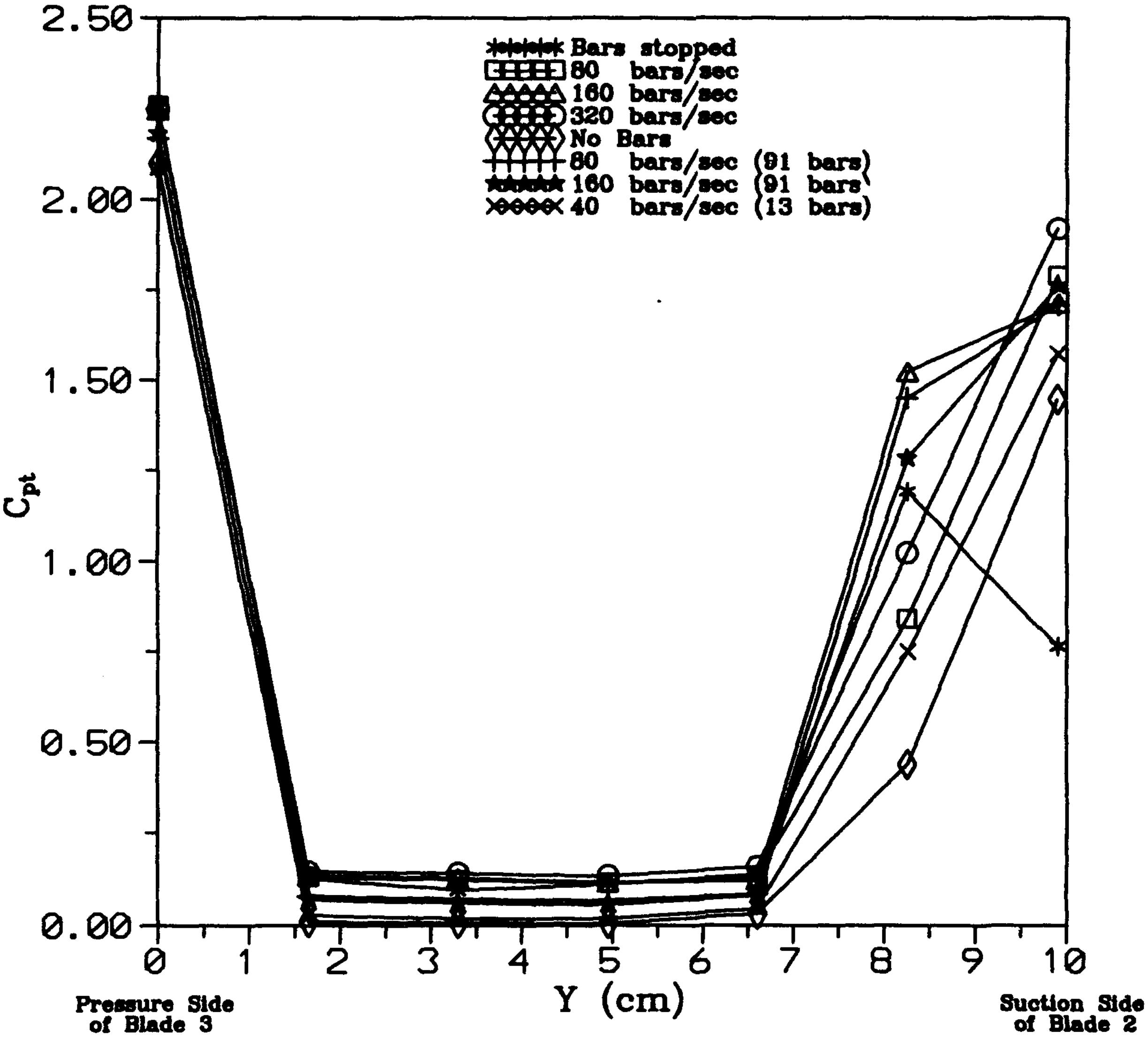


Fig. 5.20 Plane 5 Mid-span C_{pt} at Re 4.55 X 10^6

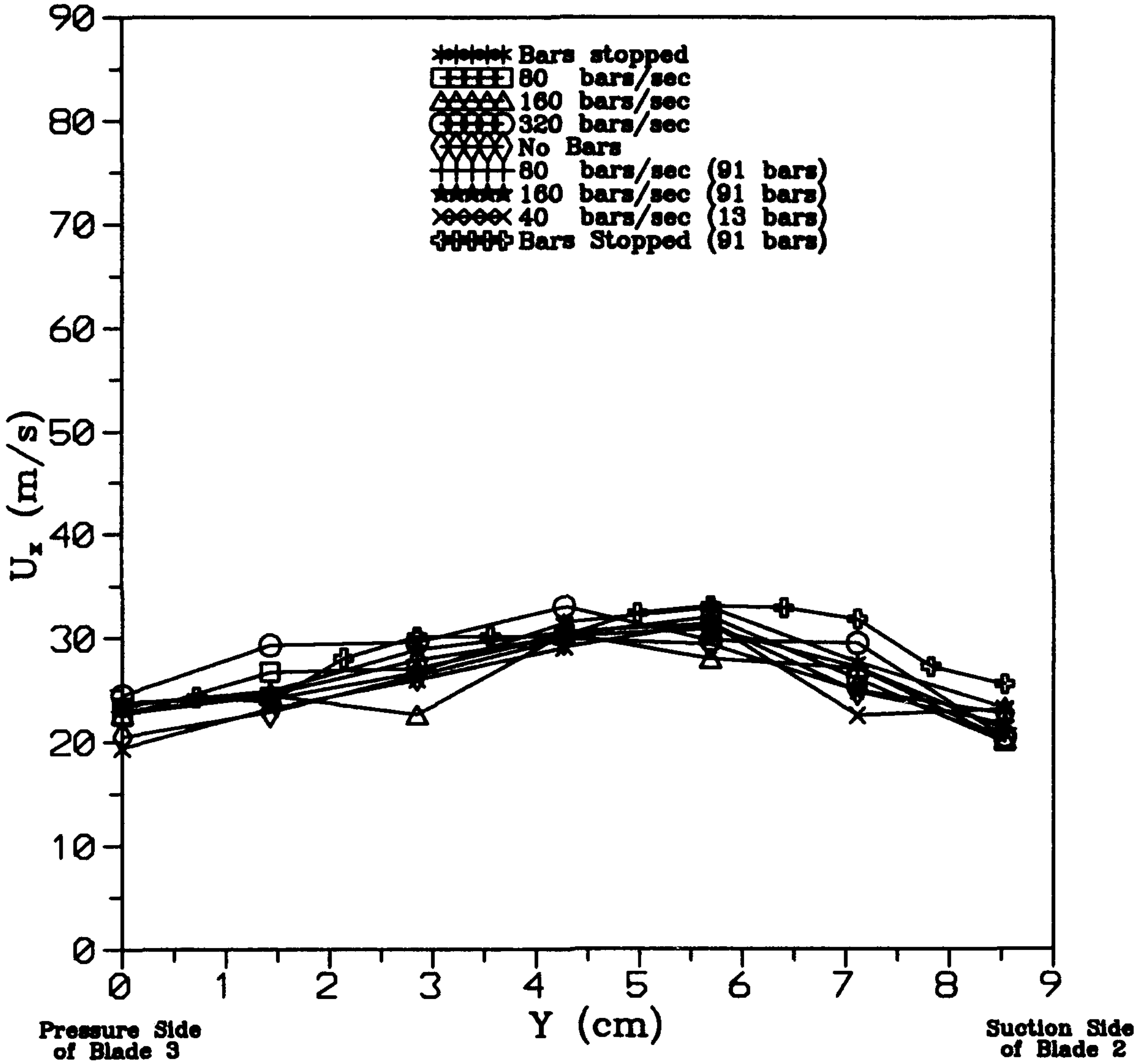


Fig. 5.21 Plane 1 Mid-span U_x at Re 4.55 X 10^5

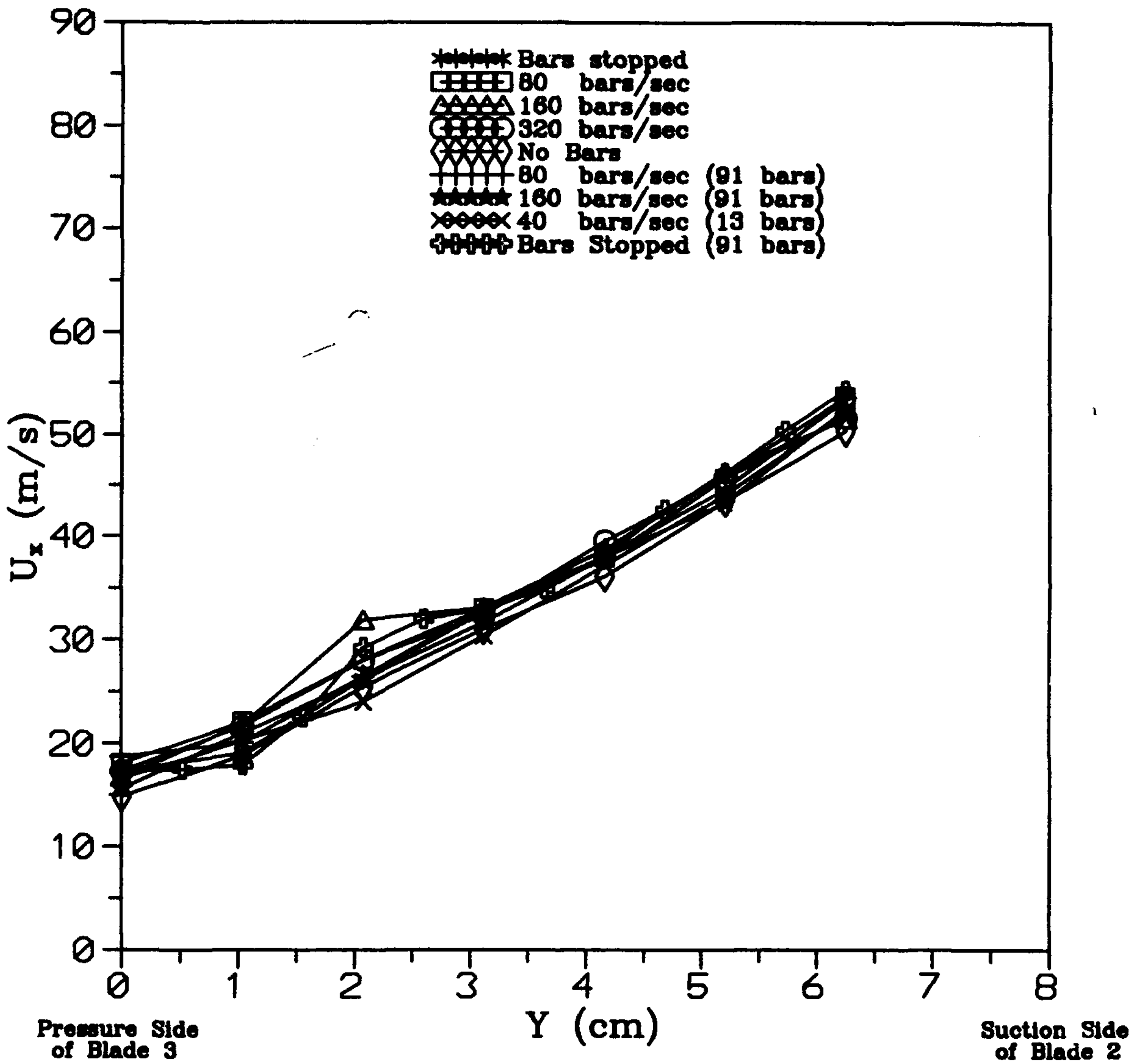


Fig. 5.22 Plane 2 Mid-span U_x at Re 4.55 X 10^5

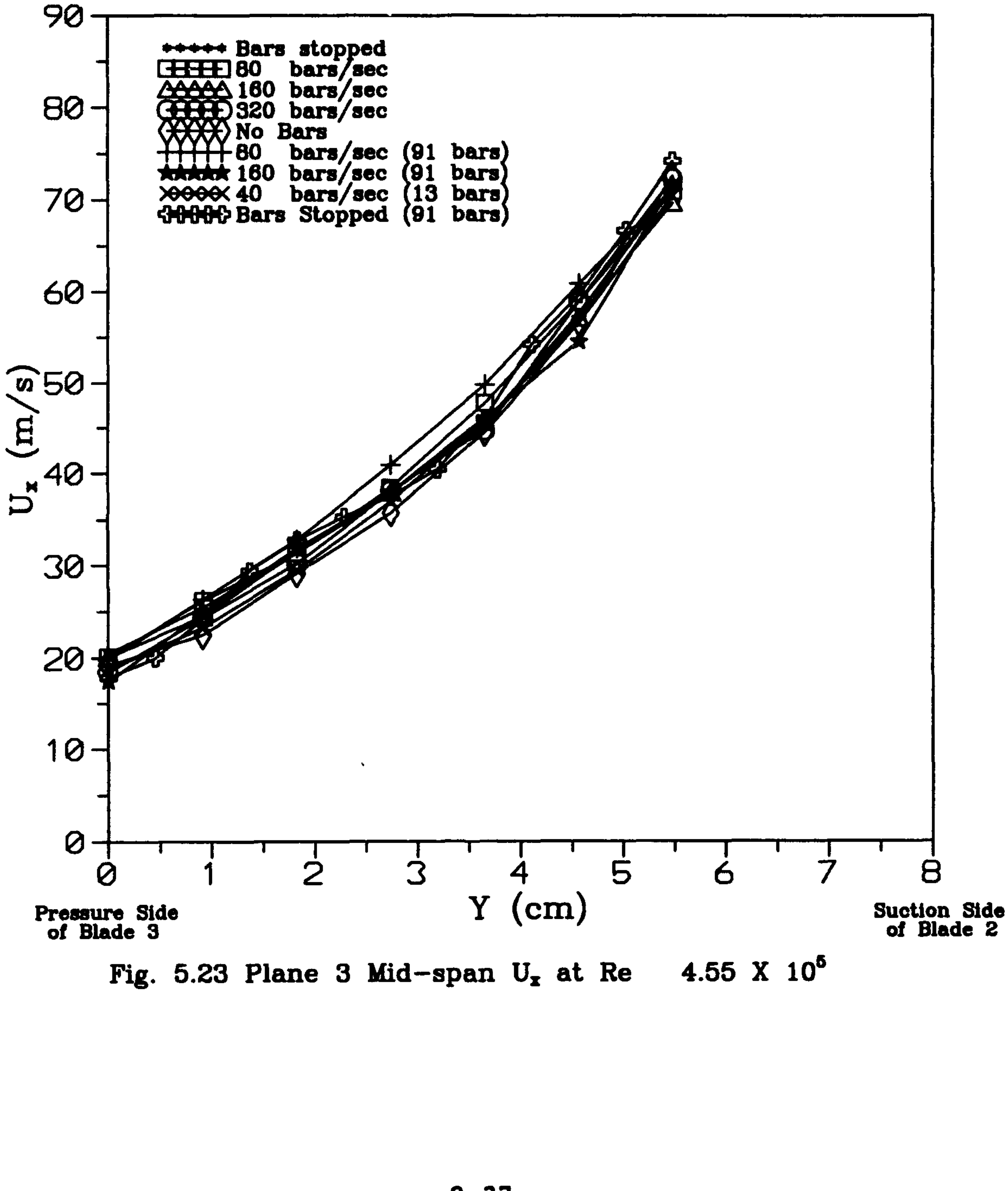


Fig. 5.23 Plane 3 Mid-span U_x at Re 4.55 X 10^5

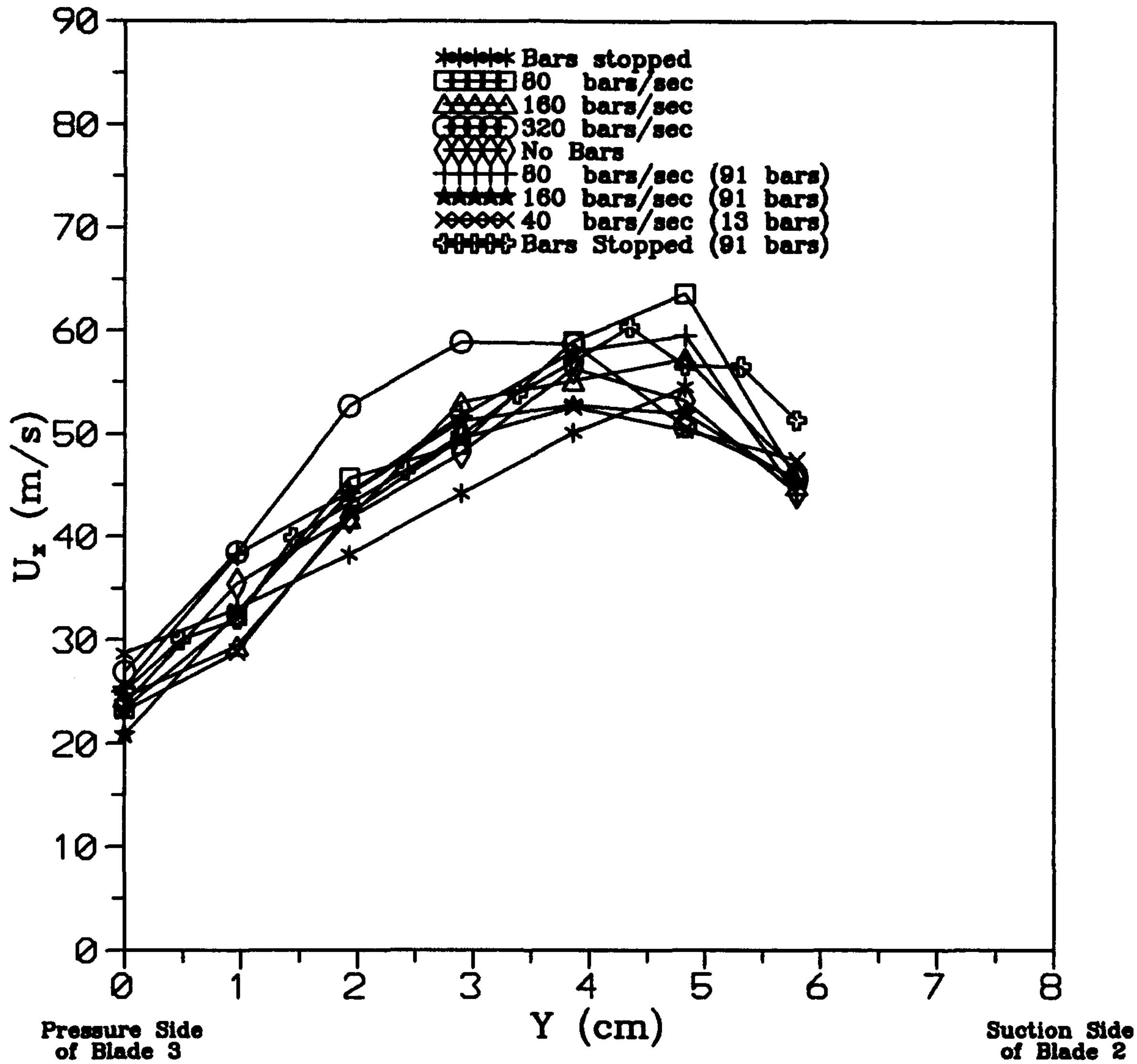


Fig. 5.24 Plane 4 Mid-span U_x at Re 4.55 X 10^6

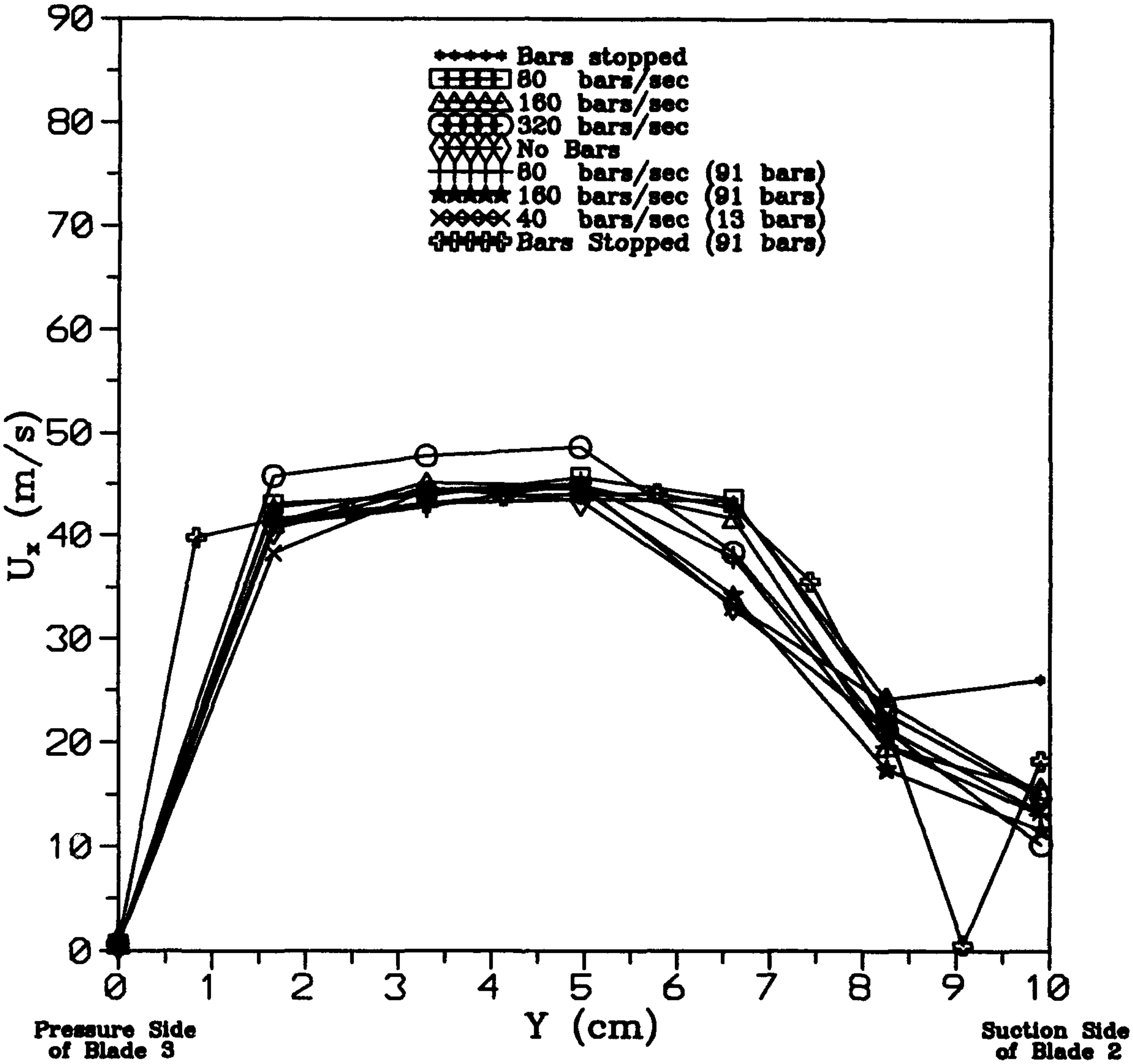


Fig. 5.25 Plane 5 Mid-span U_x at Re 4.55 X 10^6

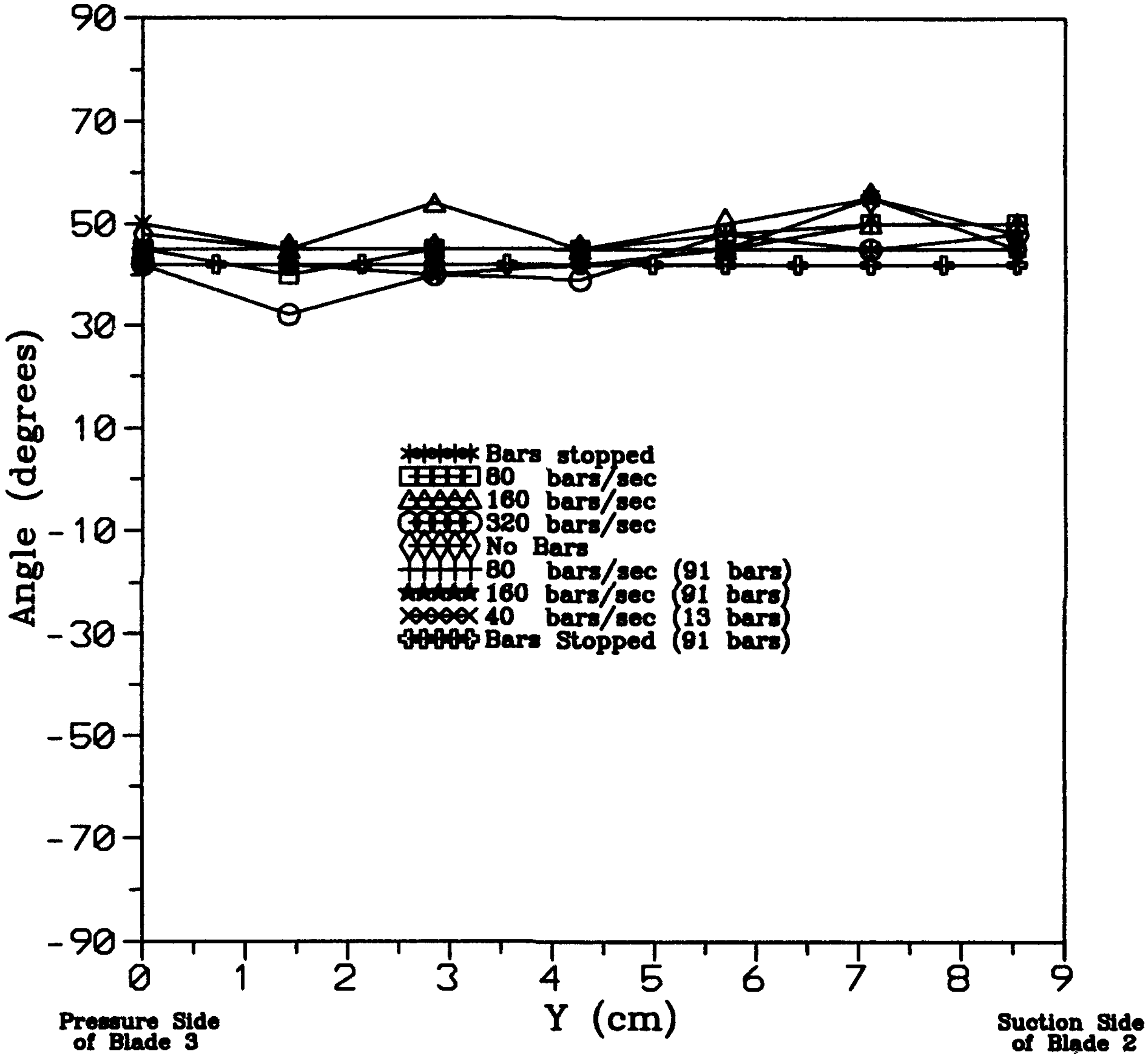


Fig. 5.26 Plane 1 Mid-span flow anlge at Re 4.55 X 10^6

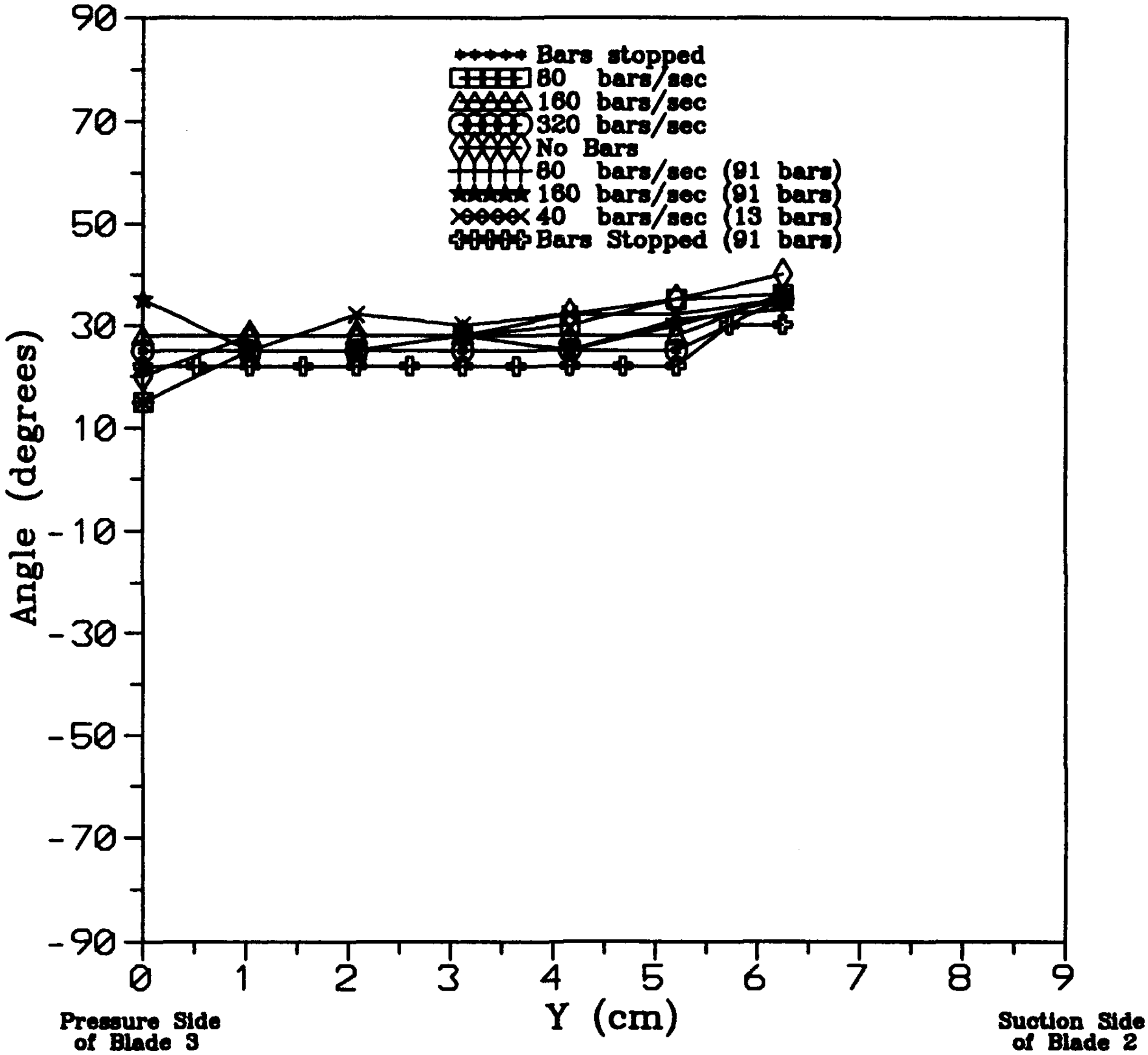


Fig. 5.27 Plane 2 Mid-span flow angle at Re 4.55 X 10^5

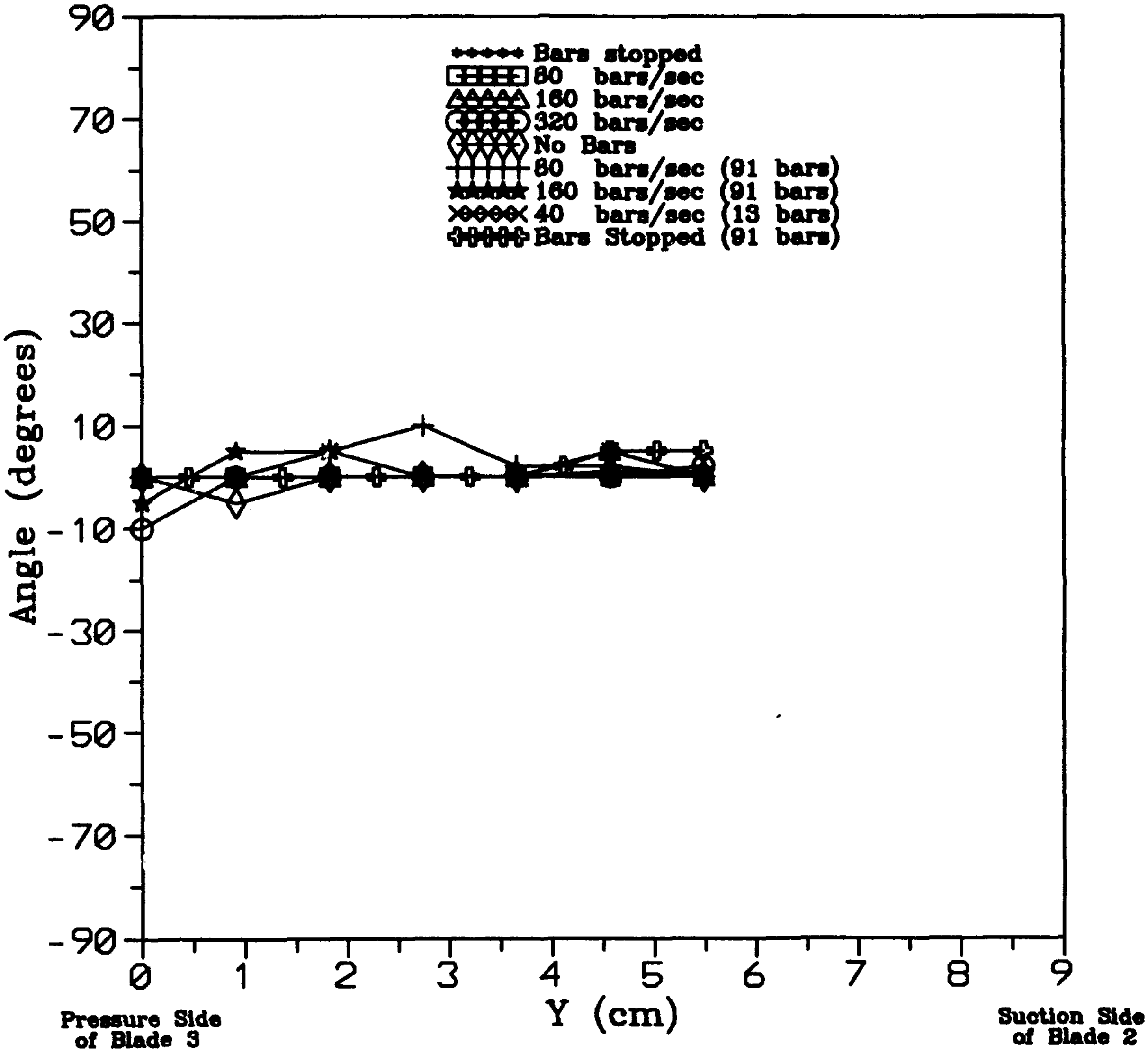


Fig. 5.28 Plane 3 Mid-span flow angle Re 4.55 X 10^5

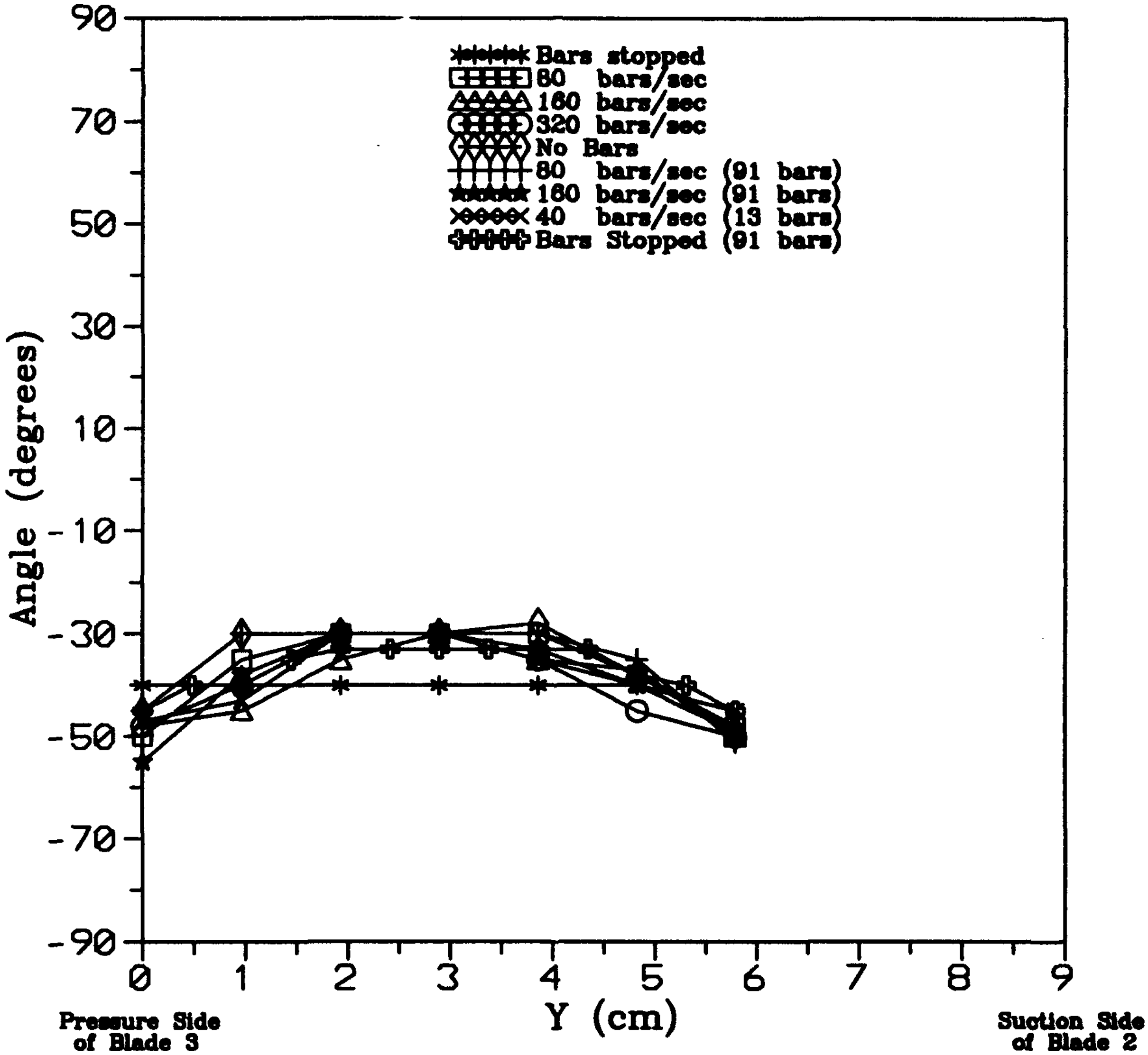


Fig. 5.29 Plane 4 Mid-span flow angle at Re 4.55 X 10^6

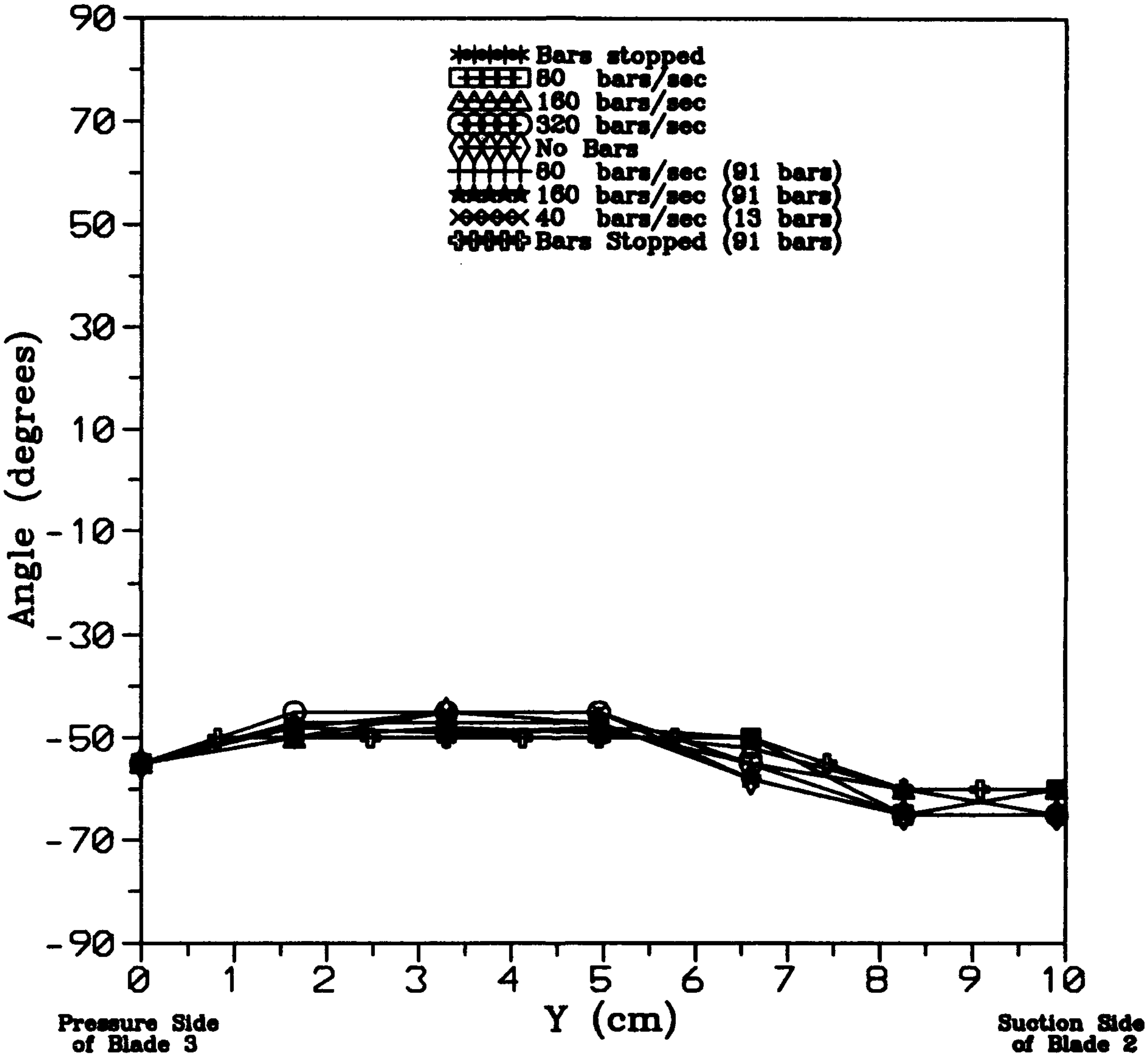


Fig. 5.30 Plane 5 Mid-span flow angle at Re 4.55 X 10^5

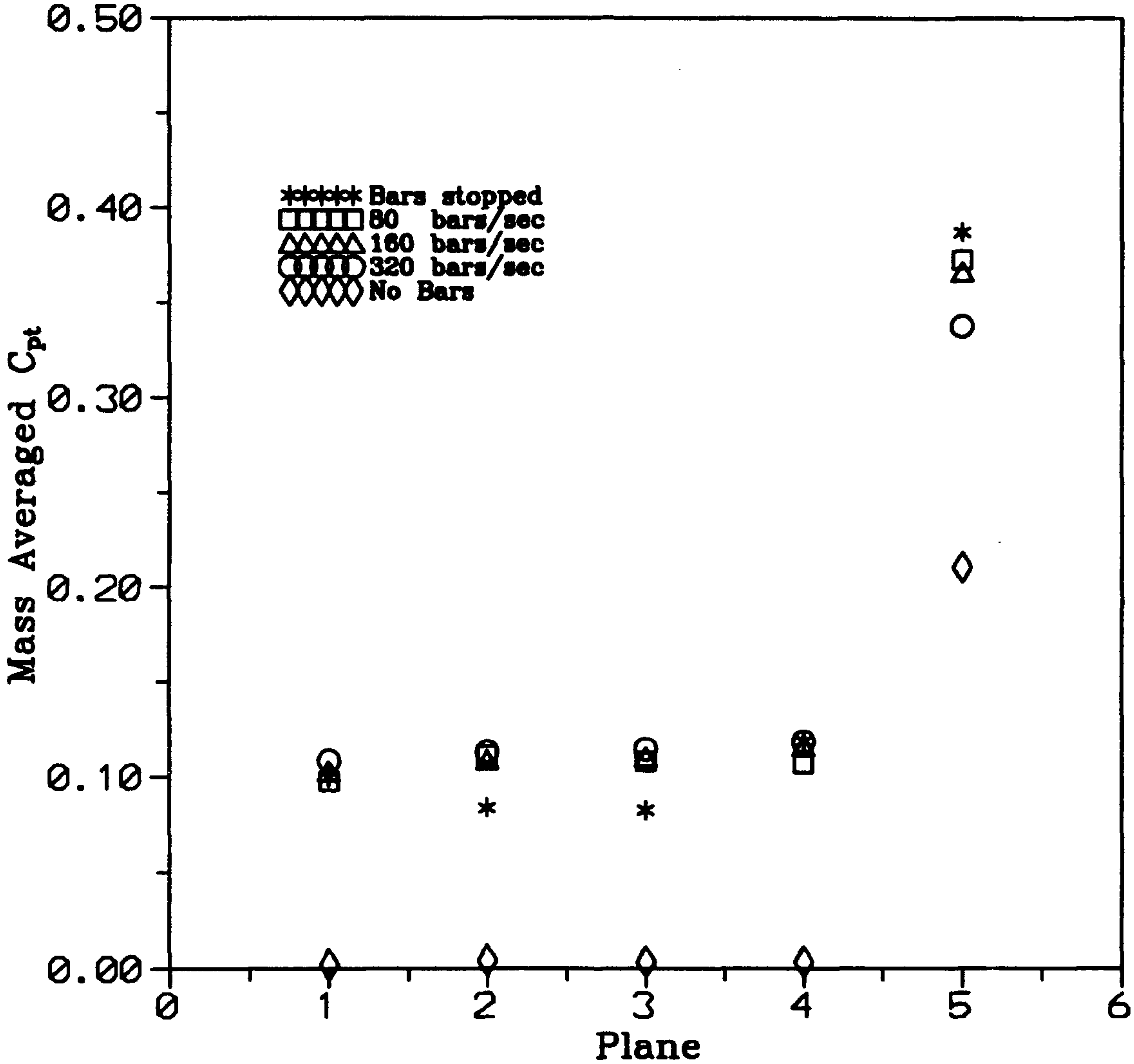


Fig. 5.31 Mass Averaged C_{pt} at Re 3.41 X 10^6

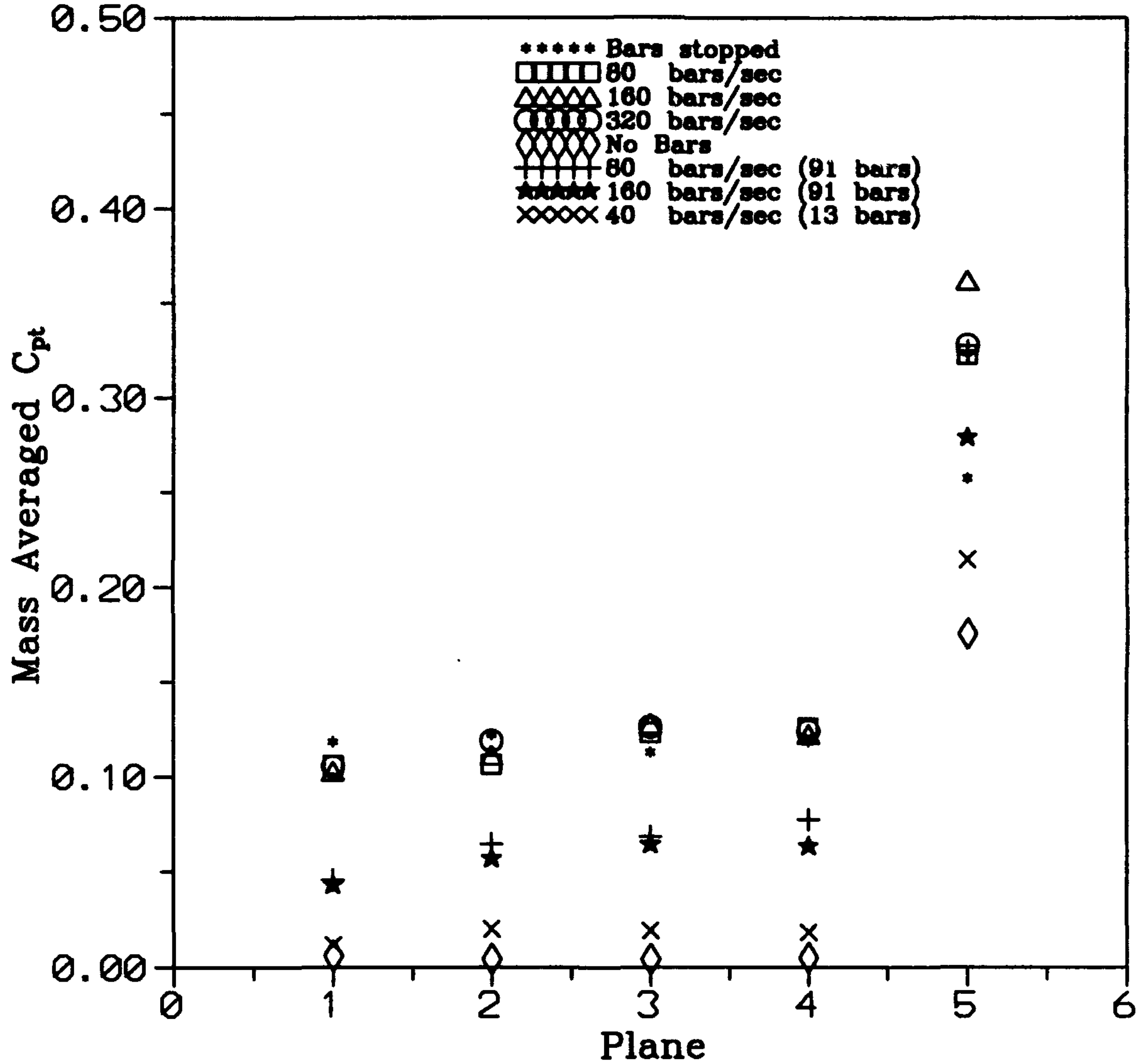


Fig. 5.32 Mass Averaged C_{pt} at Re 4.55 X 10^6

Appendix A

Appendix A contains a listing of each of the programs written for this thesis. Table A.1 is a list of the programs written and a brief description of each program.

Table A.1 Programs Used and Description

Programs Used	Purpose and Description	Output
XWRECAL.BAS	Calibrate hot wire	Calibration Curve
PRESSCAL.BAS	Calibrate pressure transducer	Calibration Curve
VELAQ3.BAS	Velocity measurements with hot wire	Velocity and Angle
ISOBAR3.BAS	Total pressure measurements	C_{pt}
ISOBAR6.BAS	Total and static pressure measurements, velocity, and angle	C_{pt}, Angle, Velocity, U_x

XWIRECAL.BAS

```
'*****************************************************************
'
'  * This program was written by Lt James Braunschneider
'    Summer/Fall 1993.  The program aquires voltage measurements
'    from IFA-100 Intelingent Flow Analyzer.  The
'    data is used to screate a calibration curve for a single
'    hot wire
'
'*****************************************************************

'*****************************************************************
'   Set up the HP3852A Digital Aquistion Unit
'*****************************************************************

    CLS
    CALL IBFIND("HP3852", dvm%)            'Find the HP3852A address

'*****************************************************************
'   Prepare XWIRECAL.DAT to recieve calibration data
'*****************************************************************

    outfile$ = "c:\emj\cal\xwirecal.dat"
    OPEN outfile$ FOR OUTPUT AS #1

'*****************************************************************
```

```
'     Loop to aquire data
'*********************************************************************

      DO
            PRINT "input height of water"
            INPUT h
            PRINT "reading voltage for height of "; h; " in....."
            CALL IBWRT(dvm%, "REAL W,L,H,AV1,AV2,S")
            CALL IBWRT(dvm%, "USE 400")
            CALL IBWRT(dvm%, "SCANMODE ON")
            CALL IBWRT(dvm%, "TERM RIBBON")
            CALL IBWRT(dvm%, "CONF DCV")
            CALL IBWRT(dvm%, "MEAS DCV 321 INTO W")
            CALL IBWRT(dvm%, "VREAD W")
            rd$ = SPACE$(16)
            CALL IBRD(dvm%, rd$)
            E1 = VAL(rd$)
            CALL IBWRT(dvm%, "RST; CLR")

            vel = 66.2 * SQR(h) / 3.28
            svel = vel ^ .45
            f1 = E1 + 1
            PRINT "velocity "; vel
            PRINT "E1  "; E1; "    F1"; f1

            s1 = f1 ^ 2
            PRINT "writing to file ...."
            PRINT #1, svel, E1, vel, f1, s1
            PRINT "press any key to continue"
            DO: LOOP WHILE INKEY$ = ""
            CALL IBWRT(dvm%, "RST; CLR")

      LOOP UNTIL INKEY$ <> ""
      CLOSE #1
      END
```

VELAQ3.BAS

```
'****************************************************************
'
'   * This program was written by Lt James Braunschneider
'     Summer/Fall 1993.  The program aquires voltage measurements
'     from the IFA-100 Intelligent Flow Analyzer via the HP3285A
'     DATA Aquisition unit.  The data is used to determine velocity
'     in a plane of the linear turbine cascade.
'
'****************************************************************

    CLS
    SCREEN 0
    LOCATE 5, 34
    PRINT "CHECKLIST"
    LOCATE 9, 18
    PRINT "!!!   Check Scanivalve POWER switches     !!!"
    LOCATE 11, 18
    PRINT "!!!   Check 10.00 V supply voltage.       !!!"
    LOCATE 13, 18
    PRINT "!!!   RESET Scanivalve channel to ZERO    !!!"
    LOCATE 15, 18
    PRINT "!!! X-wire in flow BEFORE ch1, ch2 on RUN !!!"
    LOCATE 22, 8
    PRINT "Press any key to continue"

    DO: LOOP WHILE INKEY$ = ""

'****************************************************************
'   * Set up HP3852A to measure Tunnel temp
'****************************************************************

    CALL IBFIND("HP3852", dvm%)             'Find the HP3852A address
    CALL IBWRT(dvm%, "USE 600;RST 600;REAL Troom, Ttunnel;AZERO ONCE")

'****************************************************************
'   * Read the room temperature
'****************************************************************

    CALL IBWRT(dvm%, "CONFMEAS TEMPJ, 019, INTO Troom")
    CALL IBWRT(dvm%, "DISP Troom")
    CALL IBWRT(dvm%, "VREAD Troom")
    rd$ = SPACE$(16)
    CALL ibrd(dvm%, rd$)
    Troom = VAL(rd$)          'convert the string value into a number


'****************************************************************
'   * Read the tunnel temperature
'****************************************************************

    CALL IBWRT(dvm%, "CONFMEAS TEMPJ, 020, INTO Ttunnel")
    CALL IBWRT(dvm%, "DISP Ttunnel")
    CALL IBWRT(dvm%, "VREAD Ttunnel")
    rd$ = SPACE$(16)
    CALL ibrd(dvm%, rd$)
```

```
Tunnel = VAL(rd$)       'convert the string value into a number

'*****************************************************************
'   * Set up HP3852A to measure Pressure
'*****************************************************************

DIM CAL(30) AS SINGLE

CALL IBWRT(dvm%, "RST")
CALL IBWRT(dvm%, "RST 600")
CALL IBWRT(dvm%, "REAL C(50), L,H,M,S")
CALL IBWRT(dvm%, "USE 600; NPLC 16")      'Configure the HP44701 for
                                  ' 5.5 digits of accuracy.
CALL IBWRT(dvm%, "SUB VOLTAGE")           'Create the measurement subroutine
CALL IBWRT(dvm%, "AZERO ONCE,USE 600")
CALL IBWRT(dvm%, "CONF DCV; NRDGS 50")
CALL IBWRT(dvm%, "MEAS DCV, 221, USE 600, INTO C")
CALL IBWRT(dvm%, "STAT L,H,M,S,C")
CALL IBWRT(dvm%, "DISP M")
CALL IBWRT(dvm%, "VREAD M")
CALL IBWRT(dvm%, "SUBEND")

'*****************************************************************
'   * Setup the measuring devices in the tunnel
'*****************************************************************

CLS
GOTO 50
LOCATE 2, 15
PRINT "SETUP OF SCANIVALVE PORTS"
LOCATE 4, 5
PRINT "1) Connect port ZERO of the scanivalve to the TOTAL pressure"
LOCATE 5, 5
PRINT "   port of the upstream pitot-static tube"
LOCATE 7, 5
PRINT "   Press any key to continue"
DO: LOOP WHILE INKEY$ = ""
LOCATE 9, 5
PRINT "2) Connect port ONE of the scanivalve to the STATIC pressure"
LOCATE 10, 5
PRINT "   port of the upstream pitot-static tube"
LOCATE 12, 5
PRINT "   Press any key to continue"
DO: LOOP WHILE INKEY$ = ""

50  CALL IBWRT(dvm%, "CLOSE 101")           'zero
    CALL IBWRT(dvm%, "OPEN 101;CONF DCV")   'scanivalve


'*****************************************************************
'   * Determine what planes are to be measured
'*****************************************************************

10  CLS
    LOCATE 2, 15
    PRINT "DETERMINE WHAT PLANES ARE TO BE MEASURED"
    LOCATE 5, 5
    PRINT "How many planes do you wish to measure, 1 or 6?"
    LOCATE 6, 5
    PRINT "(sorry, those are your only choices)"
```

```
        LOCATE 8, 5
        INPUT "Enter 1 or 6"; Oneorfive
        IF Oneorfive > 6 OR Oneorfive < 1 THEN
              CLS
11            LOCATE 5, 5
              PRINT "HEY, Were you listening 1 OR 6 not "; Oneorfive; "          "
              LOCATE 7, 5
              PRINT "Press any key to continue             "
              DO: LOOP WHILE INKEY$ = ""
              GOTO 10
              ymin = Oneorfive: ymax = Oneorfive
        ELSEIF Oneorfive = 1 THEN
              LOCATE 10, 5
              INPUT "Which plane do you want to measure "; whchplane
              IF whchplane < 1 OR whchplane > 6 THEN
                    GOTO 11
              ELSE
                    ymin = whchplane: ymax = whchplane
              END IF
        ELSEIF Oneorfive = 6 THEN
              ymin = 1: ymax = 5
        END IF
              LOCATE 18, 5
              INPUT "file name "; case$

'*****************************************************************
'   * Set screen to graphics mode and draw blades
'*****************************************************************

        pi = 3.14159
        CLS
        SCREEN 9
        LOCATE 2, 1
        PRINT "Position X-wire in location indicated by  O  "

        XDRA = 50: YDRA = 100
        CIRCLE (XDRA, YDRA + 50), 50, , pi / 180 * 330, pi / 180 * 50
        LINE (XDRA + 31, YDRA + 21)-(XDRA - 40, YDRA - 15)
        LINE -(XDRA + 70, YDRA + 15)
        CIRCLE (XDRA + 30, YDRA + 50), 70, , pi / 180 * 330, pi / 180 * 60, .6
        CIRCLE (XDRA + 65, YDRA + 70), 25, , pi / 180 * 180, pi / 180 * 360, .6
        XDRA = XDRA + 150
        CIRCLE (XDRA, YDRA + 50), 50, , pi / 180 * 330, pi / 180 * 50
        LINE (XDRA + 31, YDRA + 21)-(XDRA - 40, YDRA - 15)
        LINE -(XDRA + 70, YDRA + 15)
        CIRCLE (XDRA + 30, YDRA + 50), 70, , pi / 180 * 330, pi / 180 * 60, .6
        CIRCLE (XDRA + 65, YDRA + 70), 25, , pi / 180 * 180, pi / 180 * 360, .6

'*****************************************************************
'   * Draw planes and show position
'*****************************************************************

        LOCATE 4, 50
        PRINT "TOP (Z=4.5 INCHES)"
        LOCATE 5, 45
        PRINT "----------------"
        LOCATE 7, 66
        PRINT "View from"
        LOCATE 8, 66
        PRINT "downstream"
```

```
LOCATE 9, 66
PRINT "looking"
LOCATE 10, 66
PRINT "upstream"
LOCATE 17, 45
PRINT "------------------"
LOCATE 18, 47
PRINT "BOTTOM (Z=0 INCHES)"

XDRA2 = XDRA - 75
PLANE1 = YDRA + 85
plane = PLANE1
PLANE2 = plane
PSET (XDRA2, plane)
'LINE -(XDRA2 + 130, PLANE - 3), 2, BF

'**********************************************************
'    * slope and y intercept for pressure-voltage curve
'**********************************************************

     vel$ = "c:\anj\cal\pcoeff.dat"
     OPEN vel$ FOR INPUT AS #2
          INPUT #2, m, b
     CLOSE #2

'**********************************************************
'    * slope and y intercept for pressure-voltage curve
'**********************************************************

     OPEN "c:\anj\cal\xwirecal.cof" FOR INPUT AS #3
          INPUT #3, WM1, WB1

     CLOSE #3

'****************************************************************
'    * Loop for taking data at each position
'****************************************************************

FOR YPOS = ymin TO ymax

dir$ = "c:\anj\dat\vel\"
YPOS$ = STR$(YPOS)
flname$ = "pv" + LTRIM$(YPOS$) + case$
OPEN dir$ + flname$ + ".dat" FOR OUTPUT AS #1

'**********************************************************
'    * Draw measurement plane on blades
'**********************************************************

     XDRA3 = XDRA2
     IF YPOS = 2 THEN
          PLANE2 = plane - 30
     ELSEIF YPOS = 3 THEN
          PLANE2 = plane - 60
     ELSEIF YPOS = 4 THEN
          PLANE2 = plane - 90
          XDRA3 = XDRA2 - 75
     ELSEIF YPOS = 5 THEN
          PLANE2 = plane - 120
          XDRA3 = XDRA2 - 150
```

```
ELSEIF YPOS = 6 THEN
       PLANE2 = plane - 120
       XDRA3 = XDRA2 - 150
END IF

PSET (XDRA3, PLANE2)
LINE -(XDRA3 + 130, PLANE2 - 3), 2, BF

'**********************************************************
'   * Determine the coords and increments for each plane
'**********************************************************

       zmax = 3: xmax = 7
       Zact = 2.75: Xact = 0   'Z=0 is bottom of cascade

       IF YPOS = 1 THEN
              Xinc = .417
       ELSEIF YPOS = 2 THEN
              Xinc = .358
       ELSEIF YPOS = 3 THEN
              Xinc = .375
       ELSEIF YPOS = 4 THEN
              Xinc = .38
       ELSEIF YPOS = 5 THEN
              Xinc = .655
       ELSEIF YPOS = 6 THEN
              Xinc = .655
       END IF

'**********************************************************
'   * Read UPSTREAM total and static pressure once per plane
'**********************************************************

       CALL IBWRT(dvm%, "RST")
       CALL IBWRT(dvm%, "RST 600")
       CALL IBWRT(dvm%, "REAL C(50), L,H,M,S")
       CALL IBWRT(dvm%, "USE 600; NPLC 16")        'Configure the HP44701 for
                                            ' 5.5 digits of accuracy.
       CALL IBWRT(dvm%, "SUB VOLTAGE")             'Create the measurement subroutine
       CALL IBWRT(dvm%, "AZERO ONCE,USE 600")
       CALL IBWRT(dvm%, "CONF DCV; NRDGS 50")
       CALL IBWRT(dvm%, "MEAS DCV, 221, USE 600, INTO C")
       CALL IBWRT(dvm%, "STAT L,H,M,S,C")
       CALL IBWRT(dvm%, "DISP M")
       CALL IBWRT(dvm%, "VREAD M")
       CALL IBWRT(dvm%, "SUBEND")

       CALL IBWRT(dvm%, "CALL VOLTAGE")       'read total upstream
       rd$ = SPACE$(16)                       'pressure from
       CALL ibrd(dvm%, rd$)                   'port zero
       vt! = VAL(rd$)
       Ptotal! = vt!

       CALL IBWRT(dvm%, "CLOSE 100")          'advance scani
       CALL IBWRT(dvm%, "OPEN 100;CONF DCV")  'one port

       CALL IBWRT(dvm%, "CALL VOLTAGE")       'read static upstream
       rd$ = SPACE$(16)                       'pressure from
       CALL ibrd(dvm%, rd$)                   'port one
       vt! = VAL(rd$)
```

```
Pstatic! = vt!

CALL IBWRT(dvm%, "CLOSE 100")          'advance scani
CALL IBWRT(dvm%, "OPEN 100;CONF DCV")  'one port

'*************************************************
'   * Determine UPSTREAM velocity and print to screen
'*************************************************

    LOCATE 21, 40
    Ptot! = (m * Ptotal! + b) + 101.3
    Pstc! = (m * Pstatic! + b) + 101.3
    Tstatic! = (Ttunnel + 273.15) / ((Ptot! / Pstc!) ^ (.4 / 1.4))
    IF Tstatic! <= (Ttunnel + 273.15) THEN
        velupstrm! = SQR(2 * 1.4 / .4 * 287 * ((Ttunnel + 273.15) - Tstatic!))
    ELSE
        velupstrm! = -.9999
    END IF
    PRINT "Upstream velocity is "; velupstrm; " m/s"

'*******************************************************
'   * LOOP FOR PLANE: Mark position on plane
'*******************************************************

FOR ZPOS = 1 TO zmax
FOR XPOS = 1 TO xmax
    LOCATE 20, 1
    PRINT "Z-X of next measurement:          "
    PRINT "ZPOS = "; Zact; "in   XPOS = "; Xact; "in         "
    LOCATE ZPOS + 5, (XPOS * 2) + 44
    PRINT "O"

    LOCATE 17, 1
    PRINT "Angle of flow at position O"
    INPUT "Angle is:           ", angle

    LOCATE ZPOS + 5, (XPOS * 2) + 44
    PRINT "X"
    LOCATE 18, 19
    PRINT "                          "

    '*************************************************
    '   * Take angle and voltage data
    '*************************************************

    CALL IBWRT(dvm%, "REAL W,L,H,AV1,AV2,S")
    CALL IBWRT(dvm%, "USE 400")
    CALL IBWRT(dvm%, "SCANMODE ON")
    CALL IBWRT(dvm%, "TERM RIBBON")
    CALL IBWRT(dvm%, "CONF DCV")
    CALL IBWRT(dvm%, "MEAS DCV 321 INTO W") 'read atmospheric pressure
    CALL IBWRT(dvm%, "VREAD W")
    rd$ = SPACE$(16)
    CALL ibrd(dvm%, rd$)
    E1 = VAL(rd$)
    CALL IBWRT(dvm%, "RST; CLR")

    '*************************************************
    '   * Use if using X wire
```

```
'*************************************************

'        rd$ = SPACE$(16)
'        CALL IBWRT(dvm%, "REAL W,L,H,AV1,AV2,S")
'        CALL IBWRT(dvm%, "USE 400")
'        CALL IBWRT(dvm%, "SCANMODE ON")
'        CALL IBWRT(dvm%, "TERM RIBBON")
'        CALL IBWRT(dvm%, "CONF DCV")
'        CALL IBWRT(dvm%, "MEAS DCV 323 INTO W") 'read atmospheric pressure
'        CALL IBWRT(dvm%, "VREAD W")
'        CALL ibrd(dvm%, rd$)
'        E2 = VAL(rd$)
'        CALL IBWRT(dvm%, "RST; CLR")

        '*************************************************
        '    * Calculate wire velocities
        '*************************************************

        gain = 10          ' Check settings on IFA to match
        offset = 1         ' Check settings on IFA to match

        'E1 = E1 / gain + offset
        'E2 = E2 / gain + offset
        UE1 = ((E1 - WB1) / WM1) ^ 2.22
        'UE2 = ((E2 - WB2) / WM2) ^ 2.22
        'PRINT UE1, UE2
        ux = UE1 * COS(3.1415 / 180 * ABS(90 - angle))
        PRINT #1, Xact, ux, UE1, angle, E1, velupstrm
        LOCATE 22, 40
        PRINT "Velocity at last point: "; UE1
        LOCATE 23, 40
        PRINT "Ux at last point: "; ux; "   "

        Xact = Xact + Xinc   'determine next X actual
    NEXT XPOS
        Xact = 0
        Zact = Zact - .5     'determine the next Z actual
    NEXT ZPOS

'*******************************************************
'    * Clear plane
'*******************************************************

         FOR ZPOS = 1 TO 11
         FOR XPOS = 1 TO 20
             LOCATE ZPOS + 5, XPOS + 44
             PRINT "  "
         NEXT XPOS
         NEXT ZPOS

PRINT #1, Ttunnel     'Total temp and Velocity
PRINT #1, velupstrm
PRINT #1, Ptotal!
PRINT #1, Pstatic!

CLOSE #1

CALL IBWRT(dvm%, "CLOSE 101")          'zero
CALL IBWRT(dvm%, "OPEN 101;CONF DCV")  'scanivalve
```

```
    NEXT YPOS

GOTO 50
100 END
```

ISOBAR6.BAS

```
'*****************************************************************
'
'   * This program was written by Lt James Brunnschneider
'     Summer/Fall 1993.  The program aquires voltage measurements
'     from a Scanivalve via the HP3285A Data Aquisition unit.  The
'     data is used to create a plot of Cpt and/or velocity in a
'     plane of the linear turbine cascade.
'
'*****************************************************************

    CLS
    SCREEN 0
    LOCATE 5, 34
    PRINT "CHECKLIST"
    LOCATE 9, 18
    PRINT "!!!   Check Scanivalve POWER switches   !!!"
    LOCATE 11, 18
    PRINT "!!!   Check 10.00 V supply voltage.     !!!"
    LOCATE 13, 18
    PRINT "!!!   RESET Scanivalve channel to ZERO  !!!"
    LOCATE 22, 8
    PRINT "Press any key to continue"

    DO: LOOP WHILE INKEY$ = ""

'*****************************************************************
'   * Set up HP3852A to measure Tunnel temp
'*****************************************************************

    CALL IBFIND("HP3852", dvm%)            'Find the HP3852A address
    CALL IBWRT(dvm%, "USE 600;RST 600;REAL Troom, Tunnel;AZERO ONCE")
```

```
'*****************************************************************
'    * Read the room temperature
'*****************************************************************

     CALL IBWRT(dvm%, "CONFMEAS TEMPJ, 019, INTO Troom")
     CALL IBWRT(dvm%, "DISP Troom")
     CALL IBWRT(dvm%, "VREAD Troom")
     rd$ = SPACE$(16)
     CALL ibrd(dvm%, rd$)
     Troom = VAL(rd$)          'convert the string value into a number


'*****************************************************************
'    * Read the tunnel temperature
'*****************************************************************

     CALL IBWRT(dvm%, "CONFMEAS TEMPJ, 020, INTO Ttunnel")
     CALL IBWRT(dvm%, "DISP Ttunnel")
     CALL IBWRT(dvm%, "VREAD Ttunnel")
     rd$ = SPACE$(16)
     CALL ibrd(dvm%, rd$)
     ttunnel = VAL(rd$)        'convert the string value into a number

'*****************************************************************
'    * Set up HP3852A to measure Pressure
'*****************************************************************

     DIM CAL(30) AS SINGLE

     CALL IBWRT(dvm%, "RST")
     CALL IBWRT(dvm%, "RST 600")
     CALL IBWRT(dvm%, "REAL C(50), L,H,M,S")
     CALL IBWRT(dvm%, "USE 600; NPLC 16")        'Configure the HP44701
     CALL IBWRT(dvm%, "SUB VOLTAGE")             'Create the measurement subroutine
     CALL IBWRT(dvm%, "AZERO ONCE,USE 600")
     CALL IBWRT(dvm%, "CONF DCV; NRDGS 50")
     CALL IBWRT(dvm%, "MEAS DCV, 221, USE 600, INTO C")
     CALL IBWRT(dvm%, "STAT L,H,M,S,C")
     CALL IBWRT(dvm%, "DISP M")
     CALL IBWRT(dvm%, "VREAD M")
     CALL IBWRT(dvm%, "SUBEND")

'*****************************************************************
'    * Reset scanivalve to port zero
'*****************************************************************

1    CALL IBWRT(dvm%, "CLOSE 101")              'Zero scanivalve
     CALL IBWRT(dvm%, "OPEN 101;CONF DCV")

'*****************************************************************
'    * Determine what planes are to be measured
'*****************************************************************

     CLS
     LOCATE 2, 15
     PRINT "DETERMINE WHAT PLANES ARE TO BE MEASURED"
     LOCATE 5, 5
     PRINT "How many planes do you wish to measure, 1 or 6?"
     LOCATE 6, 5
     PRINT "(sorry, those are your only choices) "; case$
```

```
LOCATE 8, 5
INPUT "Enter 1 or 6"; Oneorfive
IF Oneorfive > 6 OR Oneorfive < 1 THEN
     CLS
11    LOCATE 5, 5
     PRINT "HEY, Were you listening 1 OR 4 not "; Oneorfive; "          "
     LOCATE 7, 5
     PRINT "Press any key to continue          "
     DO: LOOP WHILE INKEY$ = ""
     GOTO 10
     ymin = Oneorfive: ymax = Oneorfive
ELSEIF Oneorfive = 1 THEN
     LOCATE 10, 5
     INPUT "Which plane do you want to measure "; whchplane
     IF whchplane < 1 OR whchplane > 6 THEN
          GOTO 11
     ELSE
          ymin = whchplane: ymax = whchplane
     END IF
ELSEIF Oneorfive = 6 THEN
     ymin = 1: ymax = 6
END IF
LOCATE 14, 5
INPUT "file name "; case$

'*****************************************************************
'   * Set screen to graphics mode and draw blades
'*****************************************************************

pi = 3.14159
CLS
SCREEN 9

XDRA = 50: YDRA = 100
CIRCLE (XDRA, YDRA + 50), 50, , pi / 180 * 330, pi / 180 * 50
LINE (XDRA + 31, YDRA + 21)-(XDRA - 40, YDRA - 15)
LINE -(XDRA + 70, YDRA + 15)
CIRCLE (XDRA + 30, YDRA + 50), 70, , pi / 180 * 330, pi / 180 * 60, .6
CIRCLE (XDRA + 65, YDRA + 70), 25, , pi / 180 * 180, pi / 180 * 360, .6
XDRA = XDRA + 150
CIRCLE (XDRA, YDRA + 50), 50, , pi / 180 * 330, pi / 180 * 50
LINE (XDRA + 31, YDRA + 21)-(XDRA - 40, YDRA - 15)
LINE -(XDRA + 70, YDRA + 15)
CIRCLE (XDRA + 30, YDRA + 50), 70, , pi / 180 * 330, pi / 180 * 60, .6
CIRCLE (XDRA + 65, YDRA + 70), 25, , pi / 180 * 180, pi / 180 * 360, .6

'*****************************************************************
'   * Draw planes and show position
'*****************************************************************

LOCATE 4, 45
PRINT "TOP (Z=4.5 INCHES)"
LOCATE 5, 45
PRINT "-----------------"
LOCATE 5, 66
PRINT "View from"
LOCATE 6, 66
PRINT "downstream"
LOCATE 7, 66
PRINT "looking"
```

```
LOCATE 8, 66
PRINT "upstream"
LOCATE 7, 45
PRINT "————————"
LOCATE 8, 45
PRINT "BOTTOM (Z=0 INCHES)"

XDRA2 = XDRA - 75
PLANE1 = YDRA + 85
plane = PLANE1
PLANE2 = plane
PSET (XDRA2, plane)

'*********************************************************
'    * slope and y intercept for pressure-voltage curve
'*********************************************************

        vel$ = "c:\enj\cal\pcoeff.dat"
        OPEN vel$ FOR INPUT AS #2
                INPUT #2, m, b
        CLOSE #2

'*****************************************************************
'   * Loop for taking data at each position
'*****************************************************************

FOR YPOS = ymin TO ymax

        dir$ = "c:\enj\dat\planesf\"
        YPOS$ = STR$(YPOS)
        fname$ = "pl" + LTRIM$(YPOS$) + case$
        OPEN dir$ + fname$ + ".dat" FOR OUTPUT AS #1

'*********************************************************
'    * Draw measurement plane on blades
'*********************************************************

        XDRA3 = XDRA2
        IF YPOS = 2 THEN
                PLANE2 = plane - 30
        ELSEIF YPOS = 3 THEN
                PLANE2 = plane - 60
        ELSEIF YPOS = 4 THEN
                PLANE2 = plane - 90
                XDRA3 = XDRA2 - 75
        ELSEIF YPOS = 5 THEN
                PLANE2 = plane - 120
                XDRA3 = XDRA2 - 150
        ELSEIF YPOS = 6 THEN
                PLANE2 = plane - 120
                XDRA3 = XDRA2 - 150
        END IF

        PSET (XDRA3, PLANE2)
        LINE -(XDRA3 + 130, PLANE2 - 3), 2, BF

'*********************************************************
'    * Determine the coords and increments for each plane
'*********************************************************
```

```
zmax = 1: xmax = 7
Zact = 2.25: Xact = 0   'Z=0 is bottom of cascade

IF YPOS = 1 THEN
      Xinc = .56
ELSEIF YPOS = 2 THEN
      Xinc = .41
ELSEIF YPOS = 3 THEN
      Xinc = .36
ELSEIF YPOS = 4 THEN
      Xinc = .38
ELSEIF YPOS = 5 THEN
      Xinc = .65
ELSEIF YPOS = 6 THEN
      Xinc = .65
END IF

'**********************************************************
'   * Read UPSTREAM total and static pressure
'**********************************************************

      CALL IBWRT(dvm%, "CLOSE 100")          'advance scani
      CALL IBWRT(dvm%, "OPEN 100;CONF DCV")  'one port

      CALL IBWRT(dvm%, "CLOSE 100")          'advance scani
      CALL IBWRT(dvm%, "OPEN 100;CONF DCV")  'one port

   '**************************************************
   '   * Loop until upstream Pt is stable
   '**************************************************

      DO
            CALL IBWRT(dvm%, "CALL VOLTAGE")      'read total upstream
            rd$ = SPACE$(16)                      'pressure from
            CALL ibrd(dvm%, rd$)                  'port zero
            vt! = VAL(rd$)
            Ptotal! = vt!
            LOCATE 1, 1
            PRINT USING "Maximize Upstream Pt  ###.###"; (Ptotal * m + b) + 101.3
      LOOP WHILE INKEY$ = ""

      CALL IBWRT(dvm%, "CLOSE 100")          'advance scani
      CALL IBWRT(dvm%, "OPEN 100;CONF DCV")  'one port

   '**************************************************
   '   * Measure static Pressure ports
   '**************************************************

      LOCATE 1, 1
      FOR port = 3 TO 9   ' 7 ports
            CALL IBWRT(dvm%, "CALL VOLTAGE")      'read static upstream
            rd$ = SPACE$(16)                      'pressure from
            CALL ibrd(dvm%, rd$)                  'port one
            vt! = VAL(rd$)
            Pstcavg(port) = vt!
            PRINT Pstcavg(port);
            CALL IBWRT(dvm%, "CLOSE 100")          'advance scani
            CALL IBWRT(dvm%, "OPEN 100;CONF DCV")  'one port
      NEXT port
            CALL IBWRT(dvm%, "CALL VOLTAGE")      'read static upstream
```

```
            rd$ = SPACE$(16)                    'pressure from
            CALL ibrd(dvm%, rd$)                 'port one
            vt! = VAL(rd$)
            ptotal2 = vt!
            LOCATE 1, 30
            PRINT USING "Ptotal2 is ###.###"; ((ptotal2 * m + b) + 101.3)

            CALL IBWRT(dvm%, "CLOSE 101")          'advance scani
            CALL IBWRT(dvm%, "OPEN 101;CONF DCV")  'one port

    '**************************************************
    '   * Determine UPSTREAM velocity and print to screen
    '**************************************************

        Pstatic = 0
        LOCATE 2, 40
        FOR port = 3 TO 9
        Pstatic = Pstatic + Pstcavg(port)
        NEXT port
        Pstatic = Pstatic - Pstcavg(6)
        Pstatic = Pstatic / 6
        PRINT Pstatic
        LOCATE 2, 1
        Ptot! = (m * Ptotal! + b) + 101.3
        Pstc! = (m * Pstatic! + b) + 101.3
        Tstatic! = (ttunnel + 273.15) / ((Ptot! / Pstc!) ^ (.4 / 1.4))
        IF Tstatic! <= (ttunnel + 273.15) THEN
            velupstrm! = SQR(2 * 1.4 / .4 * 287 * ((ttunnel + 273.15) - Tstatic!))
        ELSE
            velupstrm! = -.9999
        END IF
        PRINT USING "Ptotal ###.###  Pstcavg ###.###"; Ptot; Pstc
        LOCATE 16, 1
        PRINT USING "Upstream velocity:  ##.### m/s"; velupstrm

'*********************************************************
'   * LOOP FOR PLANE: Mark position on plane
'*********************************************************

 FOR ZPOS = 1 TO zmax

 FOR XPOS = 1 TO xmax
    LOCATE 22, 1
    'PRINT "Z-X of next measurement:          "
    'PRINT "ZPOS - "; Zact; "in   XPOS - "; Xact; "in        "
    LOCATE ZPOS + 5, (XPOS * 2) + 44
    PRINT "O"
        LINE (340, 315)-(620, 315)
        LINE (340, 200)-(340, 315)
        colr = 2
        xpress = 350
23       DO
            xpress = xpress + 6
            IF xpress > 600 THEN
            xpress = 350: colr = colr + 3
            END IF
            CALL IBWRT(dvm%, "CALL VOLTAGE")     'read total in-plane
            rd$ = SPACE$(16)                 'pressure from
            CALL ibrd(dvm%, rd$)              'port two
            vt! = VAL(rd$)
```

```
        Pmax = vt!
        LOCATE 13, 45
        Pmaxi = (m * Pmax + b) + 101.3
        PRINT USING "Maximize Ptotal ###.#####"; Pmaxi
        ypress = 250 + INT(ABS((Pmaxi - 101.3) * 30))
        CIRCLE (xpress, ypress), 2, colr
    LOOP WHILE INKEY$ = ""
    LOCATE 15, 45
    INPUT "What is the angle "; angle
    IF angle = 0 THEN
        GOTO 23
    END IF
    LINE (341, 314)-(619, 219), 0, BF

        CALL IBWRT(dvm%, "CALL VOLTAGE")      'read total in-plane
        rd$ = SPACE$(16)                      'pressure from
        CALL ibrd(dvm%, rd$)                  'port two
        vt! = VAL(rd$)
        Pinplane = vt!
        LOCATE 13, 45
        Pinplne = (m * Pinplane + b) + 101.3

LOCATE ZPOS + 5, (XPOS * 2) + 44
PRINT LTRIM$(STR$(XPOS))
LOCATE 15, 64
PRINT "      "


'*************************************************
'   * Take in plane voltage data
'*************************************************

    CALL IBWRT(dvm%, "CLOSE 100")           'advance scani
    CALL IBWRT(dvm%, "OPEN 100;CONF DCV")   'one port

    CALL IBWRT(dvm%, "CALL VOLTAGE")        'read static
    rd$ = SPACE$(16)                        'pressure from
    CALL ibrd(dvm%, rd$)                    'port two
    vt! = VAL(rd$)
    Psinplane! = vt!

'*************************************************
'   * Calculate Cpt, velocity  / output
'*************************************************

    Pt = (m * Pinplane + b) + 101.3
    Ps = (m * Psinplane + b) + 101.3
    Ts = (ttunnel + 273.15) / ((Pt / Ps) ^ (.4 / 1.4))
    IF Ts <= (ttunnel + 273.15) THEN
        velatpt = SQR(2 * 1.4 / .4 * 287 * ((ttunnel + 273.15) - Ts))
    ELSE
        velatpt = -.99999
    END IF

    Ux = velatpt * COS(3.1415 / 180 * ABS(90 - angle))
    Cpt! = ((Ptotal! - Pinplane!) / (Ptotal! - Pstatic!))
    rho = Pt / 287 / Ts

    massavgcpt = massavgcpt + rho * Ux * Cpt
    massavgux = massavgux + rho * Ux
```

```
            LOCATE 18, 1
            PRINT USING "Last Velocity was:  ##.#####"; velatpt
            PRINT USING "Last Ux was:        ##.#####"; Ux
            PRINT USING "Last Cpt was:        #.#####"; Cpt!
            PRINT USING "Last density was    ##.#####"; rho
            PRINT #1, Xact, Cpt!, Ux, ttunnel, Pinplane, Psinplane, Ptotal, Pstatic, angle
            LOCATE 23, 1
            PRINT "Press any key for measurement at O  "
            LOCATE ZPOS + 5, (XPOS * 2) + 44
            PRINT "X"

        Xact = Xact + Xinc   'determine next X actual

            CALL IBWRT(dvm%, "CLOSE 101")          'advance scani
            CALL IBWRT(dvm%, "OPEN 101;CONF DCV")  'one port


     NEXT XPOS
        '**************************************************
        '   * Preapre file and record mass average data
        '**************************************************

        Xact = 0
        'Zact = Zact - .5     'determine the next Z actual
            W = massavgcpt / massavgux
            massavgcpt = 0
            massavgux = 0
        whchplane$ = STR$(whchplane)
        flname$ = "ma" + case$
        OPEN dir$ + flname$ + ".dat" FOR APPEND AS #2
        PRINT #2, whchplane, W
    CLOSE #2

    NEXT ZPOS

    '*********************************************************
    '   * Clear plane
    '*********************************************************

         FOR ZPOS = 1 TO zmax
         FOR XPOS = 1 TO 7
            LOCATE ZPOS + 5, (XPOS * 2) + 44
            PRINT " "
         NEXT XPOS
         NEXT ZPOS

    CLOSE #1

    CALL IBWRT(dvm%, "CLOSE 101")          'zero
    CALL IBWRT(dvm%, "OPEN 101;CONF DCV")  'scanivalve

    NEXT YPOS
GOTO 1

100 END
```

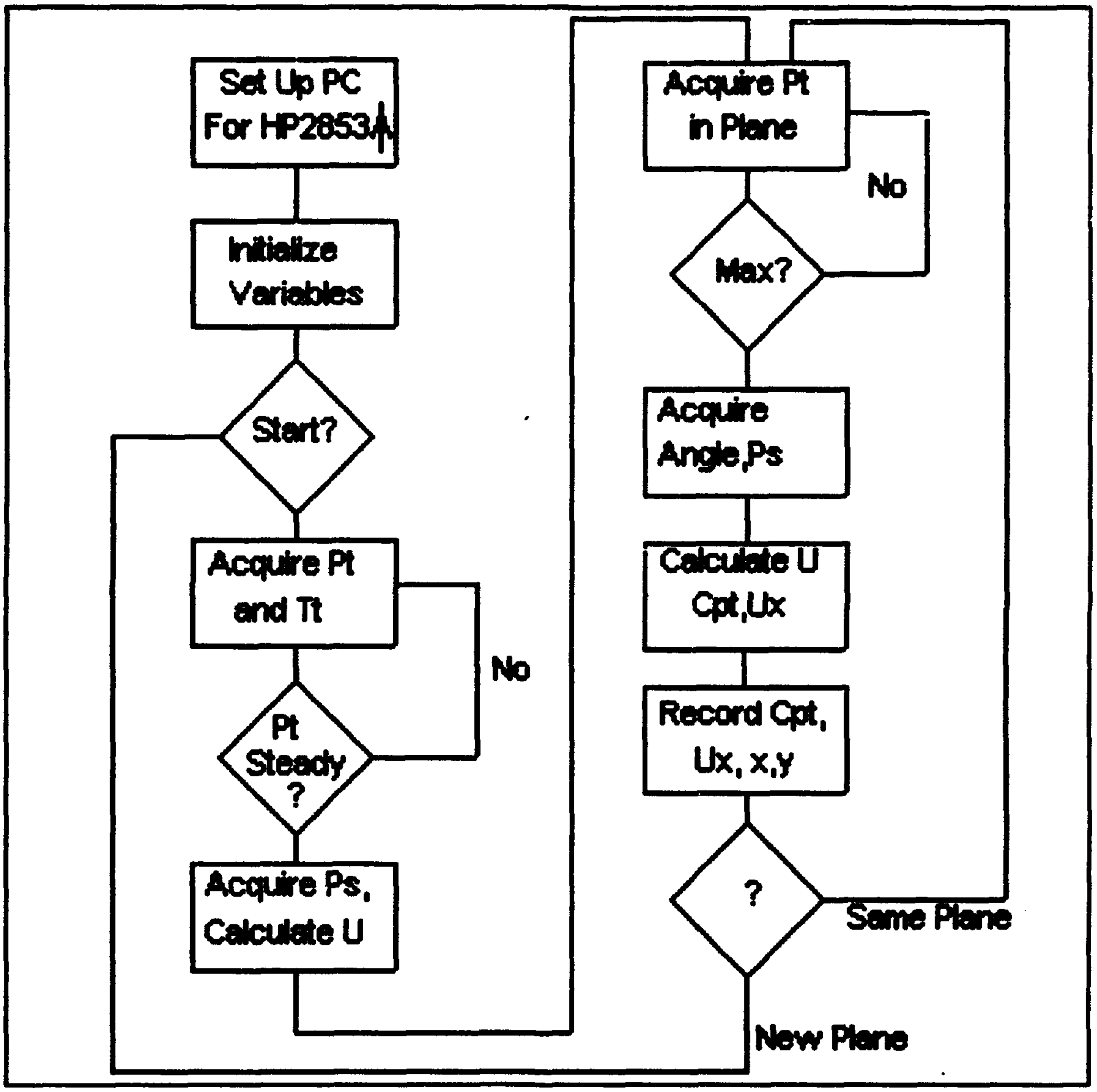


Fig. A.1 Flow Chart for ISOBAR.BAS

Appendix B

Pressure Transducer Calibration

The pressure transducer for the Scanivalve needs to be calibrated. A known pressure is applied to the Scanivalve and the associated voltage is measured and recorded. The procedure below is specific to the equipment and needs of the TCTF.

Equipment

- U-type manometer
- Compressor located on the south side of Building 19, WPAFB
- Air stilling chamber with nozzle, pitot tube, and hand vacuum pump
- Scanivalve
- Flexible rubber plastic tubing and connections
- PRESSCAL.BAS program

Procedure

1) Run PRESSCAL.BAS
2) Connect the Scanivalve and the U-type manometer with the flexible rubber tubing.
3) For above atmospheric pressure, position the pitot tube in front of the nozzle and connect to the Scanivalve and manometer with a T.
4) With air supplied from the compressor adjust the flow of the nozzle.
5) Record the height of water in the manometer. (The program converts this to pressure and records the pressure and voltage)

6) Repeat steps 3-5 for below atmosphere using the hand vacuum pump connected with a T to the Scanivalve and the manometer

The data recorded should be linear. A range of data above and below the expected pressure values should be taken.

<u>Appendix C</u>

Appendix C contains C_{pt} and $\overline{C}_{pt}$ plots at Re = 4.55 X 10^5. These plots are different, however, because they contain the results of the bars stopped measurements. They were not included in the original plots for reasons of clarity.

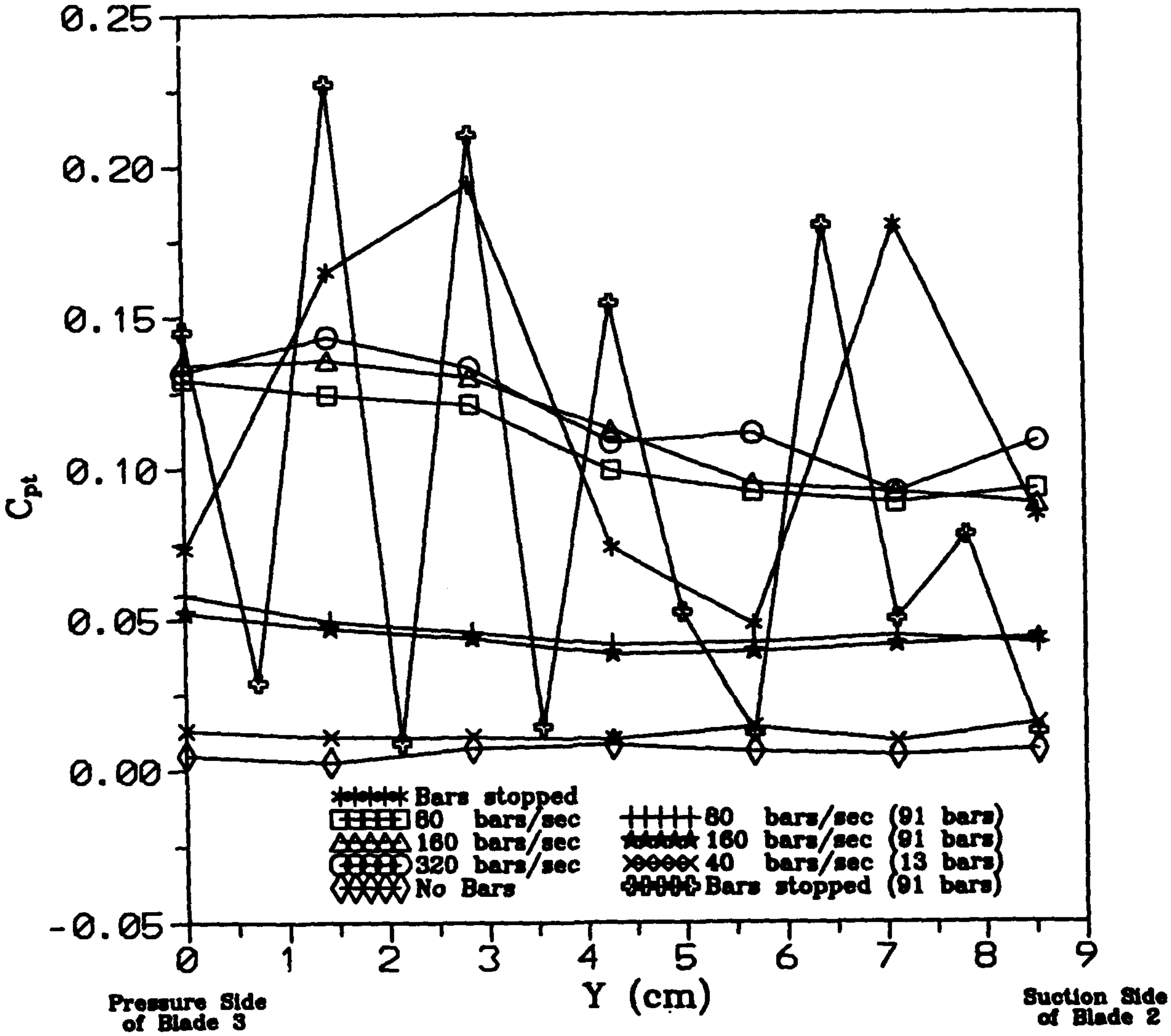


Fig. C.1 Plane 1 Mid-span C_{pt} at Re 4.55 X 10^5

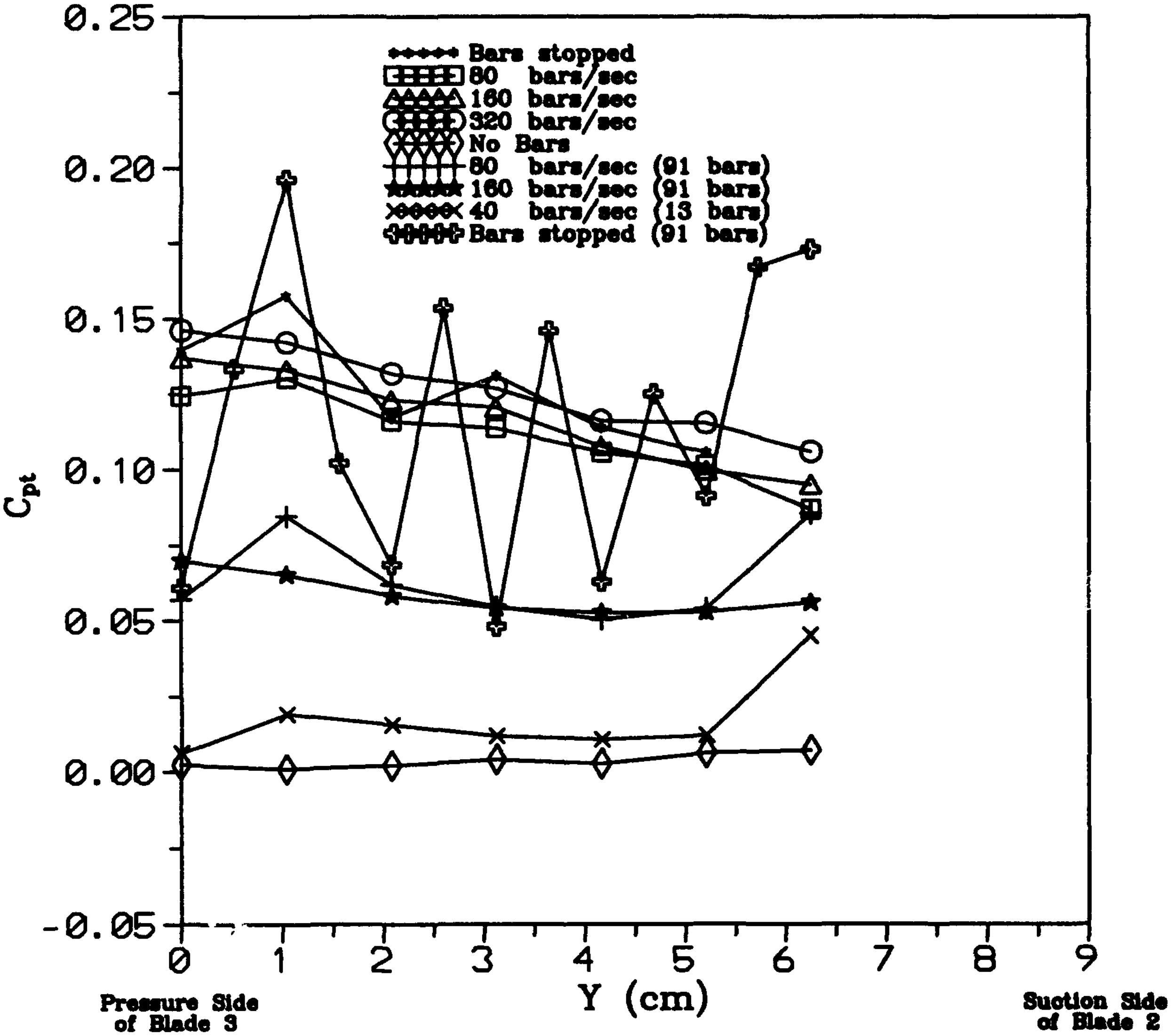


Fig. C.2 Plane 2 Mid-span C_{pt} at Re 4.55 X 10^5

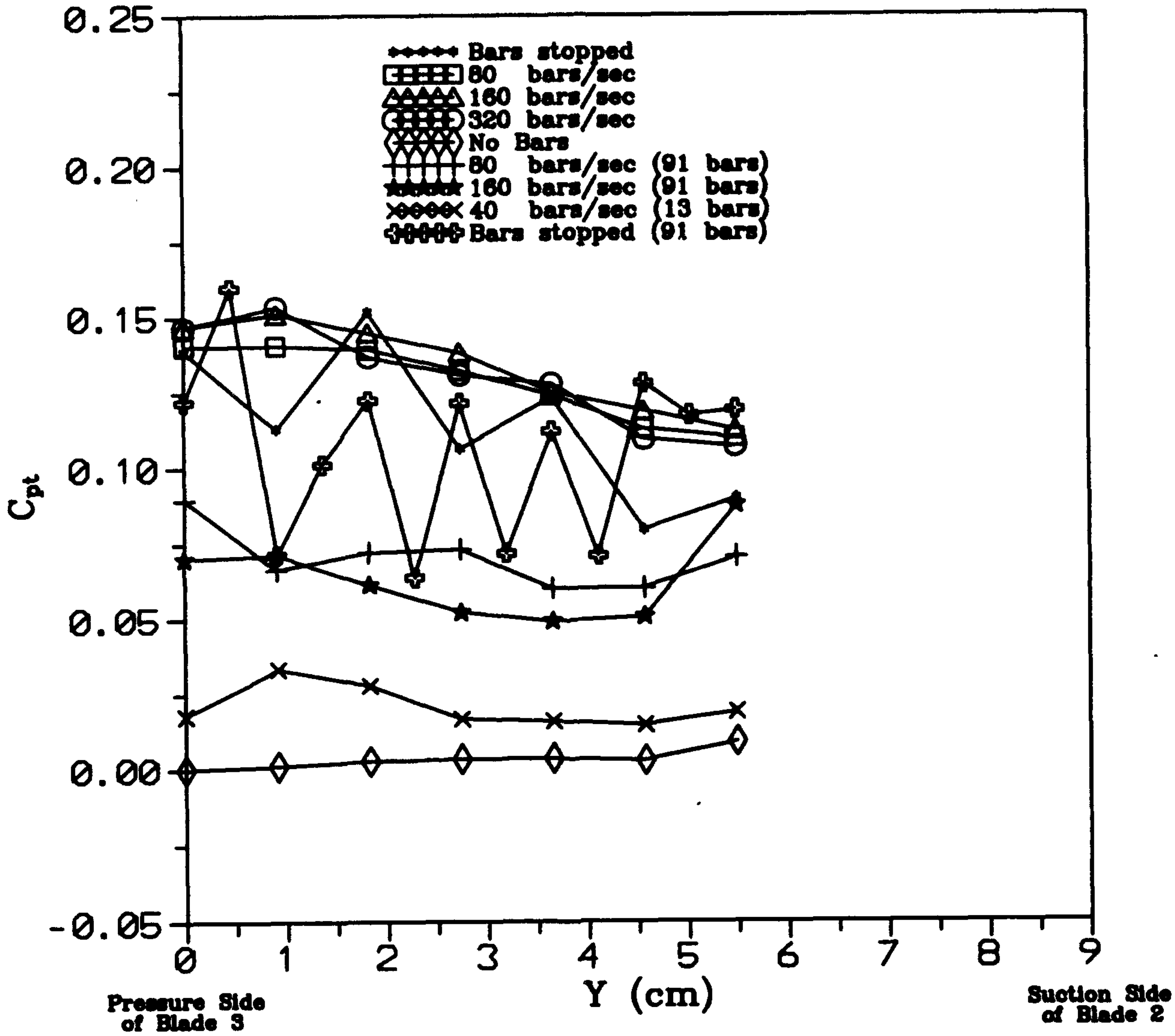


Fig. C.3 Plane 3 Mid-span C_{pt} at Re 4.55 X 10^6

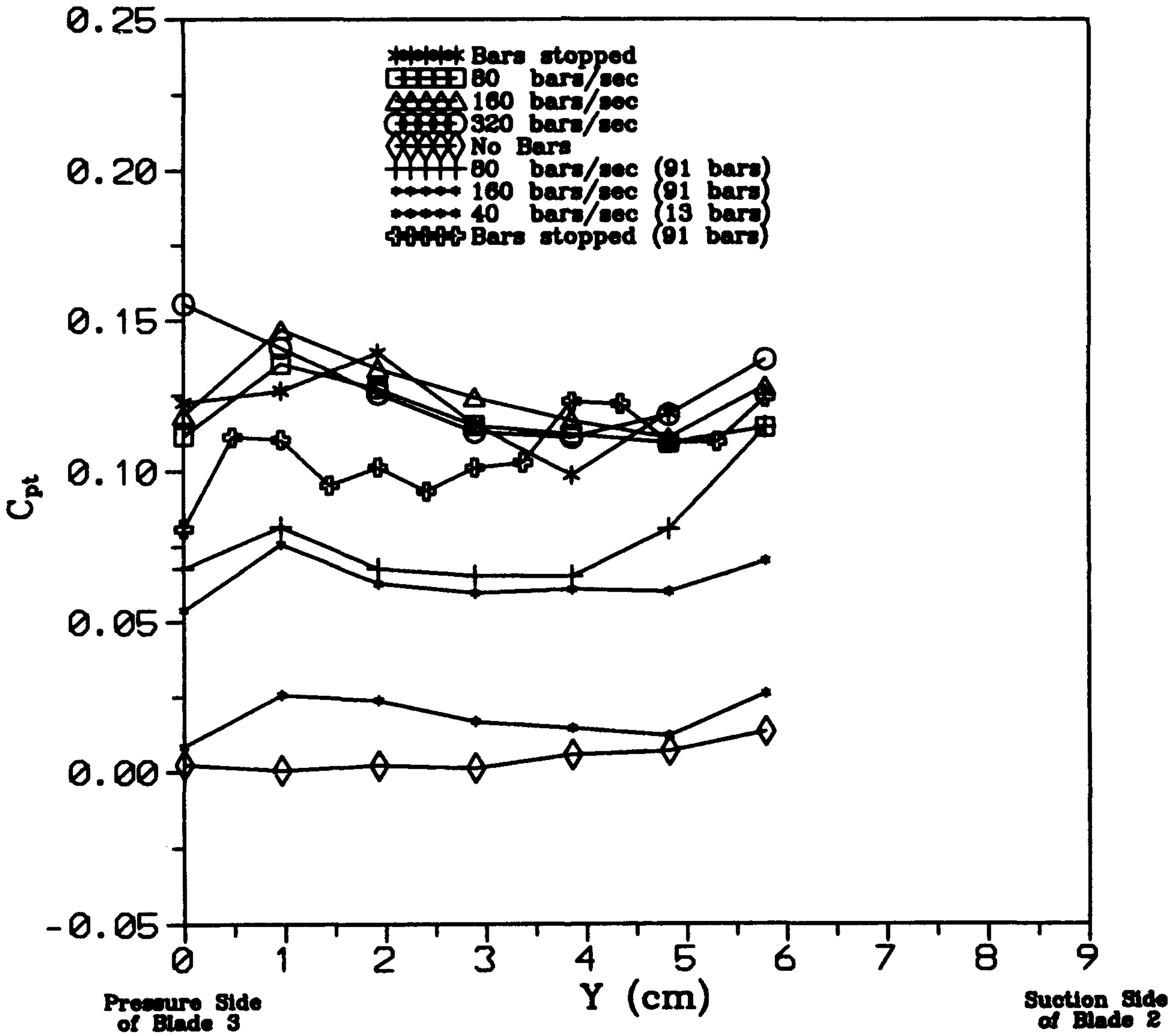


Fig. C.4 Plane 4 Mid-span C_{pt} at Re 4.55 X 10^6

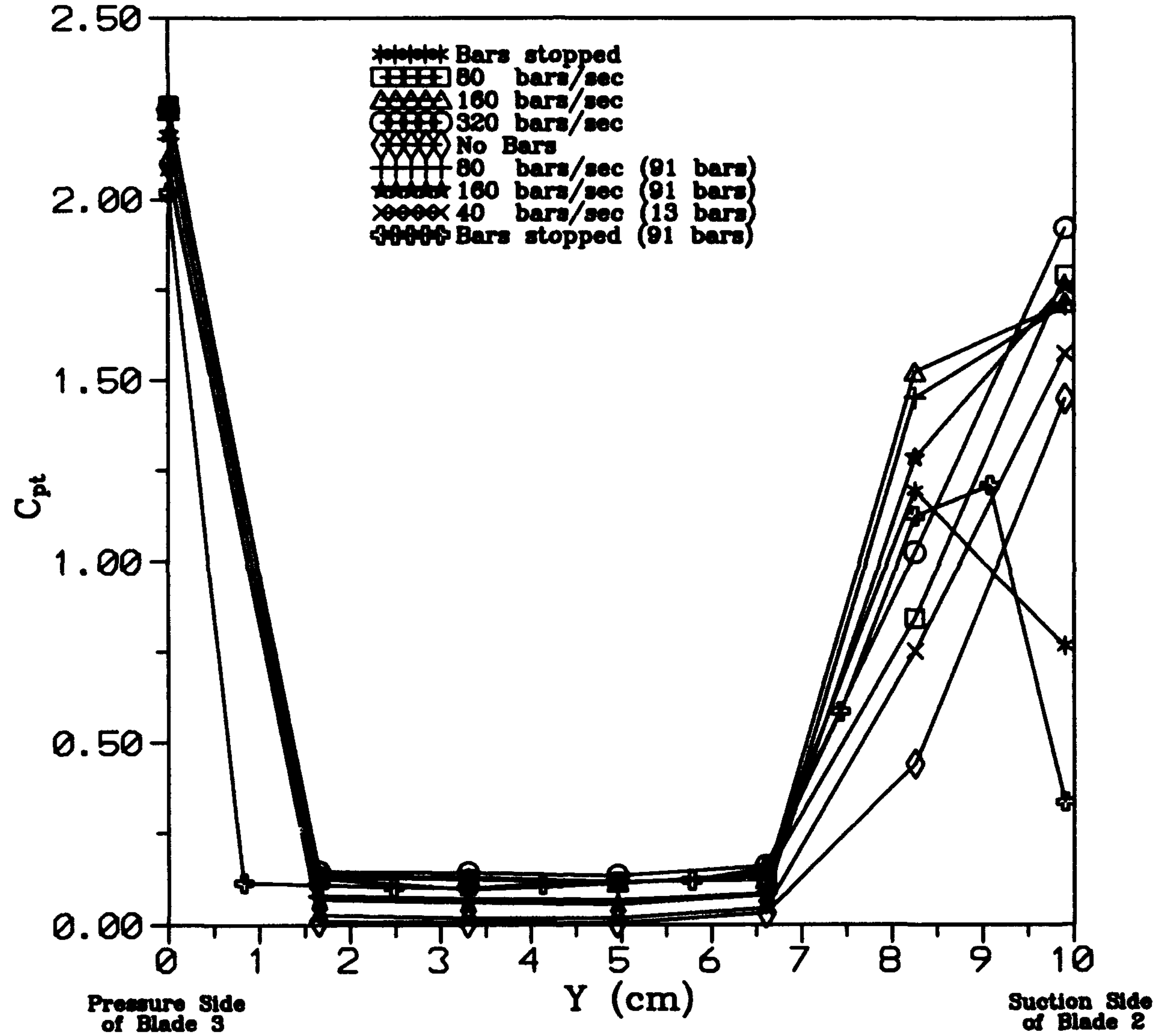


Fig. C.5 Plane 5 Mid-span C_{pt} at Re 4.55 X 10^5

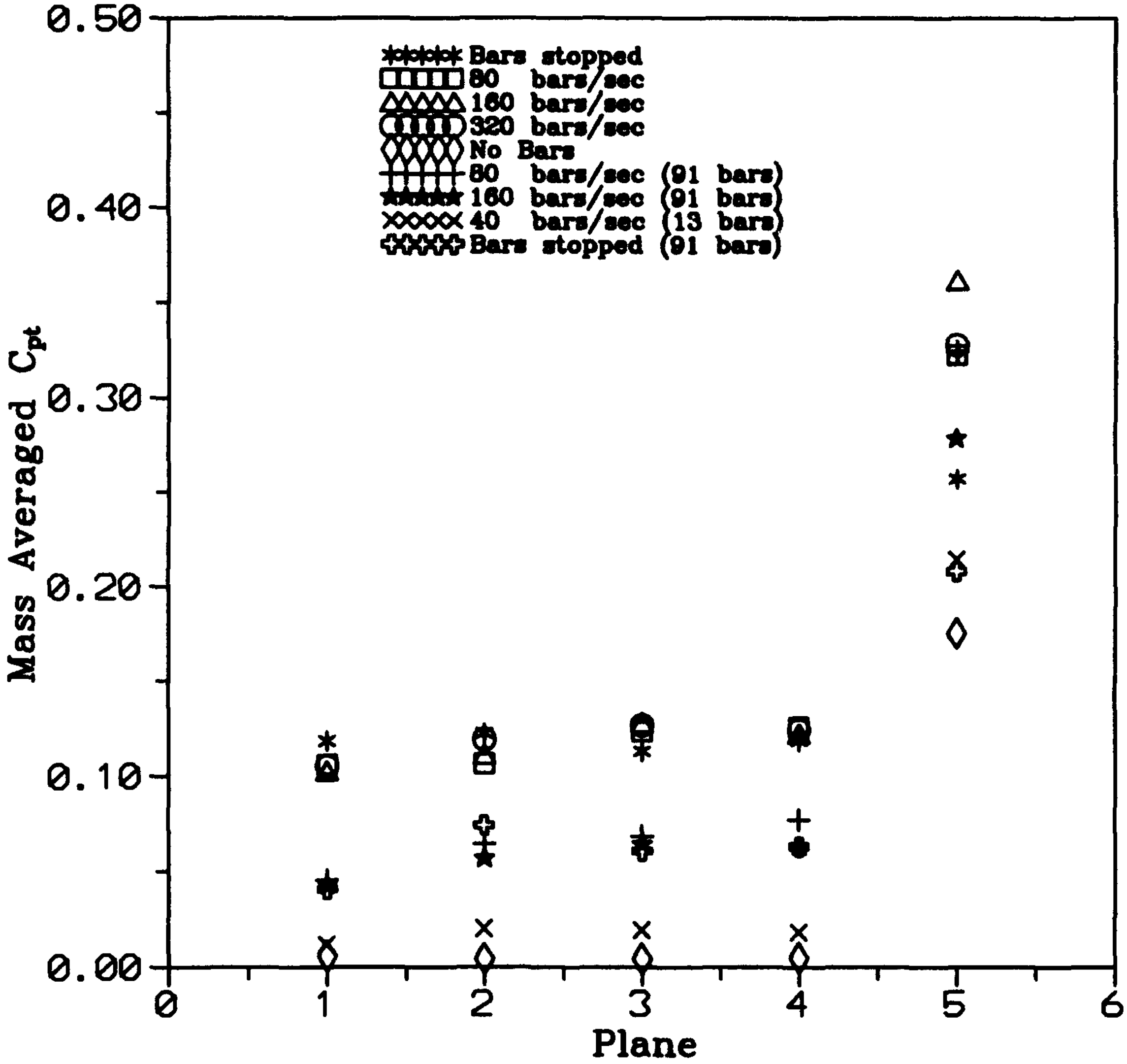


Fig. C.6 Mass Averaged C_{pt} at Re 4.55 X 10^6

References

1. Cohen, H., Rogers, G.F.C., Saravanamutto, H.I.H., *Gas Turbine Theory,* 3rd Edition, Essex, England: Longman Group Limited 1987.

2. Dixon, S.L. "Fluid Mechanics, Thermodynamics of Turbomachinery," 3rd Edition, Permagon Press, 1978.

3. Doorly, D.J. "Study of the Effect of Wake-Passing on Turbine Blades," Oxford University (England), O.U.E.L Report No. 1515/84.

4. Doorly, D.J. Oldfield, M.L.G., "Simulation of the Effects of Shock Wave Passing on a Turbine Rotor Blade," *Journal of Engineering for Gas Turbines and Power*, Vol. 107, October 1985.

5. Dring, M.F. et al., "The Effects of Inlet Turbulence and Rotor/Stator Interactions and Heat Transfer of a Large-Scale Rotating Turbine Model," NASA Contractor Report 4079, May 1986.

6. Emrich, R.J. Editor, *Methods of Experimental Physics* New York: Academic Press Inc, 1981.

7. Gostelow, J.P., *Cascade Aerodynamics,* Permagon Press, 1984.

8. Hill, Phillip G., Peterson, Carl R., *Mechanics and Thermodynamics of Propulsion,* 2nd Edition, Addison-Wesley Publishing Co, 1992.

9. Langston, L.S., Nice,M.l., and Hooper, R.M. "Three Dimensional Flow Within a Turbine Cascade Passage," *Engineering for Power,* Vol. 99, No. 1, January 1977.

10. Meschwitz, Capt S.G. "The Effect of Incidence and Reynolds Number On Heat Transfer in a Linear Turbine Cascade," MS Thesis AFIT/GAE/ENY/91D-6. School of Engineering, Air Force Institute of Technology (AU).

11. Moore, J., Ransmayr, A., "Flow in a Turbine Cascade: Part 1 - Losses and Leading-Edge Effects,"*Journal of Engineering for Gas Turbines and Power,* Vol. 106, April 1984.

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13. ABSTRACT (Maximum 200 words)

A linear turbine cascade was used to investigate the effects of wake passage due to stator-rotor interaction. The wakes were modeled by passing 1.98 mm (0.078 in) diameter bars upstream of a linear cascade blade row. Total pressure loss coefficients, mass averaged total pressure loss coefficients and velocities were used to characterize the effects of wake passage.

Bar passing frequencies of 80, 160, 320 bars/sec were tested. These frequencies were tested with the bars at 6.35 mm (0.25 in) intervals and at two Reynolds numbers, 3.41×10^5 and 4.55×10^5.

Bar spacings of 12.7 mm (0.5 in), and 89 mm (3.5 in) were also examined. For a bar spacing of 12.7 mm these tests were made at a Reynolds number of 4.55×10^5 and bar passing frequencies of 80 bars/sec, 160 bars/sec, and with the bars stopped.

The varying Reynolds numbers did not affect the results nor was there appreciable differences for the range of wake passing frequencies. However, for the same bar passing frequency, losses were effectively halved by doubling the spacing. The lack of influence of frequency and the effect of spacing was consistent with the time scale used. The maximum time scale reached was 0.95 so any influence due to changes in frequency were not felt in the blade passage. Whereas, for the same frequency, with half the bars, there were half the losses in the passage at any given time.

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