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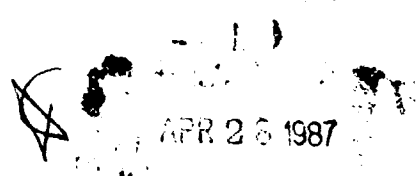


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AERODYNAMIC LOSS SOURCES IN AXIAL-FLOW COMPRESSORS
Final Report: 6 January 1983 - 31 August 1986

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FINAL REPORT
6 January 1983 - 31 August 1986

**AERODYNAMIC LOSS SOURCES
IN AXIAL-FLOW COMPRESSORS**

**T.H. Okiishi
G.K. Serovy
December 1986**

**ISU-ERI-Ames-87168
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**DEPARTMENT OF MECHANICAL ENGINEERING
ENGINEERING RESEARCH INSTITUTE
IOWA STATE UNIVERSITY, AMES**

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1. INTRODUCTION

Propulsion gas turbine engines of interest to the U.S. Air Force generally include an axial-flow compressor as a major component. In order to meet the challenging size, weight, and performance specifications for present and future aircraft engines without excessive costs, these compressors must be designed with increasingly reliable methods. Important compressor design objectives are minimization and accurate estimation of aerodynamic losses. To accomplish these goals, sources of aerodynamic loss must be clearly identified and understood. The consequences of these loss sources need to be modeled quantitatively so that designers can account for them appropriately in design calculations.

During the contract period, 6 January 1983 through 31 August 1986, several research projects related to understanding and modeling aerodynamic loss production in axial-flow compressors were carried out. The work statements which guided the work are as follows:

1. Transition dynamics of compressor airfoil surface boundary layers will be studied, emphasizing the influence of upstream turbulence properties (intensity, scale, type) and periodic unsteadiness due to wakes. Results will be incorporated into computer codes for boundary-layer prediction in inviscid-viscous interaction blade cascade performance estimation.
2. An example series of high-speed compressor cascade test case experiments will be developed. Tests will be carried out in test facilities at Deutsche Forschungs- und Versuchsanstalt für

Luft- und Raumfahrt (DFVLR) (Cologne, FRG) and Office National d'Études et de Recherches Aérospatiales (ONERA) (Chatillon, FR) with facility support and blading provided by DFVLR and ONERA. Experimental parameters will include turbulence and wake-development measurements.

3. Compressor rig experiments will be carried out to develop detailed flow-path survey data in existing baseline stages. These data will support improved accounting in compressor design for turbulence, periodic unsteadiness and secondary flows. Experiments will be coordinated with boundary-layer code improvement described in Item 1 above.
4. Overall, the program will be directed toward improvement of designer quantitative capability in accounting for loss sources in compressor flow-field prediction. New approaches to estimation of loss distributions will be studied and evaluated so as to eliminate discrepancies and inconsistencies in presently established methods.

A number of publications resulted from the effort. Several related reports are still being processed. All documents associated with the contract work are listed in Section 3 of this report.

Since the details of the work accomplished under AFOSR contract are already included in the aforementioned references, only a summary description of research results is included in this report.

The accurate prediction of aerodynamic loss levels in axial-flow compressors remains a difficult problem. This is especially true at off-design operating conditions. Further minimization of losses in

gas turbine engines will require additional systematic study of aerodynamic loss details.

2. RESULTS OF THE RESEARCH PROGRAM

Important facets of the results of the research accomplished during the contract period are summarized in this section. We made progress in clarifying loss prediction for axial-flow compressors and offer some suggestions for incorporating wake interaction effects in design calculations. Some of the inherent complications associated with supersonic blade testing are noted. Further study of specific details of loss generation is proposed as an appropriate element in future AFOSR research planning.

2.1. Transition Dynamics of Compressor Airfoil Surface Boundary Layers

In a typical axial-flow compressor stage (rotor row/stator row combination), rotor-wake fluid is continuously severed by downstream stator blades into convected wake segments that interact with and influence the boundary layers on the stator surface. Although this flow detail is important for design purposes, it has not yet been usefully quantified.

To better understand the physics of this flow phenomenon, we used the low-speed, two-stage, axial-flow research compressor [1] of the Iowa State University Turbomachinery Components Research laboratory [2]. The low-speed aspect of this compressor allowed study of the influence of the rotor-wake segment on the laminar boundary-layer development on the stator. We mounted high-frequency-response, surface hot-film gages at four chordwise positions, at midspan of the first stage stator and

on stator suction and pressure surfaces. The chordwise positions selected were 10%, 35%, 60%, and 80% chord. The high-frequency response of the data acquisition system made it possible to observe the unsteady characteristics of the stator boundary layers, including the periodic influence of rotor-wake segments. Hot-film gage output voltages were recorded as oscillograms and were logged over a period of four milliseconds during which time four rotor blades moved past the examined stator blade. Laminar and turbulent boundary-layer flows could be easily detected in the oscillograms.

The oscillograms of Fig. 1 were obtained with hot-film sensors on the stator suction surface. The periodicity of the signal is apparent. Each "bump" is associated with a temporarily higher heat-transfer rate from the gage and can thus be related to a higher shear stress at the surface. The period of occurrence of the "bumps" corresponds to the passing period of the rotor blade. It is evident that the boundary layer is laminar in the absence of passing rotor-wake segments. Also, it is apparent that as the rotor-wake segments move downstream on the stator suction surface, they become wider. The growth of the width of the wake segment is so great by 85% chord that the boundary layer is turbulent nearly all of the time there and returns to a laminar level for only an instant between wake segments. Downstream of this chordwise position, wake segments probably merge and the boundary layer is turbulent all of the time. Similar results were noted for the pressure surface of the stator blade.

From the above results and from information from several other researchers (Dring et al. [3], Larguier [4], Pfeil et al. [5], and

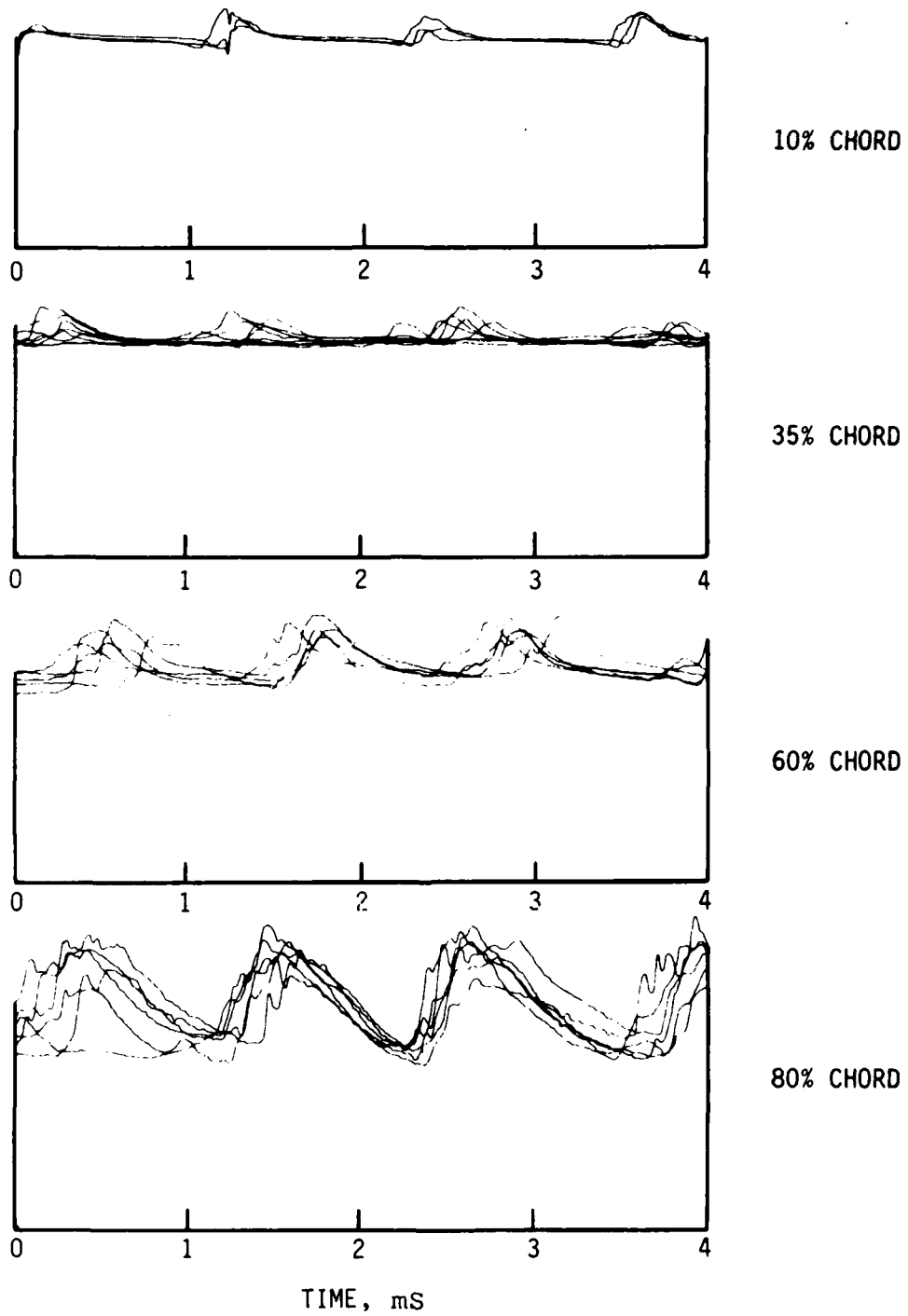


Fig. 1. Hot-film sensor oscillograms for suction surface.

Evans [6]), it is clear that a laminar boundary layer oscillates between laminar and turbulent states with the passing of upstream blade-row wake segments. The measured velocity profiles of the boundary layer of a compressor stator presented by Evans [6] suggest that the turbulent boundary layer associated with a passing wake is much thicker than the boundary layer in the absence of the wake segment. This difference in thickness diminishes as the wake segment travels downstream until the boundary layer is completely turbulent with no periodic oscillations between laminar and turbulent flow being evident. To confirm that the passing rotor-wake segments are no longer observable when the boundary layer is turbulent, the stator boundary layers were tripped near the leading edge of the blade and forced to become turbulent. Under this condition, the surface hot-film gages could no longer sense rotor-wake segments.

One way to model the convection of these passing rotor-wake segments on the stator surfaces is to consider each rotor-wake segment as if it were a moving turbulent spot in the boundary layer of the stator surface. Pfeil et al. [5] demonstrated that a wake segment will grow in size, as it travels downstream in a flat-plate boundary layer, like a turbulent spot. This growth is associated with the difference in transit velocities of the forward and aft edges of the wake segment. A literature survey by Pfeil et al. [5] suggests nominal values of 89% and 50% of local freestream velocity for the wake-segment spot forward and aft edges respectively for flat-plate boundary-layer flow. With these velocities in mind, the space-time graph of Fig. 2 was constructed for the suction surface of the stator blade. For this figure, we used

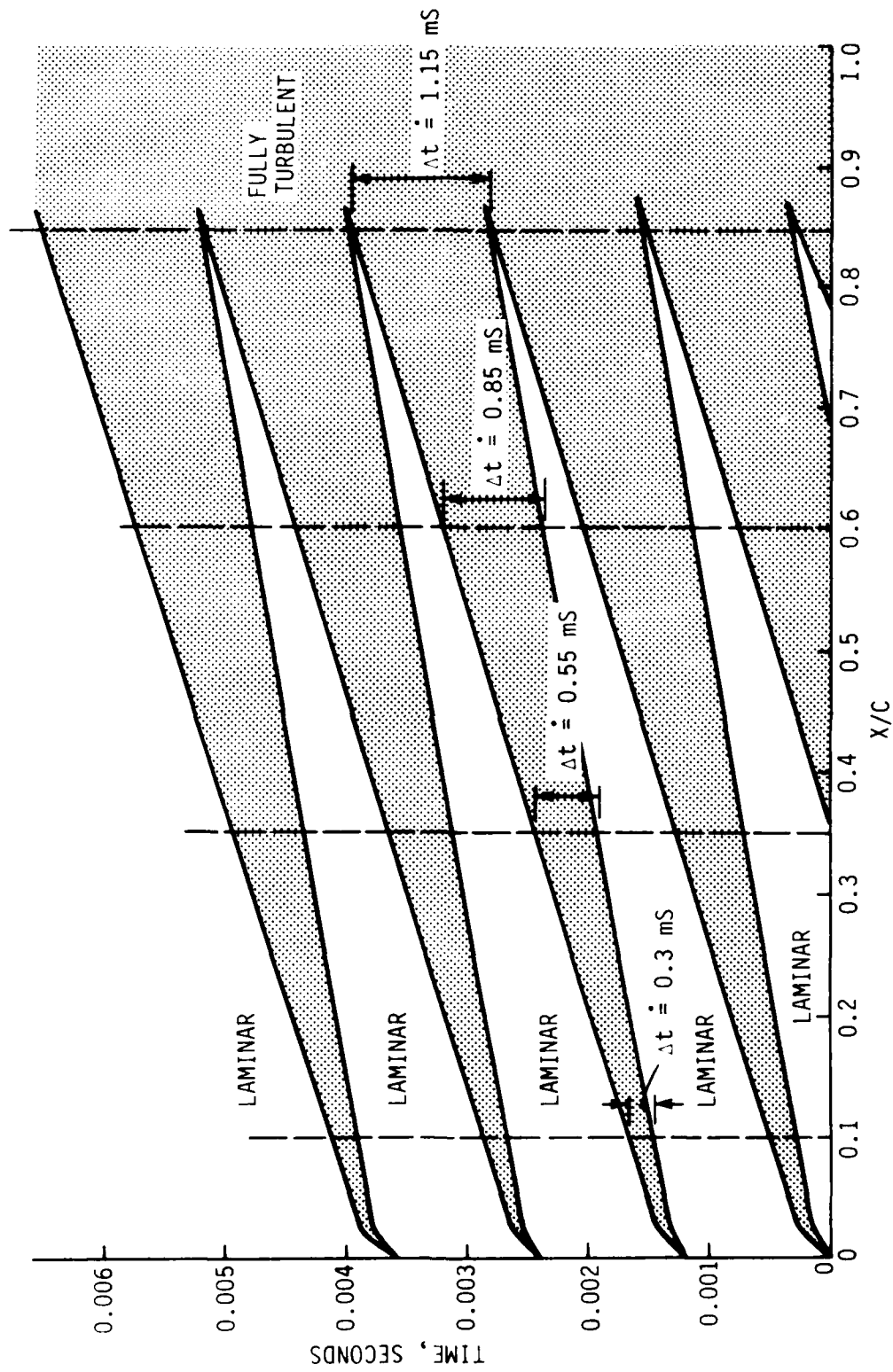


Fig. 2. Time-space distribution of turbulent spot model for the suction surface.

freestream velocities calculated by an inviscid flow code. The forward and aft edge velocities of the rotor-wake-segment spot were calculated for various chord locations and plotted as slopes in space-time coordinates. A horizontal or constant time line on this graph illustrates which portion of the suction-surface boundary layer of the stator blade is turbulent at any given instant. A vertical line shows when and for how long the boundary layer is turbulent at a given location. When a constant position (vertical) line of Fig. 2 is selected to correspond with one of the hot film locations on the suction surface, the time intervals between wake segments and the time for the wake segment to pass can be read from the graph. The time intervals from Fig. 2 and the surface sensor data (Fig. 1) match well for each of the four locations of the suction-surface sensors. A figure similar to Fig. 2 was constructed for the pressure surface of the stator. Modeled and measured results compared favorably again. The notion that a rotor-wake segment influences the boundary layer of the stator surface much like a turbulent spot does appears to be reasonable.

The computer code for inviscid-viscous flow interaction described in Ref. 7 was used to predict loss values for stator blade elements for different transition conditions of the blade surface [2]. Natural transition resulted in a code-predicted loss that was comparable to the measured value. On the other hand, when transition was computationally forced to occur at the leading edge of the stator, the code-predicted loss coefficient was much larger than the measured amount. These results were confirmed in a subsequent study at Iowa State sponsored by NASA [8]. In this latter work, several other important related

conclusions were drawn. If the location of first boundary-layer instability occurs near mid-chord or further aft on the blade surface as it does for low-speed blades, the natural transition-related loss value calculated by the computer code of Ref. 7 is not sensitive to the length of the transition region (distance between point of first instability and fully turbulent boundary-layer flow) and is comparable to measured loss. When the location of first instability is close to the leading edge of the blade as is true for high-speed blades, the value of computer-code-predicted profile loss varies considerably with length of transition region. In general, the code-predicted loss associated with boundary-layer transition occurring at the location of first instability compares favorably with measured loss values. If the boundary layer is forced to be turbulent from the blade leading edge, the code-predicted loss is high compared to measured values for high- and low-speed blades.

2.2. Supersonic Compressor Cascade Test-Case Experiments

Motivated by the availability of a series of experiments in a supersonic cascade of arbitrary airfoils designed to model a tip-region flow in a successful USAF/AFWAL high-through-flow compressor rotor, a cooperative research program involving DFVLR (Federal Republic of Germany), ONERA (France), Allison Gas Turbine (USA) and Iowa State University has been completed. New experiments on separate sets of cascade blading were run by DFVLR and ONERA. A high degree of cooperation in planning, conducting, and evaluating the test data sets was achieved. A workshop to review results and conclusions, with participation from a broad

spectrum of industry and government agencies, was held at Iowa State during July 1986. A further result of the DFVLR/ONERA/DDA/ISU program was the initiation of annular cascade experiments on the same cascade configuration in the École Polytechnique Fédéral de Lausanne (EPFL) turbomachinery laboratories. Publication of summarizing reports as technical society papers is planned by all participants.

2.2.1. DFVLR and ONERA Cascade Experiments

The existing published results of the Allison Gas Turbine (DDA) cascade program were used as the basis for specification of cascade geometry and aerodynamic test conditions by DFVLR and ONERA. An attempt was made to assure cascade geometric similarity in terms of blade profile, stagger angle, and solidity, but differences were necessary in aspect ratio and in the geometry of end and side wall boundary-layer control systems.

In supersonic cascade tests under "started" conditions, a typical cascade geometry at a fixed cascade entrance Mach number will operate at a "unique incidence" or entrance region flow angle. Under these circumstances, cascade static-pressure ratio and axial velocity-density product ratio (AVDR) are independent variables. Because this type of operation was of most interest in the cascade under study, both DFVLR and ONERA planned to operate under "started" conditions at a Mach number level of about 1.6. The static-pressure ratio was to be varied from the *minimum* attainable to the "unstarted" or spill-point value. AVDR was controlled by side-wall suction slots.

2.2.2. Airfoil Profile Checks

Sample blades from the DDA, ONERA and DFVLR cascade configurations were dimensionally checked by a single source, the NASA Lewis Research Center. These data are on file for publication and distribution to qualified requestors. Independent checks of blade sets were made by the testing groups.

2.2.3. Data Collected

In all three experimental programs completed to date, blade-surface pressure distributions and downstream blade-to-blade surveys of total pressure and flow angle were obtained. Static pressure in the downstream region was measured by a series of wall taps. Although downstream surveys were generally made at a midspan location, additional spanwise locations were utilized in some of the ONERA experiments.

Tests at additional Mach number levels were run at DFVLR. In addition, a series of wake-development measurements were made by ONERA.

A special effort was made to meet at the individual test sites so that questions regarding facilities, test protocol, instrument design and calibration, and data reduction methods could be answered. D. L. Tweedt (Iowa State) was resident at DFVLR during the entire cascade build-up and test period there. Several visits to Allison Gas Turbines, DFVLR and ONERA were made by G. K. Serovy and T. H. Okiishi.

2.2.4. Supersonic Cascade Workshop

From 29-31 July 1986 a series of presentations was made as a part of the ASME Fluid Dynamics of Turbomachinery lecture series held in Ames, Iowa. Speakers included:

H. J. Schreiber (DFVLR)
H. Starken (DFVLR)
D. L. Tweedt (DFVLR/ISU)
A. Fourmaux (ONERA)
R. L. York (Allison Gas Turbines)
G. K. Serovy (ISU)

The individual test programs were summarized and results were compared. Approximately fifty people attended, with a large number representing the United States turbine engine industry, USAF, and NASA.

2.2.5. AGARD Propulsion and Energetics Panel Test Case

AGARD/PEP Working Group 18 on Test Cases for Turbomachinery Flow Computation has selected the supersonic cascade discussed above along with the assembled data as a test case for computational fluid mechanics codes. Dr. Starken of DFVLR has been designated as the responsible WG-18 member and G. K. Serovy of ISU as United States Working Group member will assist in selection of typical result sets. The product of the Working Group will be an AGARD Advisory Report.

2.2.6. ASME Gas Turbine Conference Presentation

It has been agreed that the four participating groups will submit a series of four technical papers for presentation at a 1988 International Gas Turbine Conference. These papers will be offered for publication in the ASME Journal of Turbomachinery.

2.2.7. Status of Publications

A detailed list of the reports and other communications from the supersonic cascade work follows:

Fleeter, S., Holtman, R. L., McClure, R. B. and Sinnet, G. T. Experimental Investigation of a Supersonic Compressor Cascade. Aerospace Research Laboratory, Wright-Patterson AFB. ARL TR 75-0208. 1975.

Convention de Recherche. Office National d'Études et de Recherches Aérospatiales et Iowa State University of Science and Technology. Fevrier 1983.

Research Agreement. ONERA and ISU. February 1983.

Serovy, G. K. and Okiishi, T. H. Status of Joint Supersonic Cascade Test Program. Turbomachinery Components Research Laboratory. Iowa State University. Memorandum Report. 28 June 1983.

Prince, D. C., Jr. Cooperative Program for Two-Dimensional Cascade Tests of the ARL SL19 Cascade. Personal Communication to G. K. Serovy. 15 July 1983.

Fabri, J. Status of the ONERA-ISU Cooperative Research on Compressor Blades. Letter Report to G. K. Serovy. 1 September 1983.

Tweedt, D. L. Letter Report to T. H. Okiishi. 6 October 1983.

Serovy, George, K. Cooperative Research on Supersonic Cascade Aerodynamics. Turbomachinery Components Research Laboratory. Iowa State University. Memorandum Report. 10 January 1984.

Starcken, H., Tweedt, D. L. and Schreiber, H. A. Personal Communication to T. H. Okiishi. 20 February 1984.

Okiishi, T. H. Progress Report (Till 13 January 1984) Joint Supersonic Cascade Aerodynamics Program. Turbomachinery Components Research Laboratory, Iowa State University. Memorandum Report. 28 February 1984.

Tweedt, D. L. Personal Communication to T. H. Okiishi concerning DFVLR Cascade Program Studies. 28 February 1984.

Fourmaux, Antoine. Resultats d'essais a S5Ch d'une grille d'aubes ARL (Aerospace Research Laboratory). Direction de l'Energetique. ONERA. Rapport Technique 5/3568 EN. 13 Mars 1984. Translated as Results of S5CH Tests with an ARL (Aerospace Research Laboratory) Cascade. NASA TM-77510. December 1984.

Mesthe, P. L. Grille d'aubes supersonique A.R.L. (Mach amont = 1.615) (Soufflerie S5Ch). Direction de l'Aerodynamique. ONERA. Procès-Verbal d'essais no. 6/3568 EN 004 E. Mars 1984.

Tweedt, D. L. Letter Report to T. H. Okiishi. 28 March 1984.

Okiishi, T. H. and Tweedt, D. L. Progress Report (Till 31 Mar 1984) Joint Supersonic Cascade Aerodynamics Program. Turbomachinery Components Research Laboratory. Iowa State University. Memorandum Report. 31 May 1984.

Tweedt, D. L. Letter Report to T. H. Okiishi. 31 August 1984.

Losfeld, G. et Mesthe, P. L. Dispositif d'essais de grilles d'aubes supersoniques de la soufflerie S5Ch. Direction de l'Aerodynamique. ONERA. Rapport Technique 76/1865 AN. Juillet 1984.

Serovy, G. K. Personal Communication to C. L. Ball concerning Airfoil Section Coordinate Measurement by NASA. 19 April 1984.

Buggele, A. E. Requested Dimensional Inspection of Four Supersonic Airfoils Having Identical Design Profile but Different Scale Chord Lengths. Letter Report to Small Engine Propulsion Branch, NASA Lewis Research Center. 18 June 1985.

Losfeld, G. Grille d'aubes supersonique A.R.L. Essais complémentaires (Soufflerie S5Ch). Direction de l'Aerodynamique. ONERA. Procès-Verbal d'essais no. 8/3568 EN. Février 1985.

Starcken, H. and Schreiber, H. A. AGARD WG 18 Test Case No. 1: Compressor Cascade ARL SL 19. Institut für Antriebstechnik, DFVLR. Köln, December 1986.

2.3. Compressor Rig Experiments

In attempting to compare computer-code-predicted loss values with measured results, it became clear that the code was limited only to a consideration of blade-surface, boundary-layer loss while the measured data possibly included more information. Thus, the measured results were carefully organized and interpreted to yield a loss value that could be fairly compared with the code prediction. Further, the code had no provision for modeling the influence of upstream blade-wake segments on boundary-layer development on the downstream blade surface. As already mentioned in Section 2.1, the location and length of the boundary-layer transition region was ascertained to be an important variable in this respect.

Time-average total-pressure measurements were made at midspan in the first stage of the baseline configuration of the Iowa State low-speed research compressor between the first stage rotor and stator rows (measurement station 2.0), at the stator row leading edge (measurement station 2.5) and downstream of the stator row (measurement station 3.0) [2]. A significant portion of the observed loss in total pressure across

the stator row between measurement stations 2.0 and 3.0 occurred upstream of the stator, between measurement stations 2.0 and 2.5. The measured loss in total pressure between measurement stations 2.0 and 2.5 was attributed to rotor-wake mix out. The inviscid-viscous flow interaction computer code described in Ref. 7 includes the capability for predicting blade-wake mix-out loss values based on the wake-mixing model of Lieblein and Roudebush [9] and was therefore used to provide comparison data. The measured and computer code rotor-wake mix-out loss variations with axial distance did not compare at all favorably. Further work aimed at verifying this result is underway.

It is obvious from the previously mentioned total-pressure measurements that the value of aerodynamic loss assigned to a specific compressor blade row can depend considerably on where the measurement stations defining the axial extent of the blade row are located. If measurement stations 2.0 and 3.0 are used to define the stator blade row, the corresponding loss includes rotor-wake mix-out loss as well as stator-blade-surface, boundary-layer loss. Since the total-pressure level at station 2.5 was comparable to the total-pressure levels found in the fluid outside the stator wake at station 3.0, the loss associated with stations 2.5 and 3.0 was considered representative of stator-blade-surface, boundary-layer loss or blade-profile loss.

With smaller axial spacings between blade rows, the total pressure in the leading-edge plane of the blade may not be suitable for profile-loss assessment because the upstream blade wake may not be fully mixed out there. A more reliable technique for determining blade-profile loss from measurements is to use downstream data only. The average total-

pressure level for flow outside the blade wake is used to represent the total pressure of the flow entering the blade row. A recent NASA-sponsored study conducted at Iowa State [8], confirmed the notion that large differences can exist between blade-row loss based on total pressures measured upstream and downstream of a blade row and profile loss estimated from data acquired downstream of a blade row only. Further, estimated blade-profile-loss values determined from downstream data only compared favorably with computer-code-predicted values [7].

2.4. Accounting for Loss Sources in Compressor Flow Field Prediction

It is possible to predict accurately compressor stator-blade-element loss with a steady-flow viscous-inviscid interaction code. The time-average influence of upstream rotor-wake interaction with the stator boundary-layer development can be modeled by forcing boundary-layer transition to occur at the location of first instability on the stator-blade surface [8].

When obtaining profile-loss values for blade elements from measurements, it is essential that the loss due to upstream blade-row-wake mix-out is identified and accounted for before comparisons are made with computer-code predictions [8].

The wake mix-out loss models proposed years ago by Lieblein and Roudebush [9] for incompressible flow and by Stewart [10] for compressible flow should be tested further for suitability. Measured low-speed rotor-wake mix-out loss development did not compare well with computer-code-predicted development [2]. Similar comparisons need yet to be made for low-speed stator blades and for high-speed rotor and stator blades.

3. PUBLICATIONS

The documents listed below were published during the contract period and are based entirely or in part on research sponsored by the AFOSR.

Tweedt, D. L., Hathaway, M. D., and Okiishi, T. H. Multistage Compressor Stator/Rotor Interaction. AIAA Journal of Propulsion and Power 1:449-455. 1985.

Okiishi, T. H., Hathaway, M. D., and Hansen, J. L. A Note on Blade Wake Interaction Influence on Compressor Stator Row Aerodynamic Performance. Transactions of the ASME, Journal of Engineering for Gas Turbines and Power 107:549-551. 1985.

Parsons, J. A. Blade-to-Blade Variation of Fluid Velocity Vector Angle and Magnitude Downstream of Compressor Cascades. M.S. Thesis. Iowa State University. Ames, Iowa. 1985.

Stampfli, J. D. and Serovy, G. K. Investigation of Time Variant Flow Angles Due to Shed Wakes in Turbomachines. Iowa State University Engineering Research Institute Technical Report TCRL-30. ISU-ERI-Ames-85283. July 1985.

Serovy, G. K. Axial-Flow Compressor Aerodynamics. Chap. 3 in Aerothermodynamics of Aircraft Engine Components, edited by Gordon C. Oates, New York. American Inst. of Aeronautics and Astronautics. 1985.

- Serovy, G. K. Secondary Flows and End Wall Effects. In Thermodynamics and Fluid Mechanics of Turbomachinery, edited by A. S. Ucer et al., Vol. II, pp. 601-619. NATO ASI Series E: Applied Sciences, No. 97B. Dordrecht. M. Nijhoff. 1985.
- Serovy, G. K. Organization of Design Systems for Turbomachinery. In Thermodynamics and Fluid Mechanics of Turbomachinery, edited by A. S. Ucer et al., Vol. II, pp. 785-803. NATO ASI Series E: Applied Sciences, No. 97B. Dordrecht. M. Nijhoff. 1985.
- Hansen, J. L. and Okiishi, T. H. Axial-Flow Compressor Rotor-Stator Interaction. Iowa State University Engineering Research Institute Technical Report TCRL-31. ISU-ERI-Ames-86135. December 1985.
- Tweedt, D. L., Okiishi, T. H., and Hathaway, M. D. Stator Endwall Leading-Edge Sweep and Hub Shroud Influence on Compressor Performance. Transactions of the ASME, Journal of Turbomachinery 108:224-232. 1986.
- Hansen, J. L. and Okiishi, T. H. Rotor Wake Segment Influence on Stator Surface Boundary Layer Development in an Axial-Flow Compressor Stage. Extended abstract of proposed paper for AIAA/ASEE/ASME/SAE 23rd Joint Propulsion Conference scheduled for June 29-July 2, 1987, San Diego, California.

4. PROGRAM PERSONNEL

Two principal investigators share responsibility for the AFOSR contract research program:

- George K. Serovy, Anson Marston Distinguished Professor in Engineering
- Theodore H. Okiishi, Professor of Mechanical Engineering

Four graduate research assistants were also associated with the research program:

- Jeffrey L. Hansen
- James A. Parsons
- J. David Stampfli
- Daniel L. Tweedt

Messrs. Hansen, Parsons and Stampfli received Master of Science degrees. Mr. Tweedt is nearly through with Doctor of Philosophy requirements.

Two undergraduate students made useful contributions during the contract period:

- Brett W. Batson
- Randall C. Bauer

Both of these students continue in graduate studies at Iowa State, Mr. Batson under NASA sponsorship and Mr. Bauer under General Electric assistance.

5. INTERACTION WITH UNITED STATES AND FOREIGN GOVERNMENT
AGENCIES AND INDUSTRY

The turbomachinery research program at Iowa State University has continually focused on projects which make a contribution to the development of design systems for advanced compressors, fans, and turbines for air-breathing aircraft propulsion systems. The current contract has enhanced this activity and has made possible numerous direct contacts with outstanding individuals involved in similar objectives.

A summary list of related interactions follows:

<u>Organization and Nature of Contact</u>	<u>Individual Contacts</u>
NASA Lewis Research Center, Cleveland, Ohio: technical discussions about various aspects of axial-flow compressors; supersonic cascade blade-profile checks; test cases	J. J. Adamczyk C. L. Ball A. E. Buggele T. Gelder M. D. Hathaway D. M. Sandercock A. J. Strazisar J. R. Wood
Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio: technical discussions about axial-flow compressor technology	A. J. Wennerstrom

Organization and Nature of ContactIndividual Contacts

General Electric Company, Aircraft Engine
Business Group, Cincinnati, Ohio: mixing
in multistage, axial-flow compressors

D. C. Wisler

United Technologies Research Center, East
Hartford, Connecticut: turbomachine flow-
measurement problems

R. P. Dring

J. H. Wagner

Air Research, Phoenix Division, Phoenix,
Arizona: test cases

W. F. Waterman

Institut für Antriebstechnik, Deutsche
Forschungs- und Versuchsanstalt für Luft-
und Raumfahrt, Köln, West Germany: conduct
of supersonic cascade test program; review
of test results

H. A. Schreiber

H. Starcken

G. Winterfeld

Direction de l'Énergie, Office National
d'Études et de Recherches Aérospatiales,
Châtillon-sous-Bagneux, France: planning
of test program

S. Boudigues

J. Fabri

A. Fourmaux

G. Meauzé

Organization and Nature of ContactIndividual Contacts

NASA-Lewis Research Center, Cleveland, Ohio:
computation, test cases, review of results;
casing-treatment optimization

W. A. Benser
T. Gelder
M. J. Hartmann
D. M. Sandercock
N. L. Sanger

Middle East Technical University
Ankara, Turkey: test cases and AGARD/PEP
project T-15

A. S. Ucer

Free University of Brussels, Brussels,
Belgium: test cases and AGARD/PEP
project T-15

C. Hirsch

Flow Application Research, Fremont,
California: design-system loss correlations

W. B. Roberts

University of Cincinnati, Department of
Aerospace Engineering and Applied
Mechanics, Cincinnati, Ohio: seminar
lecture

A. Hamed
W. Tabakoff

Organization and Nature of ContactIndividual Contacts

University of Iowa, Department of Mechanical
Engineering, Iowa City, Iowa: seminar pre-
sentation

C. J. Chen

AIAA 23rd Aerospace Sciences Meeting,
Reno, Nevada: presentation of technical
paper (85-0009)

ASME 31st International Gas Turbine
Conference Dusseldorf, FRG: presenta-
tion of conference paper (86-GT-197)

ASME Fluid Dynamics of Turbomachinery
Program, Ames, Iowa: lectures

6. DISCOVERIES, INVENTIONS, AND SCIENTIFIC APPLICATIONS

No patentable concepts, devices or discoveries resulted from the contract research. However, some of the conclusions associated with blade profile-loss measurement and computer-code prediction may prove to be useful in the design of high performance axial-flow compressors.

7. REFERENCES

1. Hathaway, M. D. and Okiishi, T. H. Aerodynamic Design and Performance of a Two-Stage, Axial-Flow Compressor (Baseline). Iowa State University Engineering Research Institute Technical Report TCRL-24. ISU-ERI-Ames-84178. December 1983.
2. Hansen, J. L. and Okiishi, T. H. Axial-Flow Compressor Rotor-Stator Interaction. Iowa State University Engineering Research Institute Technical Report TCRL-31. ISU-ERI-Ames-86135. December 1985.
3. Dring, R. P., Joslyn, H. D., Hardin, L. W., and Wagner, J. H. Turbine Rotor-Stator Interaction. ASME Transactions, Journal of Engineering for Power 104:729-742. 1982.
4. Languier, R. Experimental Analysis Methods for Unsteady Flows in Turbomachines. In Measurement Methods in Rotating Components of Turbomachinery, edited by B. Lakshminarayana and P. Runstadler. ASME, New York, N.Y. 1980.
5. Pfeil, H., Herbst, R., and Schroder, T. Investigation of the Laminar-Turbulent Transition of Boundary Layers Disturbed by Wakes. ASME Transactions, Journal of Engineering for Power 105:130-137. 1983.
6. Evans, R. L. Boundary Layer Development on an Axial-Flow Compressor Stator Blade. ASME Paper No. 77-GT-11. 1977.
7. Hansen, E. C., Serovy, G. K., and Sockol, P. M. Axial-Flow Compressor Turning Angle and Loss by Inviscid-Viscous Interaction Blade-to-Blade Computation. ASME Transactions, Journal of Engineering for Power 107:28-34. 1980.

8. Batson, B. W. Axial-Flow Compressor Blade Profile-Loss Prediction by Numerical Code. M.S. Thesis. Iowa State University, Ames, Iowa. 1986.
9. Lieblein, S. and Roudebush, W. H. Theoretical Loss Relations for Low-Speed Two-Dimensional-Cascade Flow. U.S. NACA TN 3662. 1956.
10. Stewart, W. Analysis of Two-Dimensional Compressible-Flow Loss Characteristics Downstream of Turbomachinery Blade Rows in Terms of Basic Boundary Layer Characteristics. U.S. NACA TN 3515. 1955.

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