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SOME RESULTS OF NASA-IOWA STATE UNIVERSITY RESEARCH ON AXIAL-FLOW PUMPS

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INTRODUCTION

This paper is a commentary on a small chapter in the recent history of turbomachinery research. It was written to describe the positive influence of an individual, Melvin J. Hartmann, working in a federal research center, on a particular university research program. However, in its final form, it cannot help but shed some light on the long-term effects of small-scale mission-oriented, federal agency funding of engineering research in universities. Secondarily, it will recall a series of experimental investigations of axial-flow pump configurations which produced data of possible relevance to current compressor and pump problems.

LEGACY OF THE NACA COMPRESSOR RESEARCH PROGRAM

After the end of World War II, the National Advisory Committee for Aeronautics (NACA) initiated extensive research programs on compressor and turbine aerodynamics in its Cleveland and Langley Field laboratories. Numerous test rigs were built between 1947 and 1953, and in the axial-flow compressor program, there was a strong emphasis on the accumulation of systematic experimental data supporting and extending the range of applicability of the "blade-element" design system. The blade-element design method, utilizing the radial equilibrium concept, might be considered a product of the NACA Compressor and Turbine (C&T) Research Division at Cleveland. While the radial equilibrium concept did not originate in the C&T Division, there is little question in our minds that the blade-element method was first developed there as a routine design tool and that its success was based on the accumulation of experimental linear cascade data in the Langley Laboratory and on the wide spectrum of data coming from rotor, stage and multistage test rigs in Cleveland. There is no doubt that the calendar years 1947 through 1955 could be called a "Golden Age" of axial-flow compressor aerodynamics in the NACA. Among its best-known products were the empirically-based blade-element compressor design system, the transonic compressor stage, and recognition of the principal features and problems of compressor off-design performance. The work of this period has been well-documented, both during and subsequent to the time in question. Example materials include Savage, Boxer and Erwin (1961), Lieblein and Johnsen (1961), Wilcox, Tysl, Hartmann (1959), Klapproth (1961), Serovy (1966) and Johnsen and Bullock (1965).[1]

By the end of 1955, it was becoming apparent that, for the time being, the zone of diminishing returns in axial-flow compressor work had been reached. In the following years, until 1958, fewer new stages were designed, fewer results were evaluated and correlated, and many of the C&T staff were dispersed to other research assignments and work inside and outside the NACA.

INITIATION OF NASA AXIAL-FLOW PUMP RESEARCH

The National Aeronautics and Space Administration (NASA) came into existence on 1 October 1958. NASA incorporated all of the laboratories and facilities of the NACA and in its own words, NASA (1959), was soon "rapidly shifting from research primarily on air-breathing power plants, to rockets—chemical, liquid propellant, nuclear and electrical." Nearly all of those still engaged in turbomachinery programs at the new NASA Lewis Research Center became members of the Fluid Systems Components Division, and "rapidly shifted" their attention to learning about "new" turbomachines such as centrifugal and axial-flow pumps. For

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[1] Documentation of some of the personalities involved in the work is less obvious. Mel Hartmann is remembered as a large, bear-like figure with a friendly and constant smile, in continuous lumbering motion between his desk and his test rig. Mel believed in rig data and its analysis. He was exhilarated by the building and operation of test rigs, new and old. He never met a data point that he did not like and use to best advantage.

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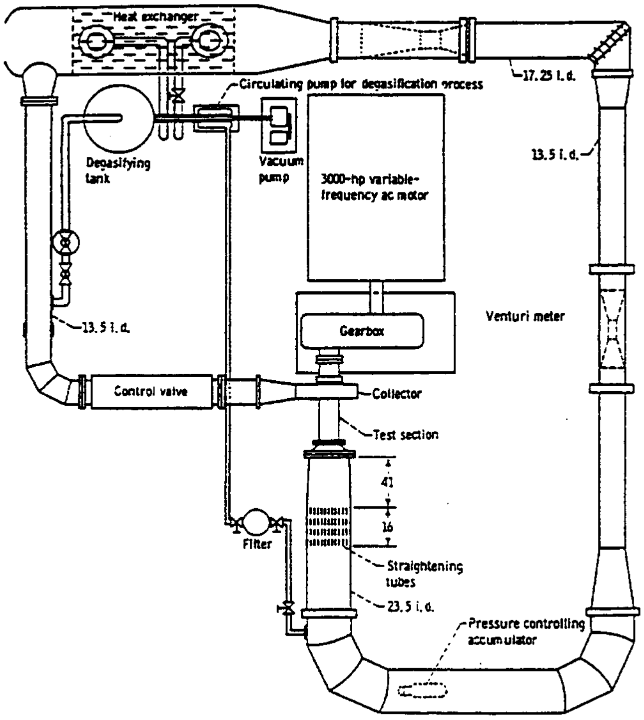

FIG. 1. SCHEMATIC DIAGRAM OF NASA-LEWIS WATER TUNNEL. (DIMENSIONS ARE IN INCHES)

axial-flow pump research, a water test loop was designed and built [Figure 1], an inducer test installation was developed and larger-scale hydrogen test facilities were constructed near Sandusky, Ohio (Plum Brook).

The design method developed at Lewis for experimental axial-flow pump rotors and stages was an incompressible flow version of the blade-element, quasi-three-dimensional compressor system. Early reports of the NASA work include Crouse, Montgomery and Soltis (1961) and Crouse, Soltis and Montgomery (1961). In fact, for most of the test configurations, design point blade selection was primarily based on the cascade correlations which had come from the NACA compressor program. This resulted in the continued use of double-circular-arc and 65-series blade section profiles and the possibility of comparison between cascade plane performance in water and air.

STATUS OF UNIVERSITY TURBOMACHINERY RESEARCH - 1958

Looking back toward the 1945-1958 time period, it is apparent that the European countries, particularly Germany and Switzerland, were moving rapidly in rebuilding and developing University teaching and research on turbomachinery fluid dynamics. In the United States, experimental research on axial-flow compressor aerodynamics reported then at MIT, Caltech and Johns Hopkins remains of interest today. Pump research related to naval applications was initiated at Penn State by George F. Wislicenus (1960).

In 1956 the textbook *Principles of Turbomachinery* by Professor D. G. Shepherd of Cornell University was published. This book had an influence which reached into universities, industry and research laboratories because it was well-organized and easily understood, and because it was an "American style" text with examples and problems. In addition, the book dealt with turbomachinery as a broad class of fluid machinery including fans, pumps, compressors and turbines.

George Serovy returned to Iowa State from NACA in 1953. He received a research grant from NACA in 1956 to study prediction of the performance of axial-flow compressors by blade-element methods. This was a one-man effort, directed toward goals including a doctoral dissertation and a NACA technical report. One of the elements of the project was the utilization of an IBM Model 650 digital computer, newly installed in the Iowa State Statistics Laboratory (Serovy and Anderson (1960)). In a report based on April 1956 discussions in Cleveland concerning the proposed grant, one of the participants was M. J. Hartmann, Head, Supersonic and Transonic Compressor Research Section of NACA-Lewis. During that same year a new course in the "principles of turbomachinery" was taught by Serovy at Iowa State. Shepherd's book was the first text used. The course has been offered each year from 1956 to the present and has involved numerous prominent guest lecturers. Students continue to be eager to learn about the application of fluid mechanics and thermodynamics to turbomachine design and analysis.

CONTRIBUTIONS TO THE NASA PUMP PROGRAM

Early in 1959 it was evident that the new NASA was, at least for the time being, not interested in sponsoring additional compressor performance prediction work at Iowa State. However, similar research directed at pumps and coordinated with the emergent Fluid Systems Components Division of NASA-Lewis was suggested and after a new proposal was submitted, NASA Headquarters awarded Grant NsG-62-60 to Iowa State in the amount of $11,430 for research beginning in February 1960 on "Application of Blade-Element Techniques to the Design and Performance Prediction Problems for Axial-Flow Pumps. This initiated a series of grants and extensions covering projects up to the last part of 1972. The work involved real cooperation and mechanisms for sharing the time of individuals at NASA-Lewis and Iowa State. Some abbreviated comments in the following subsections indicate what was done. Reference to a few retrievable reports, such as Kavanagh and Miller (1970), Kavanagh et al. (1970), Serovy et al. (1973) and Miller et al. (1973) should lead readers to more detailed technical documentation of the major elements of the 13-year effort.

DATA PLOTTING AND ANALYSIS

One of the activities supported at Iowa State by the NASA pump research group was plotting and preliminary analysis of passage survey data for a number of axial-flow rotors. Several undergraduate and graduate students were employed on a part-time basis, to hand plot the many sets of data associated with each rotor. While this was tedious and sometimes boring work, the plotting process did focus attention on trends and patterns in a way that is not likely to occur with current plotting and data presentation systems. Our best students were involved. They took their work seriously, studied the data in a critical sense and genuinely liked the idea that they were working on "real" research projects.

DEVELOPING A DESIGN SYSTEM DATA BASE

There was a strong sense within NASA that for non-cavitating performance situations, the design of high hub-to-tip diameter ratio axial-flow pump stages by the blade-element method would be successful. It was believed by all concerned that for constant-density fluids, steady-flow on axisymmetric stream surface approximations could be assumed. This meant that a radial-equilibrium condition could be used at axial stations upstream and downstream of each blade row.

Blade-element (cascade plane) profile, solidity and setting angle selection for design was based on correlation of experimental data from rotors, stators and linear cascades. There was some confidence that existing aerodynamic loading limits such as the Lieblein diffusion parameters, Johnsen and Bullock (1965), and Lieblein (1959), would be as effective in pumps as they had been in axial-flow compressors.

The radial-equilibrium condition used required experimental input in terms of correlations of deviation angle and loss parameter. These correlations generated radial distributions of blade-row exit angle and loss, which in turn permitted the computation of static head and velocities.

Considerable effort was devoted at both NASA-Lewis and Iowa State to comparing the emerging pump blade-element data with the best existing loss and deviation (turning angle) correlations from linear cascade and compressor experiments in air. Modifications were made independently at NASA-Lewis and at Iowa State. A computer code was written and tested by Kavanagh and Miller (1970) and Kavanagh, Miller and Serovy (1970) for axial-flow pump stage design.

PERFORMANCE PREDICTION USING BLADE-ELEMENT METHODS

At Iowa State, a major objective throughout the 1959-1973 period was to formulate and develop computer codes and supporting data correlations for non-cavitating axial-flow pump performance prediction. As the NASA-Lewis data appeared, it became obvious that while the NACA aerodynamic loading parameters (compressors) could be utilized as hydrodynamic loading parameters (pumps), the numerical limiting values could not be confidently transferred from compressor experience to pumps.

Furthermore, the NACA compressor-based loss correlations, which generally gave a loss parameter as functions of a loading parameter and radial location in the hub-to-tip plane, simply did not work. This influenced both design and performance estimation results conclusion was reached in the case of deviation angle, where the influences of axial velocity ratio across a blade row and incidence angle were difficult to accommodate. Consequently, a large fraction of the Iowa State work on performance prediction was devoted to studying the correlation problem and to use of the NASA rotor experiments as the base for comparison of potential improvements. An example of the type of loss correlation generated is shown in Figure 2.

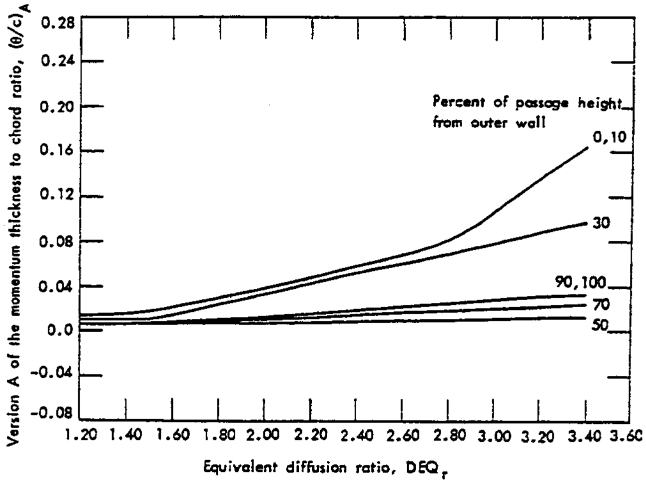

FIG. 2. LOSS CORRELATION CURVES DERIVED FROM EXPERIMENTAL DATA FOR NASA PUMP ROTORS IDENTIFIED IN TABLE 1, TAKEN FROM SEROVY ET AL. (1973)

At the conclusion of the Iowa State work, an axial-flow pump performance prediction program was reported by Serovy et al. (1973). This report included the correlation studies, the code structure and comparative results.

AXIAL-FLOW PUMP RESULTS - A FIRST LOOK

The conclusions reached in 1972 by the Iowa State group were positive. It was believed that we had, considering the limitations of the blade-element method and of the computing facilities available (IBM 350/65 System) then, done about as much as the existing data base would allow.

We certainly recognized that the correlation approach required more data, preferably from both linear cascade tests and a broader range of rotors and stages. The linear cascade experiments of Taylor, Murrin and Columbo (1969) were too new to be utilized, and the NASA test rigs were being phased out.

To end the Iowa State pump effort, we did believe that all of the NASA rotor data should be preserved in an archival document. Fortunately, we found that our NASA colleagues, D. M. Sandercock, W. R. Britsch, J. E. Crouse and most importantly M. J. Hartmann, agreed. The summary report, Miller et al. (1973) was the result. Table 1 shows for the record some design information about the NASA pump rotors. We remain very proud of this document because it represents cooperation in the ultimate research product, a carefully planned and written report of good test rig work.

REEMERGENCE OF THE AXIAL-FLOW COMPRESSOR AS A RESEARCH FOCUS

Although a small axial-flow compressor research effort existed within NASA-Lewis between 1958 and 1964, it was confined to

TABLE I. NASA AXIAL-FLOW PUMP ROTOR DESIGN DATA TAKEN FROM SEROVY ET AL. (1973)[A]

NASA configuration number	Tip diameter, inches	r_h/r_t	Number of blades	Blade section profile [b]	Blade chord length,[c] inches	Radial tip clearance,[d] inches	Design tip section D-factor	Design point flow coefficient	Minimum blade chord Reynolds number
*02	9.0	0.4	16	DCA	1.5	0.013 - 0.020	0.23	0.293	1.0×10^6
*07	9.0	0.7	19	DCA	1.5	0.005 - 0.012	0.43	0.294	1.5×10^6
09	9.0	0.7	8	DCA	3.04	0.013 - 0.020	0.46	0.294	3.0×10^6
*5	9.0	0.8	19	DCA	1.5	0.015 - 0.017	0.66	0.466	1.5×10^6
6	9.0	0.8	19	DCA	1.5	0.025 - 0.027	0.66	0.466	1.5×10^6
8	5.0	0.8	19	DCA	0.834	0.007 - 0.009	0.66	0.466	8.0×10^6
9	5.0	0.8	19	DCA	0.834	0.015 - 0.017	0.66	0.466	8.0×10^6
10	5.0	0.8	19	DCA	0.834	0.022 - 0.024	0.66	0.466	8.0×10^6
*13A	9.0	0.85	33	DCA	1.172	0.009 - 0.011	0.72	0.5	1.0×10^6
*14A	9.0	0.9	19	DCA	1.5	0.009 - 0.011	0.63	0.7	1.5×10^6
15	9.0	0.8	19	DCA	1.5	0.009 - 0.010	0.55	0.466	1.5×10^6
16	9.0	0.85	33	CUBIC	1.172	0.009 - 0.011	0.72	0.5	1.0×10^6

[a] All rotors were tested without inlet guide vanes and downstream stator blades. Data are presented in Miller et al. (1973)

[b] DCA indicates a DOUBLE CIRCULAR ARC blade section profile.

[c] All blade chord lengths were uniform along the blade span.

[d] The range of circumferential variation of radial tip clearance is indicated.

*Rotors used for obtaining loss and deviation angle correlations.

specific applications. However, during 1964 there was a realization that serious and challenging problems remained in development of turbomachinery of aeronautical air-breathing propulsion systems, and that these problems were endangering the position of leadership held by the United States in the production of both military and commercial aircraft turbine engines. Several sets of proposals were solicited by NASA-Lewis for external research on axial-flow compressors, including development of design and analysis computer codes, and design and testing of families of transonic stages and special blade profile geometries. This was a radical change from the 1947-1958 program because now much of the work was to be done by industrial contractors.

AXIAL-FLOW PUMP RESULTS - A SECOND LOOK

From a 1993 viewing point, the first thing evident is how much our understanding of turbomachine flows has improved. A second conclusion might be that, considering progress in computation hardware and in measurement systems, we should understand more and in greater depth.

The pump configurations tested after 1958 probably do not have much application outside the liquid-propellant rocket field. That they have application there is evident by such papers as Huppert and Rothe (1970) and a look at a cross-section of typical high-thrust, hydrogen turbopumps.

The differences between blade-element operation in pumps and compressors were understood to be due to the dominant end-wall and other secondary flows in the high hub-to-tip ratio, low aspect ratio pump stages. Reynolds number levels in the pump tests were known to be greatly different from those in much of the compressor-related data. It would be interesting to see how well current CFD codes predict the flows measured 25-30 years ago.

OTHER RESULTS

The NASA-Iowa State pump work motivated considerable local interest in fluid dynamics problems related to propulsion that extended far beyond the primary sponsored projects already mentioned. Thesis and dissertation research at both the M.S. and Ph.D. levels completed during the "pump years" include.[2]

J. L. Hall - Combustion-related shock tube studies
F. B. Hamm - Computation of duct flow using streamline-curvature method
B. L. Johnsen - Analysis of fluid transfer line dynamics
P. Kavanagh - Computation of linear cascade flows
J. C. Lysen - Computation and measurement of compressor inlet flows
M.-J. Miller - Deviation angle prediction
T. H. Okiishi - Velocity profile development in annular passages
C. R. Pullen - Failure of radial-equilibrium solutions
M. D. Smith - Measurement of flow in curved diffusing passage

Subsequent to the NASA pump research years at Iowa State, other organizations funded work on turbomachine fluid dynamics there. Sponsors include the U. S. Air Force Office of Scientific Research, the U. S. Air Force Aeropropulsion Laboratory, GE Aircraft Engines, the Allison Gas Turbine Division of General Motors and Textron Lycoming. Over the years, NASA support of a variety of turbomachine related fluid dynamics studies also continued. Some examples of the archival journal articles that resulted from this latter effort are listed in the References under the following authors:

Delaney and Kavanagh 1976
Hansen and Okiishi 1989
Hansen, Serovy and Sockol 1980
Miller and Serovy 1975
Schmidt and Okiishi 1977
Serovy and Okiishi 1988
Tweedt, Okiishi and Hathaway 1986
Wagner, Okiishi and Holbrook 1979
Wisler, Bauer and Okiishi 1987
Zierke and Okiishi 1982

An outstanding outcome of the research work described in this paper is the significant number of former students who are now prominent in the turbomachinery business. Mel Hartmann's positive influence on the Iowa State University turbomachine fluid dynamics program during its inception and formative years led to the placement of important contributors to the continuing advancement of turbomachine technology.

NOMENCLATURE

D = diffusion parameter defined in Miller et al. (1973)
DEQ_r = equivalent diffusion factor defined in Serovy et al. (1973)
$(\theta/C)_A$ = blade wake momentum thickness to chord ratio defined in Serovy et al. (1973)
r_h/r_t = ratio of rotor inlet hub radius to tip radius (radius measured from pump rotational axis)

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[2] Mel Hartmann supported some of this work with NASA funding. Some he tolerated as a source of data of possible future use. Some developed because he mentioned other possible contacts in NASA-Lewis. When we visited Cleveland, he usually asked us to visit his office at the end of the day. For those who knew of his Nebraska background, it will not be surprising to learn that his first words were seasonally, "How's the corn?" or "How is the snow cover?" He always kept a drawing board in his office, and often could be found checking a rig drawing. His comments were without exception, constructive and encouraging. We hope that we made a useful contribution to the NASA pump program, in keeping with the influence that he had on our lives and professional development.

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