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14. ABSTRACT

Wind tunnel studies on the laminar-to-turbulent transition mechanism known as transient growth require instrumentation suitable for the production of high but controllable levels of freestream turbulence, model surfaces relevant to transition problems of engineering interest, and hotwire instrumentation suitable for measuring disturbances that lead to transition. Ongoing and planned experiments on transient growth at the Case Western Reserve University Wind Tunnel Laboratory required instrumentation in each of these categories to enable investigations in high-disturbance environments such as those found on the blades of low-pressure turbines. The DURIP grant for which this is the final technical report provided for instrumentation purchases in each of the key areas. Specifically, the grant provided for a significant improvement in the Laboratory's hotwire anemometry capability through the addition of four additional hotwire channels and numerous hotwire probes, the fabrication of a variable-angle cascade test section and PakB blade row, and the fabrication of an active turbulence generator.

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Final Report of AFOSR DURIP Grant F49620-02-1-0287

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Abstract

Wind tunnel studies on the laminar-to-turbulent transition mechanism known as transient growth require instrumentation suitable for the production of high but controllable levels of freestream turbulence, model surfaces relevant to transition problems of engineering interest, and hotwire instrumentation suitable for measuring disturbances that lead to transition. Ongoing and planned experiments on transient growth at the Case Western Reserve University Wind Tunnel Laboratory required instrumentation in each of these categories to enable investigations in high-disturbance environments such as those found on the blades of low-pressure turbines. The DURIP grant for which this is the final technical report provided for instrumentation purchases in each of the key areas. Specifically, the grant provided for a significant improvement in the Laboratory's hotwire anemometry capability through the addition of four additional hotwire channels and numerous hotwire probes, the fabrication of a variable-angle cascade test section and PakB blade row, and the fabrication of an active turbulence generator.

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1 Introduction

1.1 Project Background and General Objectives

Fluid boundary layers that form near the leading-edges of aerodynamic surfaces (e.g., wings, turbomachinery blades, and helicopter rotor blades) are laminar, have low surface shear stress, and undergo limited mixing with the freestream. Moving downstream from the leading edge, boundary layers thicken, their Reynolds numbers increase and, eventually, instabilities cause them to undergo laminar-to-turbulent transition. Transition results in greatly increased surface shear stress and enhanced mixing with the freestream. In terms of practical applications, if an objective is to improve the range of an aircraft, it is advantageous to maintain laminar wing boundary layers as this minimizes the vehicle's viscous drag. However, increased range is also aided by promoting turbulence in the low pressure turbine (LPT) of the same vehicle's engines where turbulence can reduce separation losses at high-altitude, low-Reynolds-number cruise conditions. Maintaining laminar flow wings at high Reynolds number and promoting turbulence in LPTs at low Reynolds number requires a very detailed understanding of how to exploit or suppress the boundary layer instabilities that promote transition.

In order to develop a detailed, mechanisms-based understanding of boundary-layer transition it is necessary to perform basic experiments on the various transition mechanisms that can affect real engineering systems in simplified environments. Once an understanding of how these mechanisms behave in isolation is achieved, the complexity of experimental investigations can be increased to represent more of the features of the engineering systems of interest. In this way it is possible to understand what features of the full system are important to the transition process, how transition might be controlled, and how to safely extrapolate from laboratory results to full-scale systems.

Transition studies at the Case Western Reserve University (Case) Wind Tunnel Laboratory are intended to provide experimental data on fundamental transition processes, especially those related to the newly discovered mechanism of transient growth. The most basic of these experiments on the behavior of stationary transient disturbances generated by surface roughness elements in zero-pressure-gradient boundary layers (White and Reshotko 2002; White 2002; White and Ergin 2003) can and have been conducted with flat-plate and hotwire instrumentation system similar to a number of classical flat-plate transition studies. However, ongoing and proposed studies are intended to extend this work into the behavior of transient disturbances in curved-surface boundary layers with pressure gradients and high levels of freestream turbulence. These factors are of significant interest because freestream turbulence is an important source of transient disturbances and because pressure gradient and curvature are suspected to affect transient growth rates but neither have been investigated experimentally. Additionally, these conditions represent conditions that are more representative of those found inside gas-turbine engines than have been considered in previous transient growth experiments.

It is the overall objective of this project to provide a variety of instrumentation improvements to the Case Wind Tunnel Laboratory that will permit experimental studies of a broader range of factors affecting transient growth. The focus will be on providing the capability to study those factors that are most relevant to transition in high-disturbance environments representative of conditions found in low-pressure turbines. In particular, the needed improvements are

- the ability to produce and measure unsteady, freestream-turbulence-induced transient disturbances; and
- the ability to generate non-zero-pressure gradient boundary layers on curved surfaces.

1.2 Prior Laboratory Capabilities

During 2000–2001, the Case Wind Tunnel underwent a significant reconstruction effort designed to bring it's flow quality and operabilty to modern standards. The reconstruction also remade the tunnel as highly modular facility that could accommodate a variety of future improvements and extensions of its functionality. However, as of the beginning of 2002, only a very limited number of modular features existed. At that time, the tunnel consisted of a good-quality sequence of flow-quality treatments, a flat-plate test section with a high-precision three-axis hotwire traverse, and a drive section. Instrumentation included two channels of hotwire anemometers, high quality pressure absolute and differential pressure transducers for Pitot-tube velocity measurements, and a feedback-controlled DC drive motor.

1.3 Proposed Improvements to Existing Laboratory Capabilities

The original DURIP proposal that resulted in this project included instrumentation improvements in four areas that were to provide capabilities in support of the two general objectives given above. These improvements provide a comprehensive capability to make detailed measurements in environments with high-amplitude but controlled disturbances. These areas are given below.

Enhanced Hotwire Instrumentation Three additional hotwire anemometer channels were to be purchased to enable simultaneous multiple-point measurements of unsteady velocities. Multiple-component hotwire probes, probe supports and cabling were to be purchased to enable multi-component velocity measurements. A hotwire calibrator was to be purchased to enable calibration for vary laboratory temperatures and flow angles.

Cascade Test Section and Hotwire Traverse A new cascade test section was to be fabricated so that boundary layers over curved surfaces with favorable pressure gradients could be studied. A row of multiple 2-D blades of the Pratt and Whitney PakB design was to be fabricated for use in the cascade. A hotwire traverse suitable for positioning hotwire probes in the blade row boundary layers was to be purchased.

Turbulence Generating Grids A number of modular turbulence generating grids that could be positioned in the wind tunnel's settling chamber were to be fabricated. These grids were to provide various levels of freestream turbulence intensity, Tu, with a maximum of $Tu = 0.15\%$.

Flat Plate Models Several additional flat plate models were to be fabricated to support ongoing studies on simple flat-plate boundary-layer flows.

Dantec Item No.	Quantity	Description
55P12	4	Single-Element Boundary-Layer Probe
55P15	1	Single-Element Slant-Wire Probe
55P61	1	Dual-Element X-Array Probe
55P64	2	Dual-Element X-Array Probe
55H20	3	Single-Element-Probe Support
55H24	3	Dual-Element-Probe Support
55H238	3	Dual-Element-Probe Mounting Tube

Table 1: Dantec hotwire probe and supporting hardware purchases.

2 Hotwire Instrumentation

The hotwire instrumentation proposed for purchase as part of this project consisted of three additional anemometer channels, a hotwire calibrator, and additional hotwire probes and supports. The anemometer channels were to be supplied by A.A. Lab Systems for that vendor's AN-1003 anemometer system. Each channel was to have special low-noise amplification, enhanced signal conditioning capability, and an automatic DC-offset function. The actual purchase consisted of four channels with the specified capabilities. All of the channels have been extensively tested and are in good working order.

The hotwire probes, probe supports, and cabling proposed for this project were all purchased from Dantec Dynamics and all are in regular use in the wind tunnel. The specific items are given in Table 1. The hotwire calibrator was also to be supplied by Dantec Dynamics. The unit was to provide the capabilities to calibrate for changes in velocity, temperature, and flow angle. Prior to beginning this project, only calibration for velocity was possible. The calibrator was required because large temperature variations (5° C) occurred in the laboratory and because flow-angle calibration is required for planned multi-component velocity measurements. After the DURIP grant was awarded, the lab's HVAC system underwent a significant upgrade and after this work was completed, the lab's temperature variations were reduced to less than 1° C per day, below the level of variation that requires hotwire calibration for freestream temperature variations. Therefore, the need for temperature calibration was eliminated and the decision was made to fabricate a hotwire sting in house that would provide better calibration for flow angle than the commercial model would provide. The cost savings of this decision permitted the purchase of the fourth anemometer channel and additional signal conditioning and data acquisition electronics to be described below. The flow-angle-calibration hotwire sting has been fabricated, tested, and is currently in use in the wind tunnel. A photograph of the flow-angle-calibration sting is included as Fig. 1. (All figures appear in the appendix.)

Once it became apparent that the commercially available hotwire calibrator would be unnecessary, it became possible to purchase additional signal conditioning and data acquisition electronics that have enhanced the lab's capability for simultaneously acquiring and processing multiple hotwire data channels. These electronics consist of an eight-channel simultaneous-sample-and-hold amplifier manufactured by National Instruments (NI SCXI-1140) for use in their SCXI signal conditioning framework, the system already in use in the laboratory. The other electronics and cabling purchased in support of the simultaneous-sample-and-hold amplifier consisted of the NI SCXI-1305 BNC terminal block, the

NI SCXI-1120B 32-channel analog-input amplifier multiplexer, the NI BNC-2095 BNC terminal block, and the NI SH96-96 shielded cable.

3 Cascade Test Section

The most significant proposed enhancement to the Case Wind Tunnel Laboratory's capabilities to occur as part of this project was the fabrication of a cascade test section and PakB blade row. The completion of these elements now permits the tunnel to be used for a wide variety of studies on boundary layers that include both surface curvature and pressure gradient. Both the test section and blade row were custom fabricated in-house by the Case Lab Services Shop.

A photograph of the completed cascade test section is given in Fig. 2. The section is designed to match the dimensions of the wind tunnel; it has a 710 mm × 710 mm cross section with its centerline located 1.525 m above the lab's floor. The precise vertical position of the cascade section's centerline is adjustable over a range of ±25 mm. The section is hinged so that a range of turning angle is possible. The hinge is fabricated with preset locater pins that give turning angles of 85°, 95° (the PakB design angle), and 105°. Floor, ceiling, and inner side wall inserts corresponding to each angle setting seals the section for any of these angles. The walls of the section are transparent to provide full visual access to the test section. The downstream half of the cascade is fitted with locater pins that support a tail board that provides the area reduction that accompanies the flow acceleration through a turbine blade row. The supporting rails for the PakB blade row bolts through the floor and ceiling panels to the structural steel of the test section. Precise locater pins fix the location and angle of the support rails relative to the section's hinge.

The PakB blade models that are to be used in the cascade section were fabricated in house by the Case Lab Services Shop. Six blades were fabricated from a high-rigidity but easily machinable prototyping material that can be sanded to provide an excellent surface finish. The blades have a chord length of 127 mm and will permit studies at blade-chord-based Reynolds numbers between 32 000 and 160 000. Significant efforts were made to produce these blades in house so that additional blades that include special features (e.g., pressure taps, patterned surfaces, etc.) will be possible to fabricate quickly at very low cost. A photograph of one blade is given in Fig. 3.

The final element of the new cascade test section is the hotwire traverse system. A commercial traverse with microstepping lead screw motors and 3-μm resolution on each axis was purchased from the Velmex Inc. The traverse has been tested and works well with the lab's existing control instrumentation.

4 Turbulence Generator

A critical element of transition studies on both transient growth and transition in turbomachinery boundary layers is the level of freestream turbulence. To enable experiments with high but controllable levels of freestream turbulence it was originally proposed that several turbulence-generating grids be fabricated that would be positioned in the wind tunnel's settling chamber. Each grid was to provide a specific turbulence intensity, *Tu*, ranging from 0.5% to 15%.

During the course of this project the decision was made to construct a single active turbulence generator rather than a number of passive grids. This decision was made based on three considerations. First, tests with a prototype passive grid made it apparent that *Tu* levels above approximately 4% could not be achieved in the wind tunnel without an unacceptably large degradation of the mean velocity field. Second, regardless of *Tu*, placing the turbulence grid upstream of the tunnel's contraction proved to produce highly non-isotropic turbulence. The remedy for this, changing the grids' location to between the contraction and test section, would not be possible for the larger turbulence intensities because these require large grid elements and spacings and, consequentially, a very large decay length before the turbulence would achieve reasonable levels of isotropy and mean-flow uniformity. Third, as experiments on roughness-induced transient growth by White and coworkers progressed it became apparent that receptivity, the mechanism by which disturbances enter the boundary layer and provide the initial conditions for disturbance growth, plays an enormously important role in determining the nature and evolution of transient disturbances and, in fact, whether transient growth even occurs. Considerations of how future experiments on turbulence-induced transient growth might be conducted suggested that the ability to rapidly vary the freestream turbulence intensity could provide a an invaluable mechanism for rigorously investigating receptivity to freestream turbulence.

An active turbulence generator of the type originally designed by Makita (1991) was selected for fabrication because it was seen as a design that could address all of the concerns outlined above. The active generator consists of a rectangular grid of rotating bars each of which has a number of square paddles. Each bar is driven by its own motor and rotates independently. The motion of the paddles produces homogeneous, nearly isotropic freestream turbulence with intensities that can exceed 10%.

The details of the active turbulence generator's design were selected based on a review of the literature on similar systems, in particular, the papers by Makita (1991), Mydlarski and Warhaft (1996, 1998), Kang et al. (2002), and Larssen and Devenport (2002). The final design consists of an arrangement of 13 vertical and 13 horizontal rods, each with 14 38-mm-square flappers. The flappers are arranged with their long (corner-to-corner) axes oriented along the rods' axes. The rods are located on a 57-mm centers. An array of static flappers is arranged around the perimeter of the turbulence generator. A scaled drawing of these elements is given in Fig. 4 and a photograph of the turbulence generator installed upstream of the tunnel's flat plate test section is given in Fig. 5.

When the turbulence generator is installed upstream of the cascade section, the PakB blade row is located approximately 30 mesh spacings downstream of the turbulence generator. This distances is found to optimal in the sense that turbulence produced by the grid reaches an acceptable level of isotropy by this point but the turbulence intensity is still high. In an effort to promote a more rapid relaxation to isotropy, the turbulence generator is built with an interior cross section of 810 mm × 810 mm, 30% larger than the test section's area. A 585-mm-long linear diffuser joins the turbulence generator to the wind tunnel's contraction cone and a 455-mm-long linear contraction joins the turbulence generator to the test section. A contraction of this type was found by Comte-Bellot and Corrsin (1966) to improve the isotropy of grid-generated turbulence and is used here for that purpose.

Based on the reports of investigators who have built similar systems, a maximum operating speed of 1800 rpm was selected for the rotating rods. During operation, each rod rotates with a randomly selected speed and direction. This randomness yields large scale turbulent structures larger than the grid spacing. This is another feature that makes an active grid preferable to a passive grid. The 1800 rpm rotational speeds and the desire to quickly change operating conditions establishes a torque requirement for the rods' drive motors. Each motor must be capable of providing an angular acceleration of at least 3800 rad/s^2, which permits a reversal from the maximum operating speed in one direction to the other in 0.1 s. The motor selected that met this and other requirements most favorably is the Vexta AXH450KC-A, a 50 W DC motor with a maximum rated speed of 2500 rpm and a maximum rated torque of 0.2 N·m. The motor is powered by a 24-VDC power supply. The full set of 26 motors is powered by a single 1300-W Lambda JSF1500-24 power supply.

The Vexta motors are controlled by three digital TTL lines, start/stop, run/brake, and clockwise/counterclockwise; and a 0–5 V analog speed control line. Control signals are generated by a 2.4-GHz Pentium-4 computer assembled in house for this project. Users control the system via a National Instruments LabVIEW software interface. The computer includes two PCI-based I/O cards, a National Instruments PCI-DIO-96 digital I/O board that supplies 96 TTL outputs and National Instruments PCI-6704 analog output board that supplies 16 voltage outputs and 16 current outputs. The 16 voltage outputs are connected directly to 16 motors while the 10 current outputs are connected across resistors to ground with the voltage drop across the resistors used as voltage input signals for the remaining 10 motors. In addition to the PCI-based I/O boards additional pieces of National Instruments hardware associated with the turbulence generator include a SCB-100 and a SCB-68 shielded I/O terminal blocks and SH100-100-Flex and SH68-68 shielded data cables.

The turbulence generator's performance has been tested over a range of operating conditions. Data for a small subset of these conditions is presented here: two turbulence generator settings and three wind tunnel fan speeds. The first turbulence generator setting consists of a uniform distribution of rotational speeds between 400 and 600 rpm and equal distribution of clockwise and counterclockwise rotations. Rotational changes occur at random intervals for each rod and the distribution of these intervals is uniform between 0.8 and 1.2 s. The second turbulence generator setting is the same except that uniformly distributed rod speeds vary between 500 and 700 rpm. The wind tunnel drive fan is is operated at 200, 300, and 400 rpm for each of the two turbulence generator settings. The mean velocity, U_∞, the turbulence intensity, Tu, and the isotropy, γ, that are obtained 1.0 m downstream of the grid for these settings are given in Table 2. For the purposes of this report, the isotropy is reported in terms of the ratio $\gamma = u'_{\rm rms}/v'_{\rm rms}$ where u' is the longitudinal velocity fluctuation and v' is the transverse fluctuation. Using this approach, $\gamma = 1$ indicates isotropic turbulence and higher values indicate the degree to which longitudinal fluctuations exceed transverse fluctuations. The two transverse velocity fluctuations $v'_{\rm rms}$ and $w'_{\rm rms}$ are assumed to be equal. The turbulence intensity is defined as

$$Tu = \sqrt{\frac{1}{3}\frac{{u'_{\rm rms}}^2 + {v'_{\rm rms}}^2 + {w'_{\rm rms}}^2}{U_\infty^2}} = \frac{u'_{\rm rms}}{U_\infty}\sqrt{\frac{1+2/\gamma^2}{3}}.$$

The results shown in Table 2 show that, in general, the turbulence intensity increases with the mean speed and decreases with the turbulence generator rods' rotational speed. The isotropy improves with decreasing mean speed and with increasing rotational speed of the rods.

5 Flat-Plate Models

The final element of the original proposal was the purchase several additional flat plate models for zero-pressure-gradient boundary layer studies. This element of the project was not completed because of two separate considerations. First, as flat-plate transient growth experiments progressed it became apparent that the existing flat plate model is and will be sufficient for the entire range of transient

Wind Tunnel Drive Fan Speed	Flow Parmeter	Slow Grid	Fast Grid
200 rpm	U_∞	2.8 m/s	2.9 m/s
	Tu	6.8%	6.5%
	γ	1.06	1.02
300 rpm	U_∞	4.2 m/s	4.3 m/s
	Tu	8.0%	7.6%
	γ	1.16	1.04
400 rpm	U_∞	5.6 m/s	5.9 m/s
	Tu	9.4%	8.4%
	γ	1.20	1.16

Table 2: Mean flow and turbulence parameters resulting from two turbulence grid operational settings and three wind tunnel fan speeds. The data are obtained using slant-wire anemometers located 1 m downstream of the grid. The "slow" grid operates with rod rotation speeds between 400 and 600 rpm, the "fast" grid operates between 500 and 700 rpm.

growth experiments that are envisioned for the Case Wind Tunnel. Second, producing additional flat plate models with significantly enhanced features relative to the existing plate proved to be more expensive than originally estimated and, therefore, the decision was made to focus design efforts and the available budget on the active turbulence generator as this element was seen as providing a much more important capability than additional flat plates.

6 Summary

In summary, three of the four major elements of the original DURIP proposal have been purchased or fabricated. These three elements are additional and enhanced hotwire anemometry equipment, supplies, and data acquisition electronics; a cascade test section and PakB blade row with a computer-controlled micro-stepping hotwire traverse; and a computer-controlled active grid turbulence generator. These three elements are those from the original proposal that bear most directly on problems of anticipated interest in Case Wind Tunnel: unsteady transient disturbances, high levels of freestream turbulence, curved-surface boundary layers, and non-zero pressure gradients. Both the hotwire and turbulence grid purchases were modified from the original proposal in response to changes in the lab environment (in the case of the hotwires) and results of experiments with a prototype unit (in the case of the turbulence generator). In both cases the instrumentation and operational capability that resulted is superior to that originally proposed.

The one element of the original proposal that was not completed, the purchase of additional flat plate models, was abandoned both to provide additional financial resources to the construction of the active turbulence grid and because experience gained with the wind tunnel's existing flat plate model made the purchase of additional plates unnecessary.

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Appendix

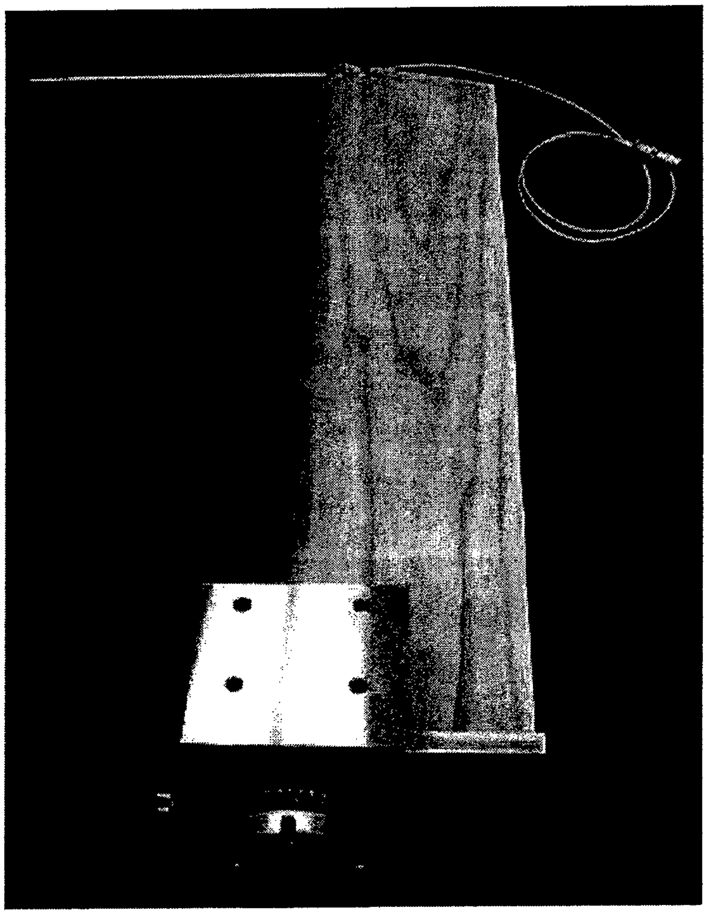

Figure 1: Flow-angle-calibration hotwire sting.

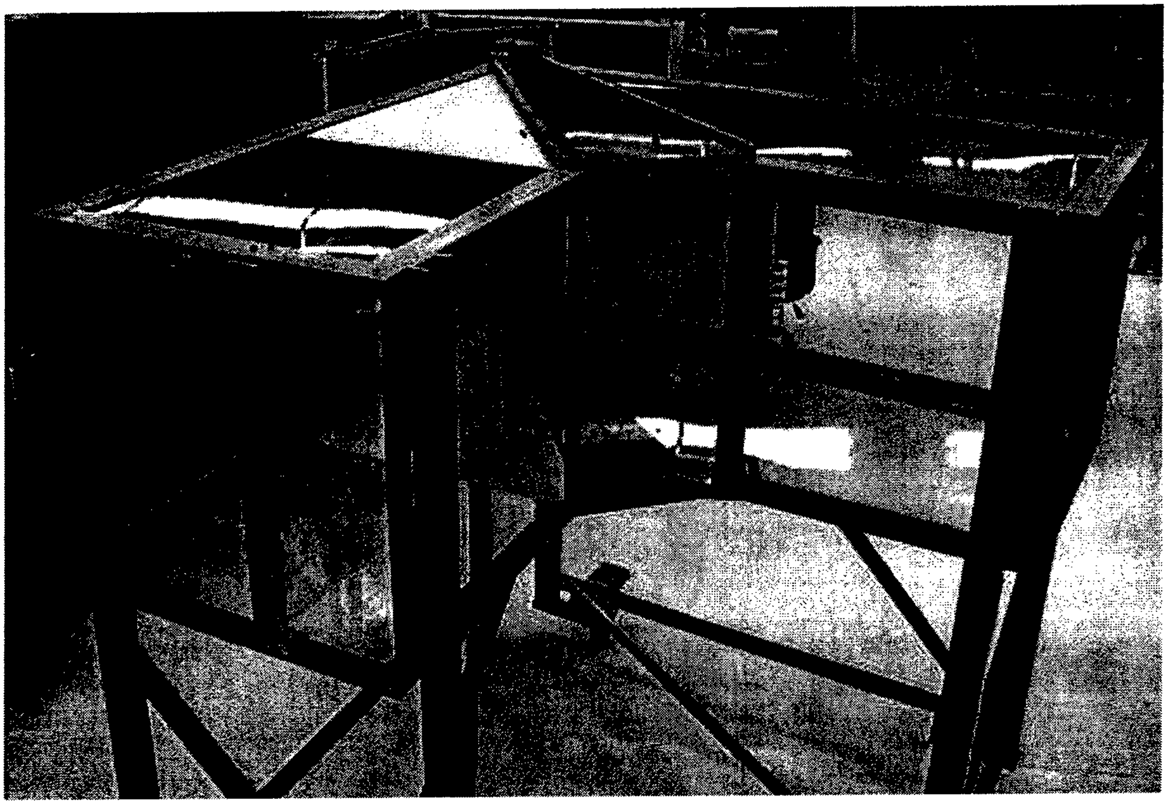

Figure 2: Cascade test section.

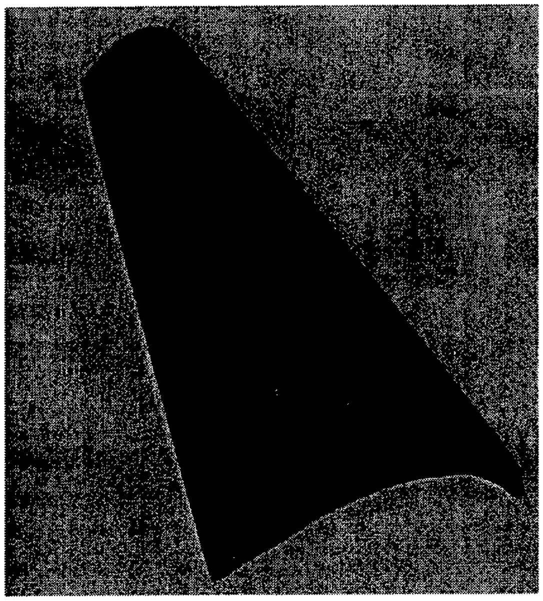

Figure 3: PakB blade model.

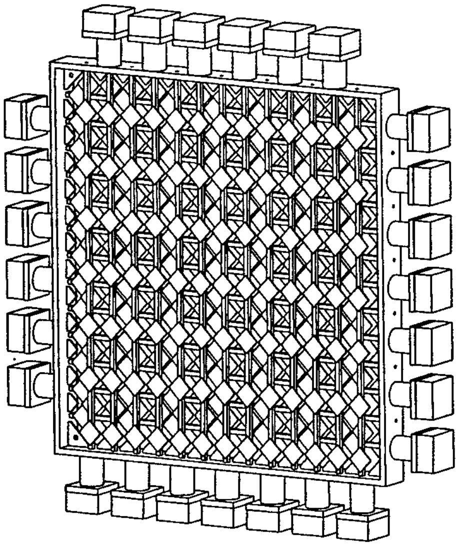

Figure 4: The active turbulence generator's rod and flapper arrangement (left) and a single vertical rod with flappers (right).

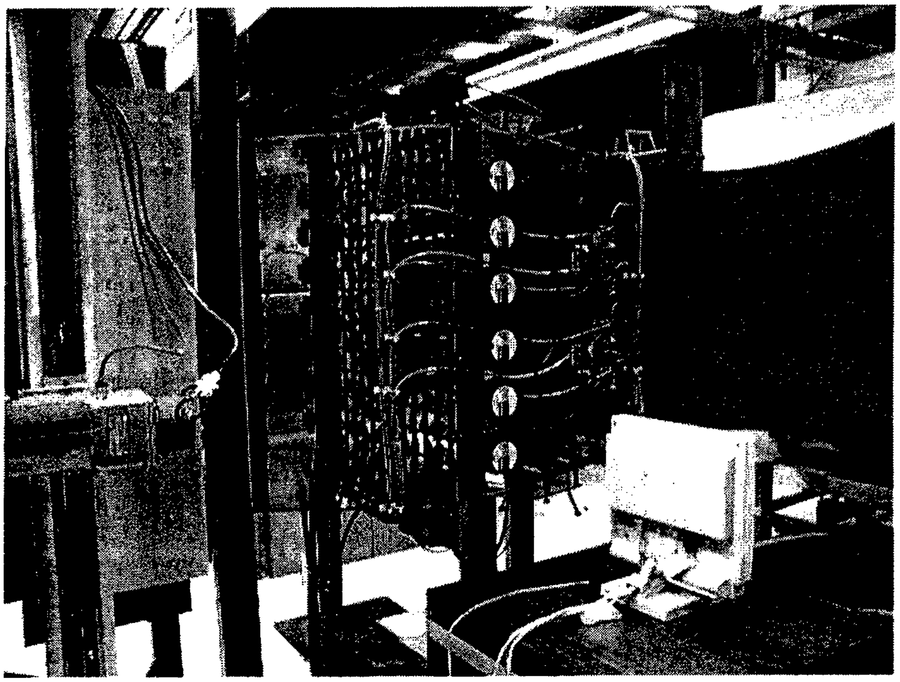

Figure 5: The active turbulence generator installed upstream of the flat-plate test section.