A Review on Advanced Methods for Cascade Testing

(AGARDograph Nr. 328)

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ABSTRACT

The Propulsion and Energetics Panel of AGARD decided to collect available experience and information on advanced testing methods for compressor and turbine cascades in a single document. This initiative resulted in an AGARDograph (Nº 328), co-authored by some of the best experts in the field, covering linear, annular, cold and hot cascades, as well as steady and transient operations. Various specific measuring techniques are presented, including 3D laser anemometry for annular cascades.

INTRODUCTION

Cascade testing has been, and still is, an essential component for the understanding of the basic flow mechanisms of axial turbomachinery blade rows.

Notwithstanding the considerable development of numerical prediction techniques, the experimental investigation of cascade flows, under well controlled initial and boundary conditions, still remains an essential element in the understanding of the complex flow interactions inside blade rows. Many experimental facilities and measuring techniques have been developed over the years with the objective of a more realistic and accurate determination of flow quantities.

This AGARDograph was set up by the Propulsion and Energetics Panel of AGARD in order to collect the large amount of know-how and expertise accumulated over the years at various institutions, on various aspects of modern cascade testing.

It is subdivided in seven chapters, starting with an introductory chapter on the basic concepts and requirements for representative modeling of realistic turbomachinery flow conditions. The second chapter, devoted to linear cascades, deals separately with subsonic, transonic and supersonic conditions. Annular cascades are considered in the third chapter, followed by a description of particular aspects of hot and transient cascades. Unsteady flows in cascades are treated in the sixth chapter, while the seventh chapter deals with the specific aspects of 3D laser anemometry in annular cascades.

CHAPTER 1: MODELING TURBOMACHINERY FLOW CONDITIONS

This introductory chapter, co-authored by L.Fottner and C. Sieverding, presents a concise description of the real flow conditions in turbomachinery environments and discusses the problems associated with their cascade representation. The main topics covered are the representativity and limitations of 2D linear cascades as well as of annular stationary or rotating cascades.

Although largely used since many years, due to their simplicity, linear cascade experiments for blade section data suffer from the three-dimensionality of the real flow conditions (convergence/divergence of stream tubes, endwall effects) and the difficulty to set up rigorous periodicity conditions. These difficulties can be largely circumvented through the use of numerical simulations to improve the reliability of the data and their interpretation, accepting to consider the blade section data in a quasi-three-dimensional environment.

Full three-dimensional cascade data are being produced increasingly for the investigation of secondary flows and end-wall effects, including effects such as wall contouring, blade stacking, tip clearance with or without the simulation of relative motion. Although these data are extremely useful for code validations, they cannot be used directly to calculate the flow in the turbomachine, since the radial pressure gradient has a significant influence on the spanwise distribution of losses and exit flow angles.

Annular stationary cascades allow the representation of radial pressure gradient effects, resulting from the swirling flow, as well as a more accurate simulation of periodicity. They come therefore closer to the turbomachinery environment. This is however at the expense of more difficult experimental conditions and higher experimental set-up costs. A major advantage of annular cascades occurs for the investigation unsteady effects, such as wake-blade interference and simulation of flutter conditions.

Rotating annular cascades come still closer to the real turbomachinery environment and allow the study of the effects of centrifugal and Coriolis forces on the flow, as well as tip clearance phenomena and flutter for realistic rotor flow conditions.

Simulating the cascade flow parameters for representative turbomachinery flow conditions requires separate control of inlet Mach number, Reynolds number and turbulence intensity. The latter two quantities are particularly important for the valid investigation on cascades of laminar-turbulent transition and separation.

This first introductory chapter contains also a short presentation of the different types of cascade tunnels available at various Research and industrial Laboratories.

CHAPTER 2: LINEAR CASCADES

This chapter contains five sections covering a short introduction into basic boundary conditions of cascade wind tunnels, subsonic compressor and turbine operations, subsonic choked turbine cascades, transonic and supersonic cascades and testing techniques for compressor transonic and supersonic linear cascades.

The first section, by H. Starken, summarizes the various operating conditions of subsonic, transonic and supersonic conditions of cascades, including the conditions of choked flows, unique incidence or unique deviation. An important observation is connected to the difficulty of the accurate determination of inlet flow angle at transonic and supersonic conditions. A combination of experimental measurements and computational simulations is recommended.

Subsonic compressor and turbine cascades

The second section, by L. Fottner, discusses the experimental arrangements for subsonic compressor and turbine cascades. In particular a detailed discussion is given of different methods for control and verification of periodicity and two-dimensionality, in particular through side wall contouring and/or boundary layer control (by suction or blowing). It is observed that it is increasingly difficult to adjust the cascade periodic flow conditions with increasing Mach number.

As an example of an efficient cascade facility with variable Mach number and Reynolds number options, L.Fottner describes the cascade wind tunnel of the Jet Propulsion Institute of the University of the Federal Armed Forces-in-Munich. It is a closed loop facility driven by a six stage axial compressor. Mach number is controlled by the rotational speed of the compressor, while Reynolds number can be selected independently by controlling the pressure level of a pressure tank containing the wind-tunnel test section. Control of adequate cascade conditions are provided through a centrifugal compressor for end-wall/side-wall suction, while an additional screw compressor delivers an air blowing capability for boundary layer control and for the simulation of turbine blade cooling. Furthermore, turbulence generators, installed in the contraction/nozzle upstream of the test section control the inlet turbulence level between 0.3% and 6%.

A variety of modern measuring techniques are available, covering Schlieren measurements for transonic effects, a laser two focus velocimeter for detailed velocity fields inside the cascade, hot wire probes for turbulence measurements and heated thin films for identification of laminar-turbulent transition and separated regions on blade surfaces.

Subsonic choked turbine cascades

Subsonic, choked turbine cascades are discussed in the third section by C. Sieverding. The experimental conditions for two-dimensionality at subsonic inlet with transonic or supersonic exit conditions are less severe in the case of turbine cascades, compared to compressor cascades. This is due to the overall acceleration of the turbine flow and the thin end-wall boundary layers. Hence control of the two-dimensionality is easily obtained through a single upstream suction slot, parallel to the blade leading edge, or even without any aspiration mechanism.

Outlet flow periodicity is more difficult to achieve however, due to the presence of exit shock and expansion waves which interfere with the boundaries limiting the cascade exit, being reflected back into the flow field and deteriorating the flow periodicity. These reflections cannot be totally eliminated, resulting in errors on the exit wake measurements. The three boundary options for control of these reflections are discussed separately, namely the free shear layers developing downstream of the trailing edge, solid tailboards hinged to the trailing edges of the upper and lower blades of the cascade, and perforated tailboards. The first option, free shear layer boundaries, are unfavorable since they lead to the strongest shock reflections and also to unsteady effects. The second option, solid tailboards, is viable when the outlet angle strongly depends on exit Mach number, that is in the supersonic range. In the transonic regime this approach is not recommended. Perforated tailboards imply many design parameters and some encouraging attempts are reported.

Another important effect on measurement accuracy at transonic/supersonic exit conditions is connected to the blockage effect of the pressure probes. This effect is strongest around sonic exit Mach numbers and recommendations are given for the optimal ratios of probe diameter to cascade tunnel geometrical parameters such as to minimize the probe interference. Since the strongest effects come from the probe stem, it is advised, whenever possible, to introduce the probe from far behind instead of inserting it from the side walls, where in addition the probe blockage varies with the degree of immersion.

The accuracy of the pressure measurements with multi-hole probes is strongly affected in regions of strong pressure gradients and non-uniform flow conditions. A detailed discussion is presented, particularly on adequate calibration tests to evaluate and correct the pressure probe readings in presence of shocks and expansion fans.

Transonic and supersonic cascades

Transonic and supersonic cascades, particularly compressor cascades, are extensively discussed by H. Schreiber, H. Starken and W. Steinert. Compared to the turbine case, referred to above, the difficulties arise from the transonic and supersonic inlet flow field. In addition the sensitivity to variations of boundary conditions is maximum at transonic inlet Mach numbers and the effects of blade boundary layers can be considerable, as a consequence of the adverse pressure gradients.

The difficulties in controlling the transonic and supersonic inlet flow fields are connected to the phenomenon of *unique incidence*. This makes it very difficult to ensure perfect periodicity of the incoming flow, when combined with the reflected shock and expansion waves by the upper solid wall of the cascade. A theoretical analysis leads to the conclusion, for supersonic inlet conditions, that the right running characteristics, generated by the leading edge suction surface, should lead to a uniform upstream flow field. A further consequence of the theoretical investigations is the determination of the region where accurate measurements of the inlet flow angles and Mach numbers should be performed.

At transonic conditions however, the reflections at the upper wall always enter the blade passages. Therefore, the upper wall should be made porous, with an appropriate suction system, in order to reduce the strength of the reflected shock waves.

At transonic and supersonic compressor inlet conditions, the exit region requires a throttle device in order to control the back pressure independently of the upstream flow. The interactions with the tailboard system can be quite complex and setting accurate inlet flow parameters, periodicity together with a wide range of operation conditions can be quite delicate to achieve.

Due to the relatively thick end-wall boundary layers, it is nearly impossible to achieve two-dimensional conditions. However, this can be put at an advantage since the real flow in the turbomachine is also affected by the contraction of the stream tubes and the variation of the axial velocity-density ratio (AVDR). It is known that this variation has a considerable effect on turning, pressure increase and loss development. Therefore, realistic turbomachine conditions can be simulated in the cascade by controlling the AVDR through side wall suction. A detailed discussion of side-wall effects is presented, together with indications on the various suction devices and their range of operation.

Since measuring inlet flow angles with pressure probes becomes increasingly difficult at higher Mach numbers, roughly above 0.8, a technique is advocated based on systematic comparisons between measured and computed blade surface pressure distributions, even with an inviscid Euler flow model. Similarly, inlet Mach numbers may also be obtained by comparing measured and calculated inviscid surface Mach number distributions at selected points in the first 5% to 20% chord of the suction surface. This new approach has been accurately validated and is a spectacular example of the growing importance of the interaction between numerical simulations and experimental research.

The operation modes of supersonic inlet flow compressor cascades, namely unstarted, unstarted and choked, started at subsonic or supersonic axial velocities are further analyzed in this section in detail. In particular, the third mode which corresponds to the unique incidence case is given special attention with regard to the determination of the experimental inlet conditions. This section closes with some considerations of the uncertainty of test results. In particular, the uncertainties connected to the non-perfect modeling, such as lack of perfect periodicity, side-wall controls deserve special attention.

The last section of this chapter is an account by Hoorelbeke, Gaillard and Losfield of the experience and facilities developed at ONERA, France. Various test techniques, including control of lateral boundary layers and specially shaped walls for the realization of 2D flow conditions, as well as instrumentation, are described, in particular, profile boundary layer measurement methods.

CHAPTER 3: ANNULAR AND ROTATING CASCADES

Annular cascades

Annular cascades are reviewed by H.Hodson and R.Dominy. Their main advantage being the ability to simulate radial gradients, it is essential to be able to control the inlet and exit radial distributions. At inlet, most facilities have nearly constant stagnation pressures and temperatures, with the exception of the end-wall boundary layer regions. Inlet swirl angles are generally produced by inlet guide vanes. These vanes produce fixed wakes and secondary flow vortices, which, if not located sufficiently far upstream from the cascade, will affect the periodicity of the inlet flow.

Several facilities allow the simulation of the periodic wakes as produced by an upstream rotor in a turbomachine. This is can be obtained through either a spooked wheel or a lightly cambered, nearly unloaded blade row. Hub inlet skew is sometimes generated via a rotating hub, but its similarity to the typical flow skewing of real turbomachines has to be verified.

At exit, the main objective is the control of the radial pressure gradient, although most facilities have a constant annulus exhausting in a constant pressure plenum. Care should be taken to avoid or control hub end-wall separation, particularly in presence of swirl.

High speed annular cascade test facilities are continuous or of limited duration blowdown type, generally in a closed system. The usual configuration has the cascade located between two plenum chambers, the upstream one being pressurized, while the back pressure is controlled by a throttle in the exit duct. Short duration facilities require complex control systems, fast response instrumentation and rapid traverse tools. In addition they can be subject to considerable aerodynamic forces, but their main advantages are the lower requirements on power and the larger size of the cascade models.

The high power requirements of continuous flow tunnels is generally limited by using lower size cascades, providing therefore less detailed data than larger short duration facilities. However, they will cover a wider range of operational conditions. As an example of a typical continuous type transonic annular cascade, the authors describe the facility of the Whittle Laboratory at the University of Cambridge. This closed loop tunnel allows separate control of Mach number and Reynolds number.

Low speed annular cascades, basically at incompressible flow conditions, have low power requirements, hence can be of larger size and are much easier to operate than the high speed tunnels. In addition the measurement conditions are also much easier, allowing more detailed flow investigations and improved spatial resolution.

The main problem is connected to the dynamic similarity with the flow conditions of the high speed turbomachine stage. Standard practice is to produce an equivalent set of velocity triangles at the mean streamline, with a radial equilibrium calculation to obtain the desired radial variation. Since Mach number similarity is excluded by the low speed environment, Reynolds number similarity is applied. However, since density, temperature and viscosity vary rapidly in advanced compressor or turbine stages, Reynolds numbers can not be made equal at inlet and at exit. Hence an average reference value has to be selected. Hence an average reference value has to be selected.

Various facilities and associated instrumentation are presented in this section.

Rotating annular cascades

Rotating annular cascades are discussed by J.Amecke and F.Kost. They allow, in addition to the potential of annular cascades, to investigate the interaction of centrifugal and Coriolis forces with the secondary flows.

This section gives an overview of the properties and operational conditions of rotating cascades as influenced by centrifugal and Coriolis forces, such as the boundary layers. After a discussion of the measurement techniques, various facilities are presented.

CHAPTER 4: PARTICULAR ASPECTS OF HOT CASCADES

This short chapter by C. Scrivener presents design and operating conditions of cascades developed for the validation of hot turbine components. The essential motivation lies in the investigation of metal temperatures and cooling techniques. Although hot cascades are still considerable simplifications of full engine environments, they allow more extensive measurements because of their relative simplicity.

In a typical test facility, air is supplied from compressors and heaters. Temperature and pressure of the mainstream and cooling air are independently controlled and combustion chambers are installed for high temperature testing. Separate configurations are set up for rotor blades and nozzle guide vanes, since they generate different gas deflections.

Similarity between engine and hot cascade conditions is essential. In addition to current similarity laws for Mach and Reynolds numbers, gas-to coolant temperature ratios, as well as gas-to-coolant and gas-to-metal conductivity ratios are required.

The primary measurements to be made in hot cascades are of metal temperature, via thermocouples. Although easy to use for surface temperatures, they require much effort for their installation. Other alternatives are temperature sensitive paints or optical pyrometry. In addition, heat transfer coefficients can be obtained from continuously running high pressure/high temperature cascade facilities, measuring the variation of external wall temperature.

CHAPTER 5: TRANSIENT CASCADE TESTING

Transient cascades, including shock tubes, are described by T. Jones, M. Oldfield, R.Ainsworth and T.Arts. Various transient facilities have been developed. A significant advantage of short duration facilities is the gain in scale for a given size of high pressure tank. The tank allows to produce quasi-steady flow through the cascades for a short testing time which is function of the reservoir pressure and temperature. On the other hand, the scale of the cascade is inversely proportional to the testing time. An important parameter is the flow establishment time, which is dominated by viscous diffusion.

Various existing facilities are described, including typical components, such as the fast acting valves, controlling the operating conditions. Particular attention is given to the transient measurement techniques, such as pressure transducers, surface thin film gauges or liquid crystal methods for heat transfer and shear stress measurements, flow visualization and optical methods. High speed probe traversing mechanisms are also described, including the requirements on the propulsive systems.

CHAPTER 6: UNSTEADY FLOW IN CASCADES: FLUTTER AND FORCED RESPONSE

The important field of cascade simulations of unsteady flows in turbomachinery components is treated by D. Buffum and S. Fleeter. Simulating flutter and forced vibration of turbomachinery blade rows is an essential step in the definition of the life time cycle of advanced compressors and turbines.

Flutter is a self-excited oscillation of a blade, depending on the blade motion, the flutter frequency corresponding to one of the lower blade or coupled blade-disk natural frequencies. while with forced vibrations the aerodynamic forces are independent of the blade motion. Forced vibrations are generated at a multiple of the engine rotational frequency close to a resonant natural frequency, and arise from various aerodynamic perturbations, such as struts, inlet nonuniformities, stator-rotor interactions.

The essential consequences of blade vibrations is high stresses and reduced life time due to fatigue failure.

In order to investigate these vibration problems in a laboratory environment, typical cascade vibration test facilities are designed. Since flutter plays an essential role in the engine development program, it has received considerable attention, although forced vibrations can have a stronger impact on the overall number of observed fatigue failures.

The development of experimental facilities require correct simulations of typical parameters, such as the reduced frequency and the interblade phase angle. In addition, the test facility should be able to achieve an essential two-dimensional motion of the airfoils, while the drive system for torsion and rotational modes should be capable of forcing the airfoils at a specified frequency.

Various type of facilities are considered, ranging from linear cascades to annular, fixed or rotating, cascades. Although annular configurations provide better simulations of periodic excitations and overall periodicity conditions, the linear oscillating cascades remain the most attractive due to their relative simplicity, easy instrumentation access and flow control.

Two main experimental techniques are applied in practice, all airfoils of the linear cascade are oscillating, or a single airfoil is oscillated with stationary neighbors. Various techniques for generating blade oscillations are described.

Instrumentation includes surface pressure taps for determination of unsteady force and damping coefficients, strain gauges, light probes, hot wire and hot films.

Attention is given to the specific problems of data acquisition and analysis as well as to the frequency response of the pressure transducers and other instruments, particularly Fourier decomposition for the extraction of the various harmonics.

CHAPTER 7: THREE-DIMENSIONAL LASER ANEMOMETRY IN ANNULAR CASCADES

This last chapter, by L. Goldman, deals with specific aspects of three-dimensional laser anemometry instrumentation when applied to annular cascades.

Reviewing the different types of laser anemometers, attention is given to optical access, flow seeding, probe volume positioning in turbomachinery geometries. Five experimental set-ups are described, all based on Doppler fringes, as applied in US University laboratories and at NASA Lewis RC to axial or radial compressors and turbines.

The essential difficulties are connected to the lower accuracy of the on-axis velocity component compared to the transverse components. This difficulty comes from the geometrical constraints on the angles between the different optical orientations.

Detailed descriptions are given of single, two- and three-channel fringe systems as applied to these geometries. Differences in experimental set-up occur according to the simultaneous measurement, or not, of the three velocity components.

Special care has to be given to the seeding particle size, in order to ensure that they track the complex turbomachinery flow. The best accuracy is obtained with three channel, three color systems and simultaneous measurement of the three components. Finally, several enhancements of the current systems are discussed.

CONCLUSION

This AGARDograph covers most of the present day problems and experience in cascade testing. It relies on the accumulated experience of a large number of authors, from research as well as from industrial organisations. Linear, annular, stationary and rotating cascades are treated, including steady and transient testing techniques including the simulation of flutter in cascades.

We would like to thank here all the authors for their efforts and their willingness to share their experience and knowledge.