Cascade Testing
Paper 4

DATA ACQUISITION AND CONTROL WITHIN THE ZÜRICH ANNULAR CASCADE TEST STAND

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Abstract

The Zürich annular cascade is a new test facility designed specifically for the acquisition of high quality data for the purpose of validating Computational Fluid Dynamics (CFD) codes and investigating basic fluid mechanics, in particular secondary flow phenomena.
The design requirements dictate that the test stand should have a high parametric flexibility, in order to achieve the broad data base required, coupled with a wide range of accurate measuring techniques. Productivity at all phases of operation is a core operational philosophy.
This paper concentrates mainly upon the implementation of the data acquisition system of the test stand. The basic elements are described and the approach to coding these elements is presented. This is achieved through the use of a single central processor operating the "Labview" programming environment. Within Labview, an element of the measurement system, for example a multi-channel pressure scanning unit, is represented by a software driver. The flexibility and productivity of the system comes through the ability of the user to select in test stand operation a combination of these drivers to create coherent measurement modules. This is permitted through the use of programming techniques such as 'Serial Markov Machines'. This results in a robust data acquisition system which is flexible both in terms of applying the chosen measurement technique and in permitting rapid extension of the data acquisition system without extensive reprogramming. The ability to incorporate easily a range of other software based control techniques, such as fuzzy logic control for probe alignment, is an inherent strength of the approach.

Introduction

The Zürich annular cascade is a new state of the art test stand. There are two objectives which have driven the design of the facility. The primary aim is the collection of high quality data of known and repeatable accuracy for the validation of CFD codes. The secondary aim is to improve understanding of the main loss producing flow mechanisms, in particular to propose strategies applicable in design to control and minimise their effect.
The main emphasis in the CFD validation programmes is the comparison of loss, both assessed globally as a mass averaged value, and locally as the comparison of the strength, and more importantly the position, of individual loss structures such as the passage vortex, wakes and boundary layers.
It is important to validate codes at a range of conditions, and when assessing loss reducing strategies it is critical to discern the influence of changing any geometric and fluid boundary conditions .
With this in mind the rig has been designed as a highly flexible, parameter lead test stand, which allows operating points in the parameter map to be altered efficiently. At all points the design has been made with the emphasis on high experimental accuracy.
In order to take full advantage of the experimental opportunities offered by the new facility, a new data acquisition system was planned to complement the test stand.
The objective of this paper is to describe the design criteria and implementation of the data acquisition system. It is not the purpose of this paper to describe in detail the design and function of the new test stand, which is the subject of [1].

Overview of programme objectives

The test stand was designed to fulfil two experimental objectives. With the explosive development of CFD and computer hardware, CFD is increasingly being used as a design tool. The clear advantage of CFD is that it offers the prospect of fast numerical prototyping of designs, without having to undergo expensive (in terms of both cost and time) experimental programmes.
Before using CFD in design, clearly confidence in the numerical results must be generated by comparing the numerical simulations against

experimental results of known and high and repeatable accuracy.
CFD validation programmes, on a national and international basis [2,3,4] have been established in order to pool resources and allow for an objective assessment of individual code quality. Some validation experimental data sets are more or less abstract (for example [4]), concentrating on a particular feature of the flow physics. However in turbomachinery more realistic experimental data is required, representative of true components. For turbomachinery design the ERCOFTAC series [3] represent the most important set of current CFD validation data. These experiments have been carefully selected to represent a broad range of turbomachinery flows, eg cascades, pumps and rotors at a variety of conditions; for example data for part load behaviour in a pump is extremely important for assessment of CFD codes at off design conditions.
The data bases for turbomachinery CFD validation, with relatively few exceptions, have been *post hoc* usage of existing experimental data sets generated for other reasons, for example secondary flow studies. This is without question acceptable practice, provided that all experimental data is well documented, which is the case in the ERCOFTAC series.
An occasionally overlooked, but important aspect of CFD validation, is the ability to compare calculations over a range of conditions. This is particularly important when considering turbulence, where the level of turbulence can materially affect both the fundamental flow behaviour [5], but also the computation where for example the false interpretation of turbulence level can result in incorrect evaluations of losses [6]. This is not the only example; Reynolds number dependencies and sensitivity of (say) losses to inlet boundary conditions are further important cases for study. This leads to the need for a parameter lead test stand. That is a test stand with enough flexibility to enable the systematic investigation of the variation of a range of important parameters.
The second aspect of the project is the need to provide better understanding of the basic fluid phenomena involved in cascade blade flows. The objective is to help formulate design strategies which will result in the control and minimisation of the loss producing secondary flows. This is best performed by investigating flow parametrically, whereby tendencies and interactions are more clearly resolved. Potentially profitable areas for investigation include end wall shaping and also the effects of novel blade forms to minimise loss, see for example [7].
The resultant project therefore called for a highly flexible test stand which has the ability to generate a range of parametrically interesting test cases. Clearly because a validated code is only as good as the validating data base, retaining the highest possible accuracy of the experimental technique became an important adjacent design driver.

Overview of the Zürich annular cascade

The test stand, and the criteria used in the design, is discussed in more detail in reference [1]. In brief, figure [1] shows the overall layout of the test stand, which is constructed vertically over two floors.
The test stand is of closed loop design, with the test section operating at quasi-atmospheric conditions. The air circulates clockwise from the compressor through a cooler. After the cooler the long inlet stretch contains flow calming devices such as sieves and a honeycomb in order to produce a highly homogenous two dimensional inlet flow with low turbulence levels. After flowing through the test section the flow returns to the compressor.
The performance of the test stand is indicated in table [1]. The base line design called for the investigation of prismatic turbine blade profiles with an exit Mach number of 0.5. This provides for shock free, yet compressible test cases for CFD validation.
The main compressor can be either replaced by, or have its volume flow rate boosted by, a supplementary compressor termed "Mustang". This allows higher exit Mach numbers to be achieved, and when operated alone, in a region of the operating map which is not achievable with the main compressor very low exit Mach number (essentially incompressible) test cases can be generated.

Main Compressor			
Drive		730	[kW]
Volume Flow Rate		4.6 ... 11.4	[m^3/s]
Supplementary compressor "Mustang			
Drive		440	[kW]
Volume Flow Rate		...4	[m^3/s]
Cascade			
Tip Diameter		800	[mm]
Blade Height	l	90	[mm]
Blade Number	z	48	[-]
Chord Length	s	60	[mm]
Tip-Hub ratio	Y	1.24	[-]
Chord to Pitch Ratio	hub (s/t)	0.67	[-]
Outlet Mach number	max.	0.7	[-]

Table [1]

Figure [2] shows the detail of the cascade section. The cascade section is horizontally mounted surrounded by a stiff instrumentation table. The main feature driving the design is the method by which the probes are traversed. In order to develop an understanding of the flow features, it is necessary to measure fields of data at a series of axial locations downstream of the cascade blade row exit.

Usually this is achieved by traversing the probe (of any sort, from Pitot through fast response type probes to externally mounted laser velocimetry optics) relative to the blading. This requires some mechanism or strategy whereby the relative positioning can be achieved. This usually entails a series of holes or slots to be cut into the outer wall of the test stand. The result is that with an annular geometry a complex traversing mechanism is required, or at the minimum a need to demount and remount probes from one hole to another, with new alignments to be made each time. Furthermore the large number of holes or slots required to derive a highly resolved flow field can, with poor design, introduce undesired flow disturbances.

In the new test stand the alternative approach has been taken, namely the blades are positioined relative to the probe. This being achieved by using a large stepping motor driving the blades which are mounted on a bearing. The combination allows the blades to be moved to any desired circumferential position.

This permits a stiff and highly accurate probe traversing system to be built. The probes can be introduced to the flow through simple holes, one for each axial measurement plane. With this system the spatial resolution in each measuremenit plane of all flow field features can therefore be extremely high.

A potential disadvantage of this approach is that in order to allow for the movement of the blades, a tip gap must be introduced. This tip gap could introduce unwanted additional secondary flows, such as leakage flows and tip vortices, which would not be accounted for in the interpretation of the flows, nor present in the geometrical or fluid boundary condition specifications for CFD simulations.

In the design and manufacturing phases care was taken through the specification (and monitoring during construction) of tight tolerances to ensure that the resultant tip clearances were minimised. The resultant gaps, of the order of 0.002 mm are sufficiently small for the tips to be considered as aerodynamically closed, that is to say they present no measurable influence upon the basic secondary flow field structures.

A feature of the test stand is that the blades are mounted in cassettes, which are then mounted onto the central blade carrier. The cassettes each have eight blades. The advantage is that with multiple cassettes preparations for the next measurement campaign can be made without disrupting the one in progress. The cassettes are mounted into the test stand through holes cut into the test stand frame which are covered by windows.

The second novel feature of the test stand is the use of the interchangeable windows. These act as covers for the access ports but also double as the framework for the different measurement techniques. Various windows are in operation with the test stand, for example there is a plexiglass window for use with flow visualisation, a window with optical quality glass for use with a LDA system, and a window for use with traversing and pressure measurements. This window is shown, by way of example, in figure [3]. The window is split into four areas. On the left are a series of pre-planned holes designed to cover the region of the intra-blade passage. Next is a region of static pressure taps. Because of the movement of the blade relative to the outer wall, a complete field of static pressure measurements of the tip can be generated by relatively few static pressure taps. Notice that in the region of the blade the pressure taps match the suction and pressure side profile shape. This permits a high resolution in the important corner regions.

To the right of this region are predominantly traversing holes in the outlet region, which are used to capture the details of the secondary flow features as they develop downstream of the trailing edge. The final region is a series of holes prepared to accept flush mounted surface fast static pressure transducers, which are used to resolve any time dependencies in the static pressure.

The test stand is highly flexible in terms of the parameters which it can simulate, and these are described in more detail in [1]. One feature of interest is the so-called 'pin-wheel'. Stator-Rotor interactions are known to have a marked influence upon the performance of the turbine, both through the further processing of the rotor loss distributions through the stator, and the direct influence of wakes, through for example by-pass transition. There are two approaches to the modelling of such effects, both with advantages and disadvantages.

Firstly the full stage can be re-created in the laboratory. This has the advantage of being the most realistic in terms of the actual machine fluid flow, however it is difficult to construct accurately and more importantly it has less parametric flexibility and produce compromises with experimental accuracy.

The second approach is that a partial representation of the most important effects can be made. The disadvantages is that it is not the correct fluid flow, correct in the sense of complete, however generally they are easier to engineer, and offer more flexibility in parametric representation and measurement accuracy.

The latter approach is that taken in the new test stand. It was decided to provide only for the effects of wake interaction, as they represent an important class of phenomena whose understanding, particularly through by-pass transition effects, may lead to improved turbomachinery design. The wakes are constructed using a rotating array of pins, which have been arranged so that at the design point they deliver a wake of similar turbulence strength as the design rotor wakes [8,9].

Data Acquisition system

A new data acquisition system has been developed in order to take full advantage of the design strengths of the new test stand. The design of the data acquisition system centres upon four basic criteria.

The first criterion is high automation. A test stand designed for parametric studies will necessarily have a large data throughput as the various design points are sequentially investigated. A highly automated test stand not only improves productivity but also allows for the handling of data in a consistent manner.

The second criterion is robustness. The test stand must be capable of being run for hours without software induced disruption.

Software induced disruption implies not only accurate coding, but also the ability to detect and handle anomalous situations with the measurement hardware. This improves productivity and reduces user frustration as unknown faults do not have to be traced.

The third criterion is user friendliness. User friendliness is important as it impinges upon test stand operation in three ways. Firstly it aids in the reduction of user frustration, which is important when the aim is to concentrate upon the fluid flow not the data acquisition programme. This implies all requisite information should be readily accessible, and operations are intuitive to the user.

The second aspect is that because the range of measurement options presented by the test stand is large, user friendliness implies the ability to set up quickly and efficiently any measurement technique, without the need to install and operate additional programmes.

Thirdly a user friendly system should have a fast learning curve, resulting in new or guest researchers being able to contribute more quickly and effectively to any given aerodynamic problem under study.

The final design criterion is often overlooked, but nevertheless it is of equal importance to the other three points. The final results file, generated at the end of an experimental session should be oriented to data reduction and display. A highly effective and productive test stand is of little use when the data reduction and presentation takes a disproportionate amount of time. In essence, productivity in taking results shouldn't force the bottleneck in experimental planing into the post processing area. Ideally data reduction should be in real time, or as close to real time as possible. Clearly real time post processing presents problems, especially with large, time dependent, data sets. However well organised data and reduction strategies can reduce post processing times considerably.

In order to implement a system with these goals, a software tool is required. One choice could have been to programme the entire system using a suitable software language such as C, however the interfacing of the hardware can become problematic. In particular to write fully functional device drivers is not a trivial task, especially the communication between the hardware and the computer. Also, with the large code required debugging could be become problematic. To overcome these potential problems the decision was made to programme the system within National Instrument's *Labview* programming environment [9-11]. *Labview*, which is rapidly becoming the *de facto* standard for data acquisition and control, offers several advantages.

Firstly the necessary hardware, in terms of A/D cards, mulitplexers, GPIB communication links have already been developed and integrated into the software environment by National Instruments. Removing the need to write these hardware device drivers substantially eases the difficulty of taking measured signals from the device into the computer for further processing.

Secondly, *Labview's* object oriented approach means individual device drivers can be written and later integrated as required, thus allowing the coding and debugging tasks to be modularised, thus shortening the development time.

Another advantage is that the programme is a graphical based language. The graphical strengths lie not only in the coding, which is straightforward, but also in the development of the user interface. Because these can mimic the operating system's own user interface this provides for familiarity and increases the user friendliness of the resultant systems.

Furthermore *Labview* is a data flow programme environment. A data flow programming environment is one in which a command is only executed when all necessary input conditions are fulfilled. This is in comparison to other programming languages, such as C and FORTRAN which are so called control flow languages, that is the commands execute in order written as the programme control is passed sequentially from one line to the next.

Data flow graphical programming is not ideal for "number crunching" type applications, because in these cases the graphical based programmes are less elegant and clear than their FORTRAN or C equivalents. In data acquisition situations though, data flow programming is ideal, because it allows very effective tracking of the errors that have arisen. For example, if an error has been generated by a hardware failure somewhere in the system, it is possible to handle that error, for example through a software reset or user alert, before passing the system to another piece of hardware.

Having decided upon the environment the hardware chain for the measurements could be constructed. Figure [4] shows the resultant system. On the right are the various system devices, on the left is the host processor and in between are the necessary hardware connections.

The measurement equipment fall into three categories, the first test stand control, covers such elements as temperature and pressure monitoring in the cascade inlet and exit channels. These permit the cascade operating condition, (primarily exit Mach number) to be determined.

The second set cover the "control" elements of the test stand. In particular the control of the probe traversing and blade positioning equipment, and the pinwheel.

Finally comes the cascade measuring equipment itself, covering such elements as multiple channel pressure scanning, constant temperature anemometry and laser Doppler anemometry measurement systems.

All of these elements are connected to the host processor, a Macintosh Quadra 840AV. This was chosen because of compatibility to other test stands within the institute. The indicated external links are to post processors, where dedicated software handle the task of presenting the acquired data in an intuitive way. Two examples are the AWS system, based on a Microvax and DEC alpha machine, which is a package which allows the handling and display of time dependent measurement results [13], and a Silicon Graphic Workstation, which has a fully functional three dimensional graphics system written and tailored for data derived from the test stand.

Figure [4], whilst displaying the "land map" of the data acquisition chain, does not indicate the true complexity of the system. As indicated, one of the design criteria was to produce at the of a day's run a data file which could be used more or less instantaneously to interpret results. This means in practice that measurements from various hardware elements have to be sensibly integrated. Figures [5] and [6] show the complexity of this. Figure [5] shows the steps required to establish and measure the cascade inlet conditions. It is seen that in order to establish the cascade flow, the system must monitor reference pressure and temperature and pin wheel rotation speed. It should be noted that it would be possible to fully automate the cascade setting, using a simple feedback loop, but because the compressor is very stable, and also because of safety considerations, this has not been implemented.

Figure [6] shows the true complexity of the measurements. The established cascade flow, (which, recall, means three measurements) must be integrated with the measuring technique and any requisite control parameters, such as the radial traverse positions and the relative blade position. In figure [6] the interdependencies between these elements are shown.

For example measuring the blade static pressure using the "Scanivalve" multiple channel pressure scanning system requires the measured established cascade conditions (four measurements) the Scanivalve system and the blade positioning unit, for a total of five measurements which must be integrated.

As can be seen not all measuring systems have the same level of interdependency, but what clearly follows from figure [6] is that the most important factors in the integration of the test stand is the probe traversing and blade positioning systems, because they interact with practically every other piece of equipment in the facility.

Thus the most important element within the software programming task is the effective integration of the traversing system to the various elements. This has been achieved by using an adapted form of software construction known as the "state" or more properly "Markov" machine. A Markov machine is essentially a construct whereby a set of connected commands can be constructed together sequentially, the consequent command (hence action) of the machine being dependent upon the current state of the machine. A Markov machine, at whose heart is the idea command execution on the basis of the current state of the machine is conceptually allied to the idea of data flow programming. This is because the current machine state is dependent upon the state of all the inputs to the machine, which is the basic philosophy behind data flow programming environments. *Labview*, being a data flow environment is ideally suited for the development of such state machines.

A relatively complex device driver can be developed using such constructions, and in fact within the *Labview* environment it is the preferred method to write a device driver. The novel adaptation for the new data acquisition system is to use the concept of a Markov machine globally to produce a very user friendly "Plug and Play" type data acquisition system.

Figure [7] shows the basic concept of the state or Markov machine. This example is based upon a simple device driver, which has four states typical of any measurement device, 'initialise', 'wait', 'measure' and 'error'. As an example, following an initialisation the device will stay in the 'wait' state until the command to jump to the 'measure' state is given. At any point, say through a hardware malfunction, the device can jump into an 'error' state waiting for either a user reset or more ideally a software driven reset if possible. Despite this trivial example, (which can be programmed by a range of software constructs), when extended to a large number of possible states, for example a large number of measurement options with a complex device the state machine becomes a powerful construction allowing very complex instrumentation measurement sequences to be developed.

The extension to the integration to the whole traversing system is to replace the individual elements of the device driver with a device driver itself. The conceptual form of this change is shown in figure [8]. The elegance of the system is thus revealed. Once the traversing system and the selected measuring technique has been selected the Markov machine automatically makes all the necessary integration, in an analogous style to the single device driver. This brings several advantages. Firstly with an extension of the measurement chain, the only additional programming needed is the addition of a driver, and hence new element into the Markov list. Hence the basic programme can be extended to all conceivable measurement possibilities, provided of course that there is a software driver available for incorporation into the machine and secondly other considerations, such as data rate, do not preclude from the outset integration into a Macintosh based environment.

This results in a system which closely resembles a "plug and play" type philosophy. The user interaction is relatively trivial, for example figure [9] shows the selection process which integrates the data acquisition elements. The figure shows a user interface in which the options are presented. On the left is the choice of traversing mechanism, which at the current time is restricted to one of a two or four axis traversing system. On the right is the choice of measurement system. All systems integration follow automatically from this choice.

Within figure [8] there is an element which is termed "intelligence" this is a loosely defined term implying any method whereby the measurement campaign is modified upon the analysis, automatic or otherwise, of measured points. Typically for example this could mean halving a traverse step when some prescribed condition, for example velocity, pressure or flow angle change is outside some prescribed limits. An application which has been programmed and has proven to be very effective is a fuzzy logic controller [14] which is used to align multihole probes with the flow direction.

In operation the entire system is comfortable and easy to use. Further system refinements, for example the use of pre-prepared data files indicating the position of static pressure taps and their dependence upon probe and blade traversing enhance user friendliness and provide for a consistent and speedy handling of the measured data.

The implementation is very stable, with to date only a few extreme cases of hardware problems causing disruption to data acquisition. A minor drawback is that the fully implemented system is relatively large, with 500 sub-programmes and requires 18 Mb of ram to function effectively.

Conclusions

The development of a new state of the art test stand has provided the motivation for the development of a new highly automated and integrated data acquisition system. Using the state machine construct and a graphical programming language allows a highly functional user friendly system to be developed which approximates to a "Plug and Play" philosophy. This results in a system which can be manipulated interactively in a simple manner to perform relatively complex tasks.

Acknowledgement

The authors wish to acknowledge the financial support of Asea Brown Boveri (ABB), The Swiss National energy research foundation (NEFF) and the Swiss Federal Institute Of Technology , Zürich (ETH).

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Figures

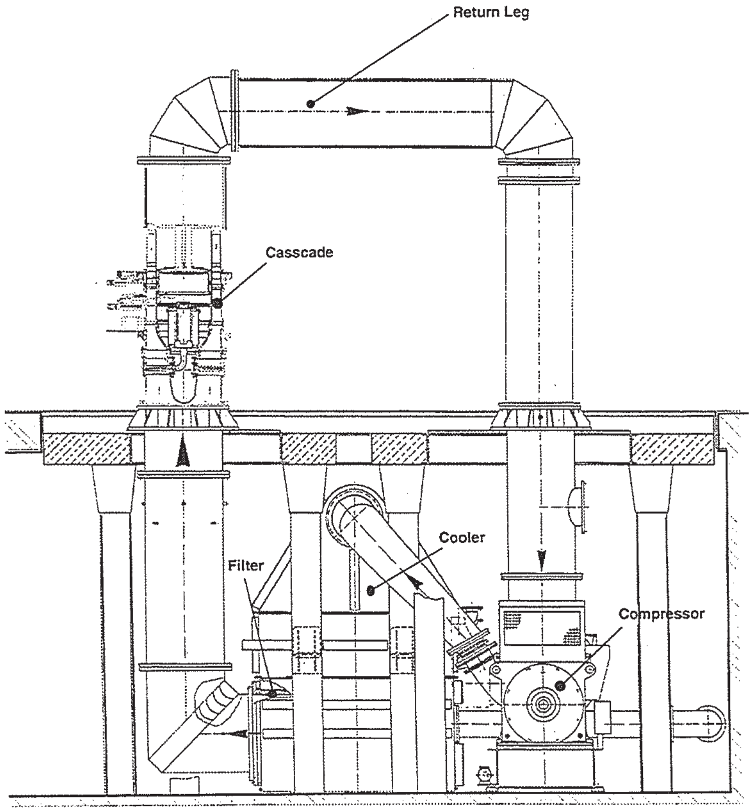


Figure [1] Test Stand Loop

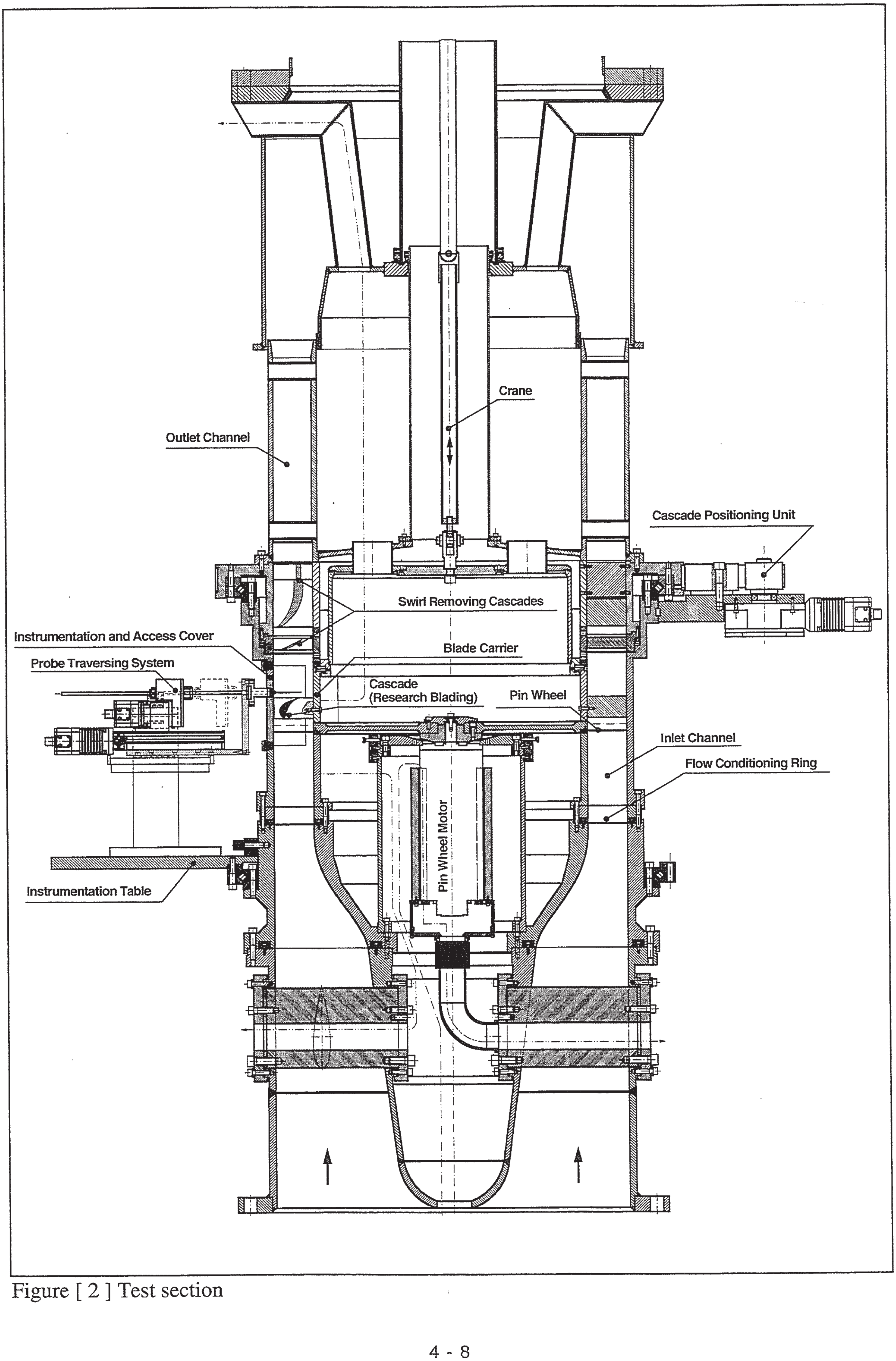


Figure [2] Test section

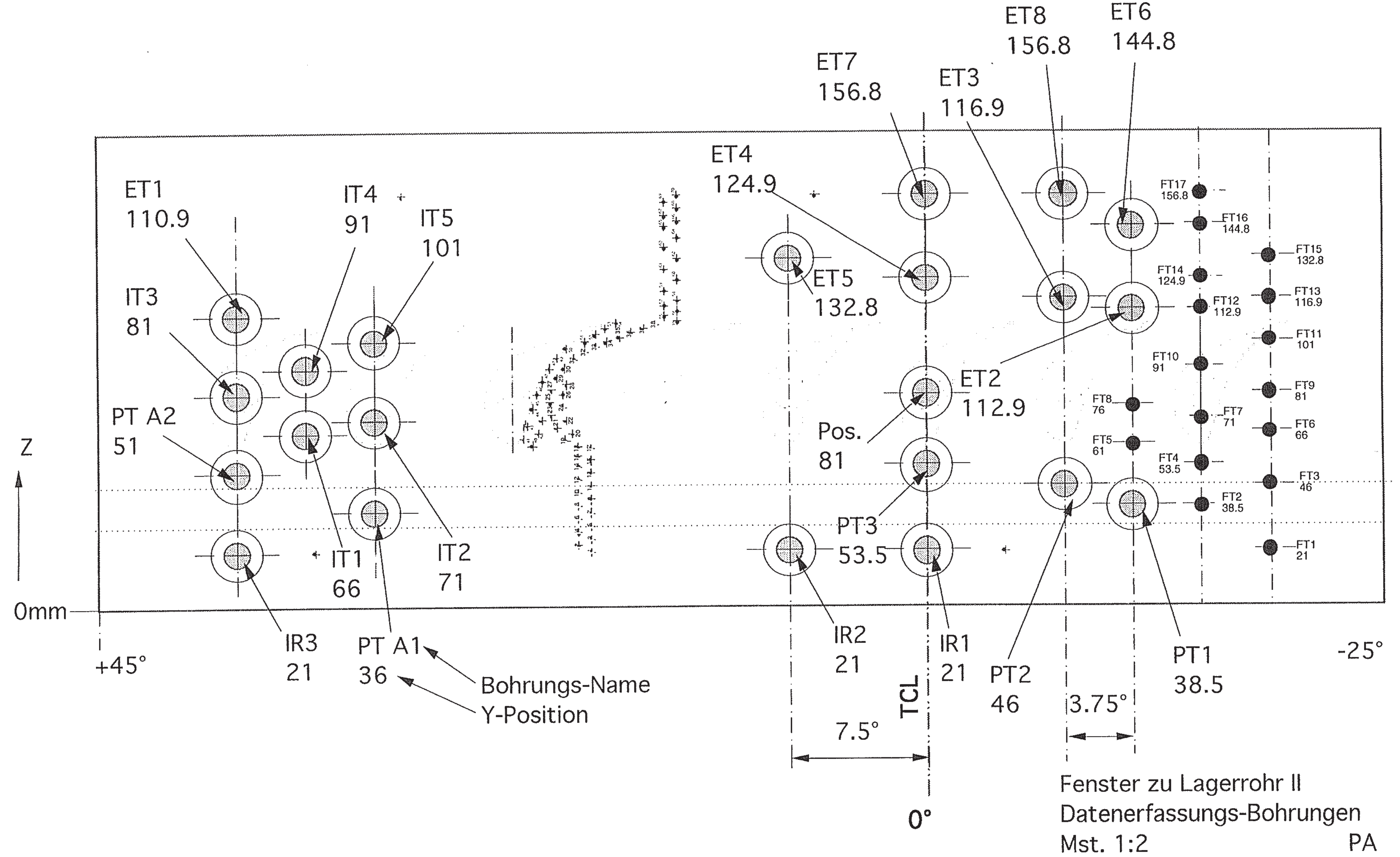


Figure [3] Pressure Measurement Window

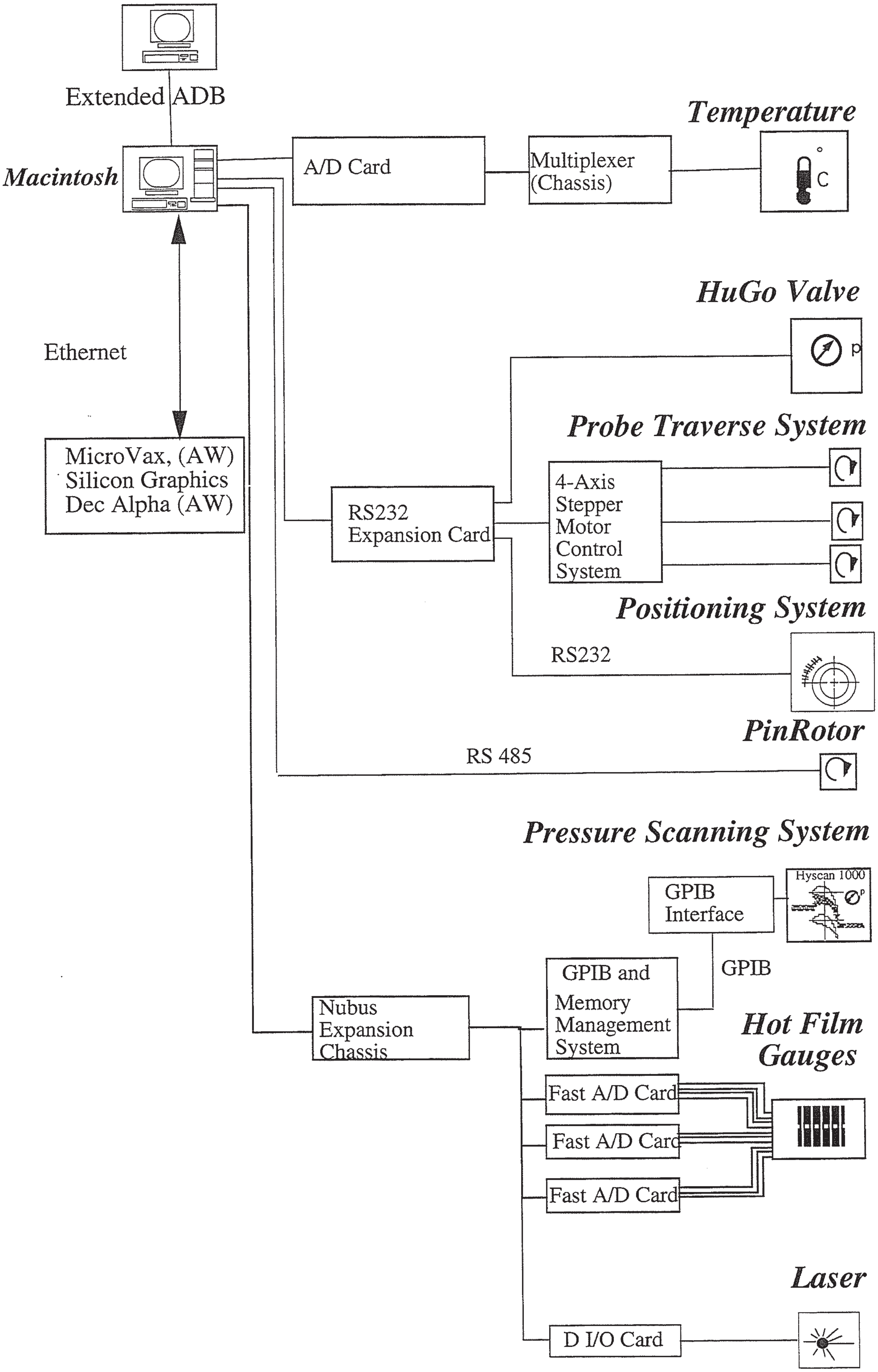


Figure [4] Data Acquisition And Control Hardware Layout

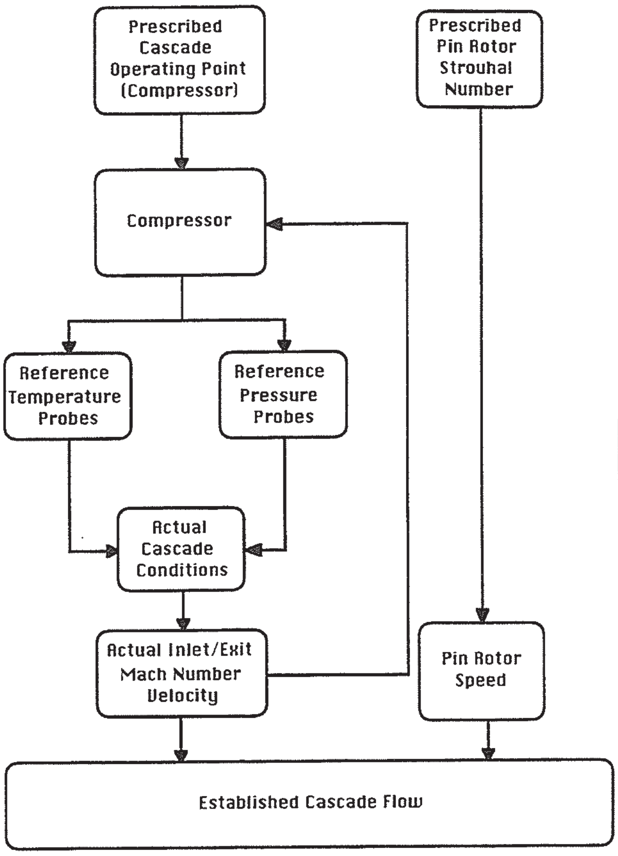
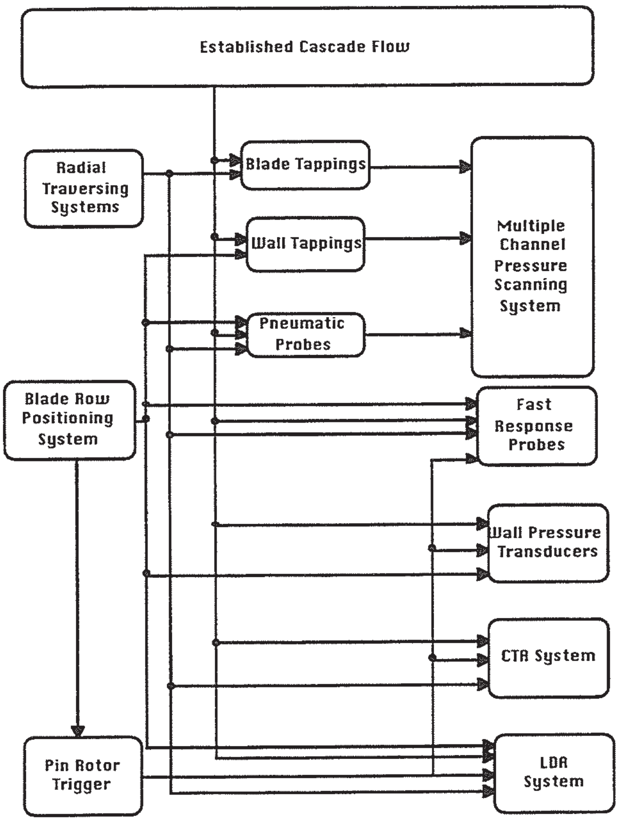


Figure [5] Flow Chart For Establishing The Cascade Operating Condition



Figure[6] Flow Chart For Integrating The Data Acquisition And Control Elements

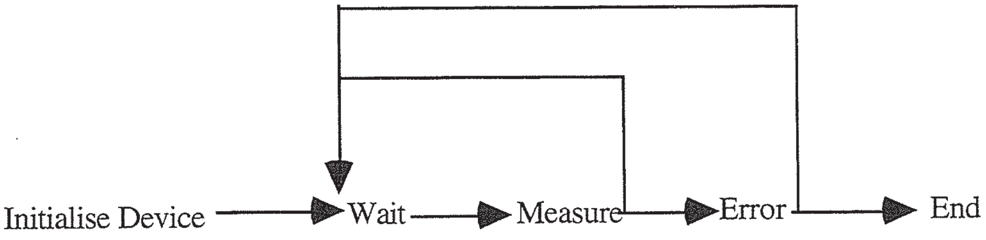


Figure [7] Simple State or 'Markov' Machine As Applied To A Device Driver

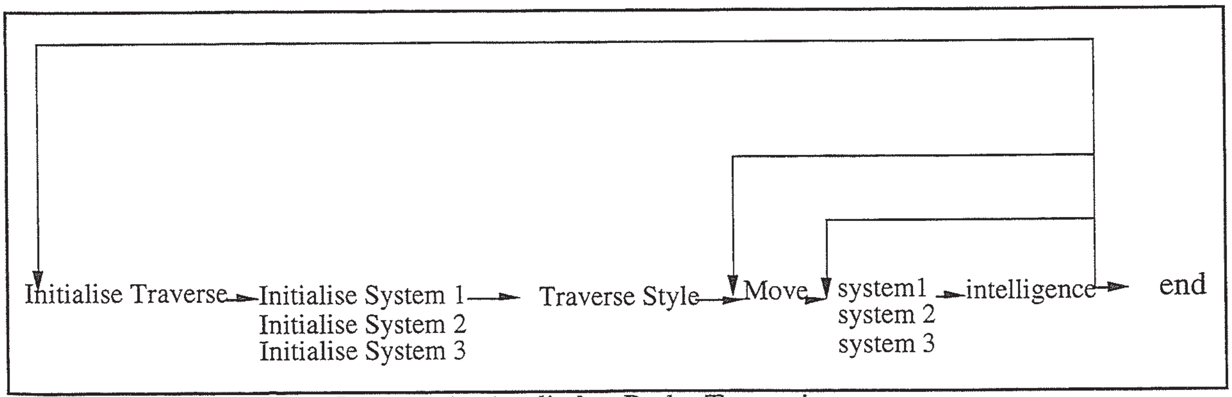
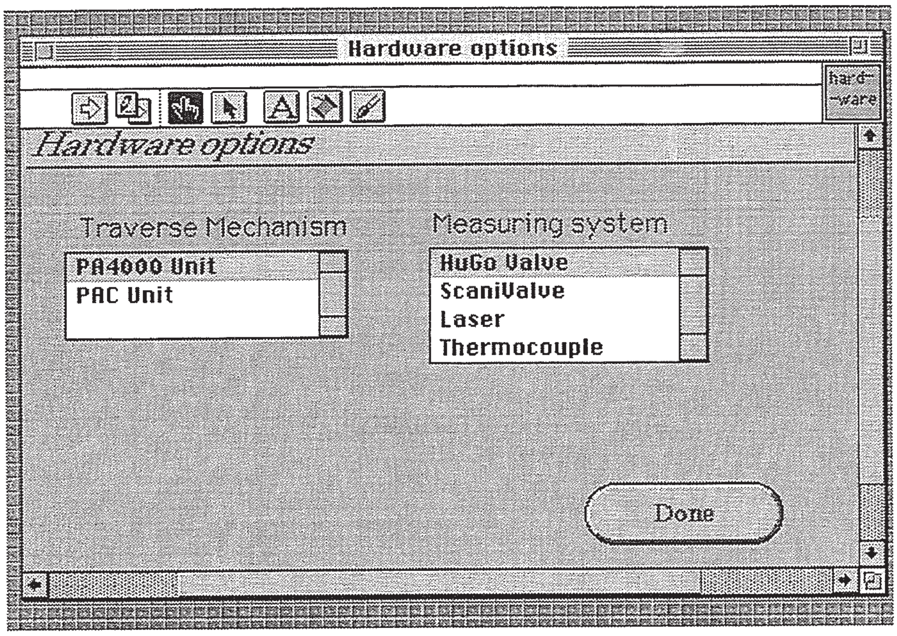


Figure [8] State machine Concept As Applied to Probe Traversing.



Traverse Mechanism

- PA4000 Unit
- PAC Unit

Measuring system

- HuGo Valve
- ScaniValve
- Laser
- Thermocouple

Figure [9] User Interface