1N-29189

NASA Technical Memorandum 88853

Advanced Instrumentation for Aeronautical Propulsion Research

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Prepared for the
Symposium on Propulsion Instrumentation
cosponsored by the National Aeronautics and Space Administration and
the Chinese Aeronautical Establishment
Jiangyou, People's Republic of China, October 6–10, 1986

NASA

E-3244

ADVANCED INSTRUMENTATION FOR AERONAUTICAL PROPULSION RESEARCH

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INTRODUCTION

Civil aeronautical systems have reached a very high level of performance and functional capability. A large transport aircraft achieves some 80 passenger seat miles per gallon of fuel. It is projected that continued advances will result in a two- or three-fold increase. This and our ever increasing desire for higher speed and longer range transports require that aeronautical propulsion systems continue to improve. Further advances, in terms of performance, decreased weight, improved durability, and maintainability of these already highly developed systems will require a substantially greater understanding of the physical phenomena that limit advances. A much more complete and detailed understanding of the aerothermal environment, the steady and unsteady interaction between the flow and structures, and the deflections, loads, and stress must be made available if we are to achieve the necessary advances.

Advances to date have been achieved by an increased ability to measure and analyze the overall processes and by the increased intuitive capability of the propulsion technologists. Continued advances are dependent on extending this understanding of the limiting physical process and on controlling or extending the limits. A portion of this can be achieved by the detailed numerical modeling of the physical processes possible with our major scientific computers. But key to our reliance on such computer-based information is our ability to validate it with physical measurements of a comparable level of detail. The instrumentation and measurement systems must continue to advance to meet these needs.

The technologist's intuition is an important ingredient to the overall knowledge base. No one calculation is "exact." No one measurement is "exact." Decisions as to how to advance the technologies are based on the <u>total information</u> available to the technologists.

This overview of the levels to which aeropropulsion research uses advanced instrumentation indicates, to some extent, the manner and some of the changing requirements necessary for this advancement. Examples of the application of instrumentation and measurement systems in several areas of aeronautical propulsion research are also included.

INSTRUMENT RESEARCH AND ADVANCEMENT

The Increasing Need

As propulsion systems have advanced, the requirements for greater instrumentation capability have increased. The need for higher and broader ranges of temperature, pressure, stress, and deflection illustrate this growth. Machinery utilizing higher rotational speeds and the ever wider range of dynamic measurements must be considered. Nonintrusive measurement methods must be devised to avoid destroying or changing the physical process involved. In some cases, massive amounts of data must be obtained and processed, impinging on expensive test time.

To develop high confidence in a numerical model, physical measurements must be taken at a level of detail that is comparable to that derived in the calculation. Overall measurements are not sufficient to validate a numerical model. It should also be pointed out that under various operating conditions or flight modes, different physical conditions may limit performance or system suitability. This may occur due to different aerothermal conditions, unsteady or resonant conditions, etc. Thus, fairly extensive detailed physical measurements are necessary to validate all aspects of a computer-based numerical simulation.

Aeronautical propulsion systems have been extended to the point where components must operate near or, briefly,in an unsuitable region. These operating conditions may be very close to real limits; for example, stressed elements that are partially in the plastic range, or metal parts with local temperatures beyond melting conditions, or a portion of a blade row vibrating in a resonant mode. Instrumentation needs to be more precise or comprehensive to detect such conditions.

As aeropropulsion systems have advanced and become more complex, the needs and capabilities of instrumentation and measurement systems have also increased. Overcoming or circumventing limiting phenomena to advance propulsion systems requires a detailed understanding of the physical phenomena involved.

The Approach

The advantage to be obtained by more advanced instrumentation is recognized by aeropropulsion technologists from all disciplines. Generally, they see that the limitations of current aeropropulsion systems cannot be overcome with the existing level of knowledge. Further, the detailed measurements needed to validate analytical models or to extend the technologist's empirical knowledge and intuition cannot be obtained with current instrumentation and measurement systems. As a new instrumentation system evolves, it is applied in a series of steps that lead to larger facilities and more realistic propulsion system environments. The requirements for advancing new instrumentation systems may be met by activities in a number of areas (noted in fig. 1). Factors such as stability and calibration and sensitivity must be explored in the physics or instrumentation laboratory or extracted from the literature. Bench tests must be conducted to determine the suitability of sensors and related components.

Once the instrument and the measuring systems have been mated, laboratory and component tests are possible. At this point suitable data recording and reduction systems must be available to provide researchers with usable information. The use of new instrumentation systems in major facilities, such as wind tunnels or engine test stands, may subject the system to new or more severe problems, such as high temperatures and pressures, as well as noise and vibration conditions. Even more limiting and severe operating conditions are usually encountered in propulsion system developments. Such activities are obviously the responsibility of the companies involved in the development of aeronautical propulsion systems.

Technologists working in all aeronautical propulsion program areas want to know more than existing measurement systems, accepted analytical methods, or their acquired intuition can tell them. Many contribute more directly to the development of advanced instrumentation systems (fig. 2). Physicists and instrumentation engineers play a major role in identifying suitable and available advances. Electronics and computer engineers may provide innovations in making new systems perform additional tasks. Component and propulsion system technologists certainly continue to look for new ways to achieve additional measurements. Test and operational engineers are faced with utilizing new measuring devices in a hostile or costly environment. Engineers responsible for the design and construction of hardware are concerned not only for more information but also for how the instrumentation can be accommodated in the hardware. Thus, as may be expected, improvements in instrumentation systems may be pursued and applied by technologists in virtually every phase of aeropropulsion research and development.

In fact, the necessary research to advance instrumentation and measuring systems is, itself, highly interdisciplinary. The following sections indicate the some of the propulsion research activities in which advanced instrumentation is used.

INSTRUMENTATION LABORATORY AND BENCH TEST ACTIVITIES

Aeronautical propulsion research requires a broad range of instrumentation systems (some are shown in fig. 3). We must have a detailed understanding of the aerothermal environment throughout the propulsion system in terms of the pressure, temperature, and flow conditions. Strain and vibration information on the various components must be measured under realistic conditions. In some cases clearance measurements between stationary and rotating parts are needed. Exhaust emissions or noise measurements may be necessary to design advanced components for propulsion systems as well as to evaluate their environmental suitability. Sensors for steady and dynamic condition measurements are required. These sensors must not interfere with the physical process being measured and thus must be minimal-intrusive or nonintrusive systems. Because of the quantity or detail of the data being taken, automated recording and evaluation systems are necessary. Advanced instrumentation systems are integrated with these computational systems.

A substantial number of evolving instrumentation systems are based on the use of lasers. One such system is the laser anemometer which is used for measuring the radial component of flow in axial-flow turbomachinery (fig. 4). This system uses a Fabry-Perot interferometer for directly measuring the frequency of the Doppler-shifted, backscattered light. The time-varying shock structure in turbomachinery blading may be visualized through the use of a holographic cinematography system (fig. 5). (The use of this system in a transonic cascade will be illustrated in a later section.) Bench test evaluations of such systems must be conducted to establish the light path, system sensitivity, etc.

A number of laser-based systems have been developed for obtaining detailed measurements of the structural modes of propulsion system components. A system for measuring the complex vibrational mode shapes of advanced propeller blades has been developed on the light bench and used in a number of cases (fig. 6). It has also been used to obtain the mode shapes associated with the interacting structures of a bladed fan rotor (fig. 7). The overall fan blade may have been subjected to the excitation, and the attachment was adjusted to more nearly represent the effects of the centrifugal loads experienced by a fan in operation. All of these laser-based systems involve extensive computer hardware and software to process the information for the instrumentation and research technologists.

LABORATORY AND COMPONENT RESEARCH ACTIVITIES

Only two of the wide variety of advanced instrumentation applications in laboratory and component research will be illustrated. The first is the measurement of unsteady pressure and flow visualization in a transonic cascade in which the blades can be rotated about the midchord position. The assembly of hardware to obtain and control the light path is especially rugged and made movable so that it can be placed adjacent to the major air piping and experimental hardware (fig. 8). The installation shown can obtain flow visualization information by holographic cinematography of the cascade blades (fig. 9). The cascade blades are rotated about the central axis by a device that provides a sinusoidal motion with precise blade relationships. The blades are instrumented with dynamic pressure measuring transducers at several chordal positions. The dynamic pressures and the flow visualization are used to determine the aerodynamic forces that may result in the stabilizing or destabilizing of the oscillating blade motion.

The holographic motion pictures provided insight to the shock motion during transonic flows (fig. 10). Similar studies involving a schlieren visualization system were used to indicate the effect of leading edge flow separation as the vanes were oscillated (fig. 11). The researchers utilized all of the measurement systems available to them to develop the necessary understanding of the major effects on dynamic moment coefficients in the transonic cascade. Some comparisons of the calculated and measured coefficients were also be obtained (fig. 11).

The determination of turbine vane temperature and heat-transfer coefficient is the second example of the application of a number of instrumentation and measurement approaches. Data have been obtained in high-temperature turbines with photoelectric scanning systems (fig. 12). In the case shown, on one blade a chevron-shaped ceramic coating was applied to provide special resolution. Typical temperature profiles are shown by scans at various radial positions. The chevron pattern is noted by a lower temperature due to the lower surface emittance in the coated area. A temperature profile for radial position 3 is shown in the figure. A similar photoelectric scanning system was used along with a number of other measuring systems in a hot-section test (fig. 13). Although the hot-section test facility was equipped to include turbine rotors, the setup is shown with only the nozzle vanes installed. Thin-film thermocouples were installed on the vanes and, in conjunction with gas-temperature measuring devices, were used to measure dynamic temperatures as the burner fuel was varied. Local heat-transfer coefficients on the vane surfaces were determined from the dynamic gas and metal surface temperatures thus obtained (fig. 14). Steady-state heat flux gauge measurements were also taken at several points along the vane surface. The various values of heat-transfer coefficient were compared with values predicted by the STAN5 code (developed at Stanford University). Although the scatter in the data is quite large, the general trend is in agreement with the prediction.

Of some interest are the two points of dynamically determined heat flux at slightly more than 0.35 of the distance from the leading edge. These measurements are from two different vanes and, since at other Reynolds number and temperature test conditions the agreement was much better, it is presumed that at this test condition the flow may have been different on the two vanes (perhaps the position of boundary-layer transition or circumferential variations occurred upstream of these two vanes). Thus, the turbine technologist has used several instrumentation approaches to improve his understanding of the factors affecting turbine vane temperatures.

The research activities in the laboratory and component areas are substantially enhanced by the advanced instrumentation illustrated. The instrumentation must be designed to withstand the working conditions and environment existing in the component test areas. In many cases the temperature and pressure conditions are more severe and increased vibration and stresses may be encountered as compared with those experienced in the instrumentation laboratory. The technologist uses a variety of measurement systems to extend his understanding of the physical conditions.

MAJOR FACILITY AND ENGINE TEST ACTIVITIES

As advanced instrumentation systems become available, they are adapted for the environment of the major aeronautical facilities, such as wind tunnels and engine test stands. Generally, the operating costs of these facilities are relatively high so it is necessary to limit the operating time. Either fewer readings or more rapid data-taking methods may be necessary. These facilities provide more realistic operating conditions and component interactions and allow the study of off-design and nonuniform flow conditions. A large number of measurements are necessary to characterize these nonuniform operating conditions. Nonuniform aerothermal conditions, along with manufacturing tolerances, can result in locally destructive conditions. As an example, a fan may have some 30 or 40 individual blades inserted into a disk. Reasonable variations in the machining tolerances of the blades and the attachments may be such that only some of the blades may flutter or respond destructively to aerodynamic disturbances. The impracticality of installing strain gauges on each blade spurred the development of a photoelectric scanning system. This system can reveal the vibrational activity of each blade (fig. 15). In this system a number of fiber optic bundles are located in the casing at various axial distances over the blade. The reflected light is passed through photomultipliers to the computer system where the signals are compared with the signal obtained from the shaft position. Then the vibrational activity of each blade is displayed for the operator. Thus the engine could be operated near to or for short periods of time into troublesome areas of aeroelastic activity.

Even with such advanced measurement techniques, the instrumentation required on an experimental engine is extensive. The energy efficient experimental engine appears relatively clean when shown installed with a certain amount of cowling (fig. 16). A picture taken during the installation phase (fig. 17), however, shows the pressure, temperature, strain, and position indicating systems to be truly extensive. Many tubes and wires are mounted on the external housings and on the internal flow path. Even when prepared for the core engine test only (fig. 18), a very large number of instrument sensors were installed. The artist's drawing showing the components and flow paths within the engine (fig. 19) illustrates some of the concerns that must be addressed and measured. The performance of the inlet acoustic treatment depends on the field generated by the fan at certain critical operating conditions. The operation of turbomachinery is sensitive to radial and circumferential flow variations that must be known to optimize the design. These must be established at many axial stations throughout the machine. As noted previously, a large number of structural measurements are necessary to determine the durability and establish the useful life of the components. Combustor temperature distributions and pattern factors vary with operating conditions. The energy efficiency engine involved a mixer which must perform suitably to achieve the high exhaust thrust coefficient along with low exhaust noise performance. The large number of components and variables result in a very large number of measurements when an experimental engine is instrumented. Further complexities are encountered when an engine system requires testing in a wind tunnel or altitude test facility. Engine vibrations and temperature environments also contribute to the instrumentation difficulties involved in the design and test of experiment engines.

High-speed propeller models have been tested in the Lewis transonic wind tunnel (fig. 20). The tunnel test section is ventilated to the surrounding chamber by the many holes in the walls so that tests can be conducted through the transonic region. Two-foot propeller models were mounted on a centerbody and driven by air turbines supplied through the pylon from the top of the tunnel. Instrumentation leads were passed through the pylon or through the instrumentation survey device. Some of the usual flow measurement instrumentation can be seen. Because of the multitude of survey measurements required, considerable effort was made to read flow direction and as many flow parameters as possible on the same survey device (fig. 21) to avoid excessive tunnel operating time. Velocimeter measurements (fig. 22) were taken to obtain flow details within the rotating propeller as well as in the regions where the flow Mach number was so close to sonic that any sensor placed in the flow field would disturb it. The laser equipment and most of the equipment to establish the necessary light path were located in the chamber outside of the test section, with the light path extending through the tunnel viewing windows (fig. 23). The test section is ventilated to this chamber and thus the chamber pressure is reduced to the static pressure of the test section. The laser was enclosed and kept at atmospheric pressure to obtain suitable performance. The flow velocities obtained by the velocimeter were converted to velocities relative (fig. 24) to the rotating blades and displayed in color graphics form following the test.

The overall aerodynamic field measurements and the laser velocimeter measurements near and within the propeller blades were further supplemented by a rotating force balance (fig. 25) which measured overall thrust. In addition blade surfaces were painted so that surface flows and shocks could be observed. In some runs tufts were mounted on the blades to further illuminate flow conditions. Thus, the propeller technologist has used a variety of advanced and conventional instrumentation systems to obtain information. Thus methods now exist to develop and validate some detailed flow computational models as well as to provide information that extends the technologists intuitive feel for flow conditions that effect the propeller.

Blade deflections at operating conditions were indicated by the use of grid sections laid out on the hub (fig. 25). When viewed with a stroboscopic light synchronized with the blade passing frequency, these grids indicated the extent of blade angle change during propeller rotation. A laser light system (fig. 26) was used to determine when blade flutter was encountered and to measure blade deflections. These detailed measurements are necessary to develop and validate computational models for structural mode and flow predictions as well as to determine and verify aeroelastic analysis models.

The use of advanced measurement systems in engine test facilities and wind tunnels has greatly enhanced the amount and quality of information available to the research engineers. Most often, the advanced instrumentation has been closely mated to sophisticated, new data reduction and acquisition systems. Not only has this combination allowed far more detailed data, but also it has allowed us to reduce the cost of test operations and to monitor conditions that could substantially reduce the life of research hardware. Further, many of the new instrumentation and measurement systems have been adapted for use in existing research facilities and with conventional instrumentation and measurement systems.

SUMMARY REMARKS

This discussion of instrumentation for aeronautical propulsion research indicates the advancing needs, the areas, and the disciplines involved in instrumentation research. The manner in which instrumentation is used to advance the researcher's understanding of limiting phenomena and the detail required to develop and verify numerical aerothermal and structural simulations is noted. The following summary remarks (fig. 27) are presented:

Advanced instrumentation and measurement systems are key to extending the researchers understanding of the various physical phenomena that limit the advancement of aeropropulsion systems.

The needs and requirements of instrumentation systems continue to increase as propulsion systems are advanced. In particular, more detailed information is required to continue the advancement of propulsion systems. The environment and the difficulty encountered in acquiring the physical measurements also have become more severe.

Research to advance instrumentation and measurement systems is very much a multidisciplinary activity. The need for and the feasibility of systems may be recognized and the research pursued by technologists in all phased of aeropropulsion research. Successful systems generally require research by virtually all disciplines of the physical sciences.

The need continues for more detailed physical information to develop and verify the numerical models required for computer-based studies. To effectively validate numerical models, physical data must be at a comparable level of detail.

As new advanced instrumentation is applied in research facilities, it is generally used in conjunction with conventional instrumentation. The research engineer obtains useful physical information by any means available. One system generally does not provide all of the desired detailed information.

APPROACH TO NEW INSTRUMENTATION AREAS OF ACTIVITY AND APPLICATION

- INSTRUMENTATION OR PHYSICS LABORATORY
- BENCH TESTS OF SENSORS AND RELATED ELEMENTS
- LABORATORY AND PROPULSION COMPONENT FACILITIES
- MAJOR FACILITY AND/OR ENGINE TEST FACILITIES
- DEVELOPMENT PROGRAMS

SUCCESSFUL PROPULSION RESEARCH INSTRUMENTATION AND MEASUREMENT SYSTEMS REQUIRE ACTIVITIES IN A WIDE RANGE OF LABORATORIES AND FACILITIES

Figure 1

DISCIPLINES OF TECHNOLOGISTS CONTRIBUTING TO ADVANCEMENT OF INSTRUMENTATION

- PHYSICISTS AND INSTRUMENTATION ENGINEERS
- ELECTRONICS AND COMPUTER ENGINEERS
- COMPONENT AND PROPULSION SYSTEM ENGINEERS
- TEST FACILITY OPERATIONS ENGINEERS AND TECHNICIANS
- DESIGNERS OF RESEARCH AND PROPULSION HARDWARE

PROPULSION INSTRUMENTATION MAY ORIGINATE WITH OR INVOLVE A WIDE RANGE OF TECHNOLOGISTS

Figure 2

ADVANCED INSTRUMENTATION FOR PROPULSION RESEARCH

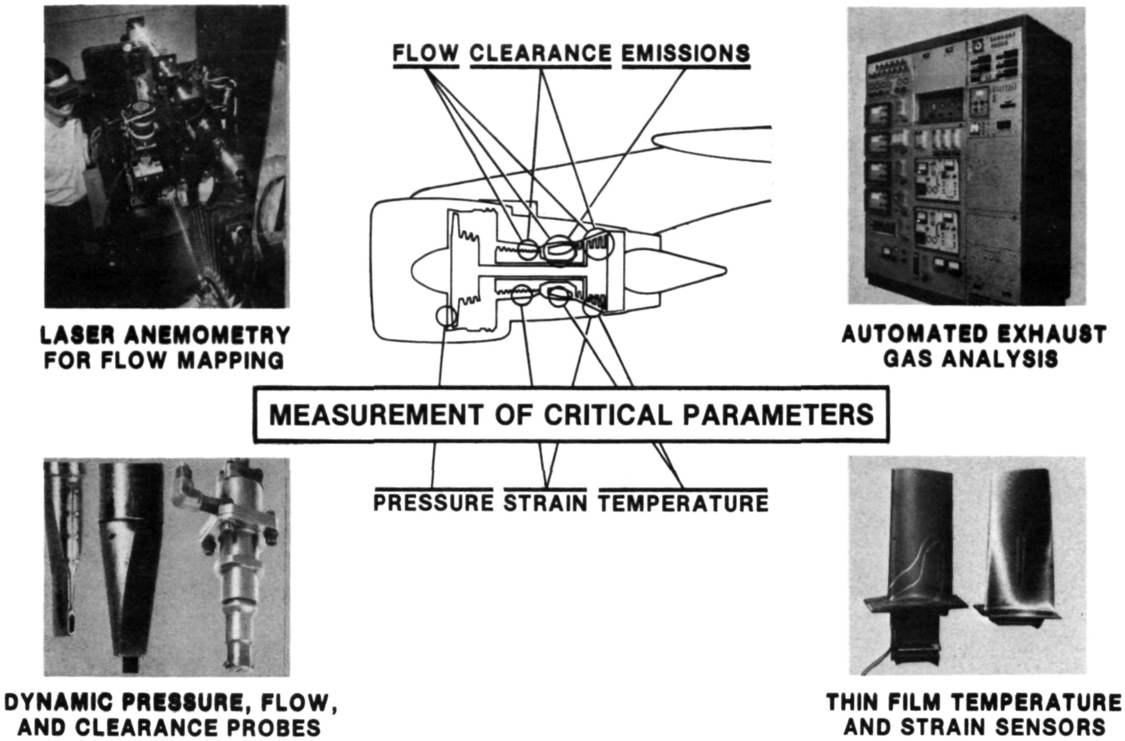


Figure 3

LINE-OF-SIGHT LASER ANEMOMETER FOR MEASURING RADIAL COMPONENT OF FLOW IN AN AXIAL-FLOW MACHINE

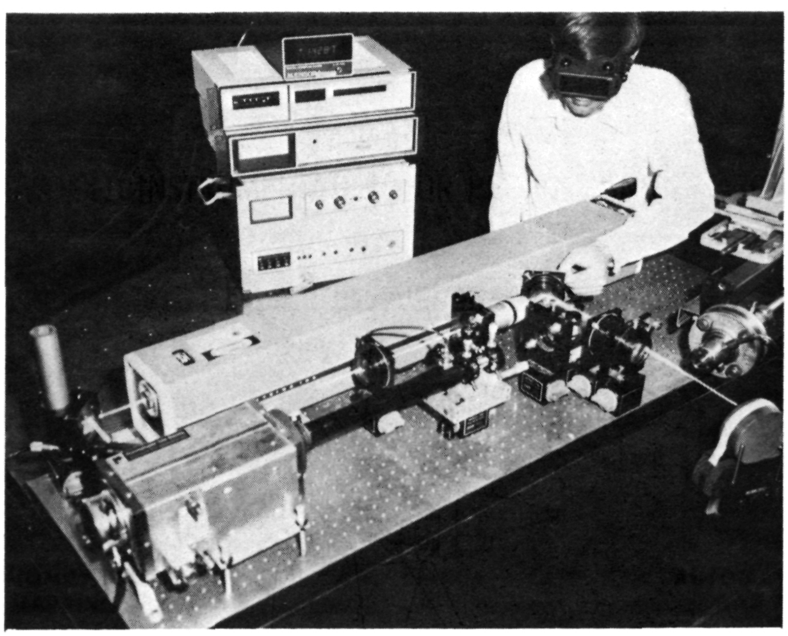


Figure 4

HOLOGRAPHIC MOTION PICTURE SYSTEM

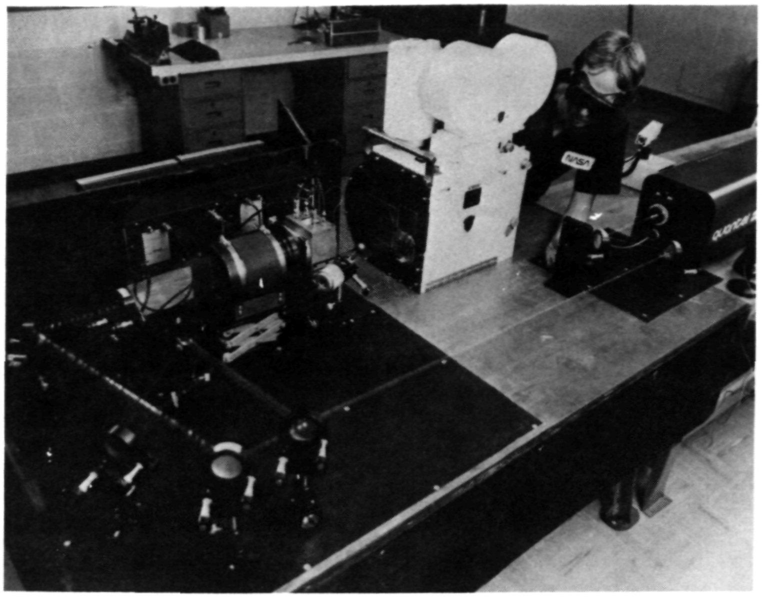


Figure 5

HOLOGRAPHIC SETUP FOR STUDY OF PROPELLER BLADES

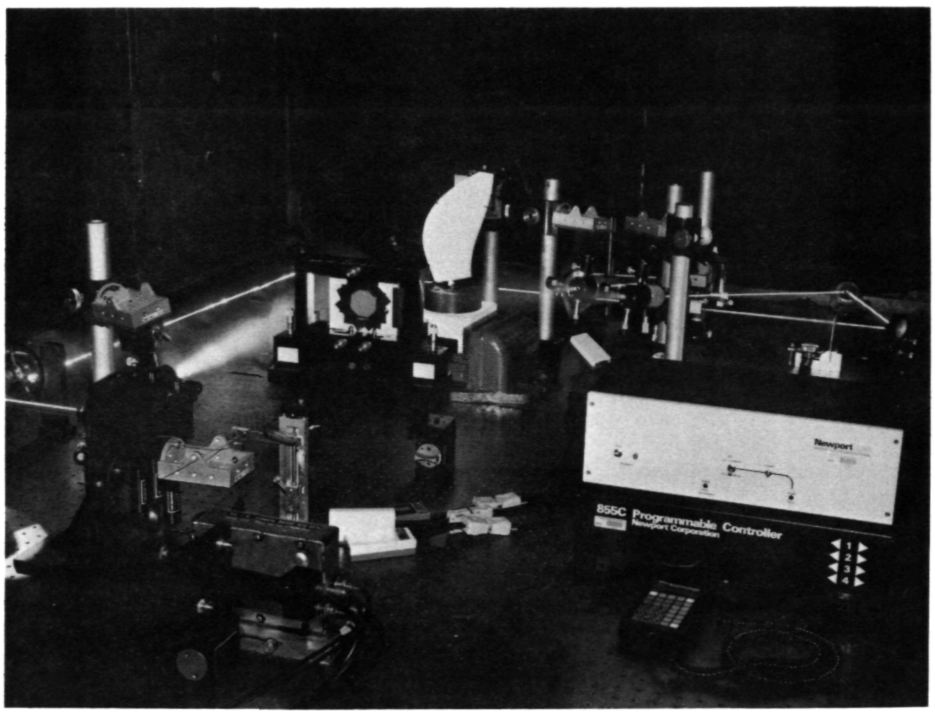


Figure 6

HOLOGRAPHIC CINEMATOGRAPHY SETUP WITH TRANSONIC CASCADE

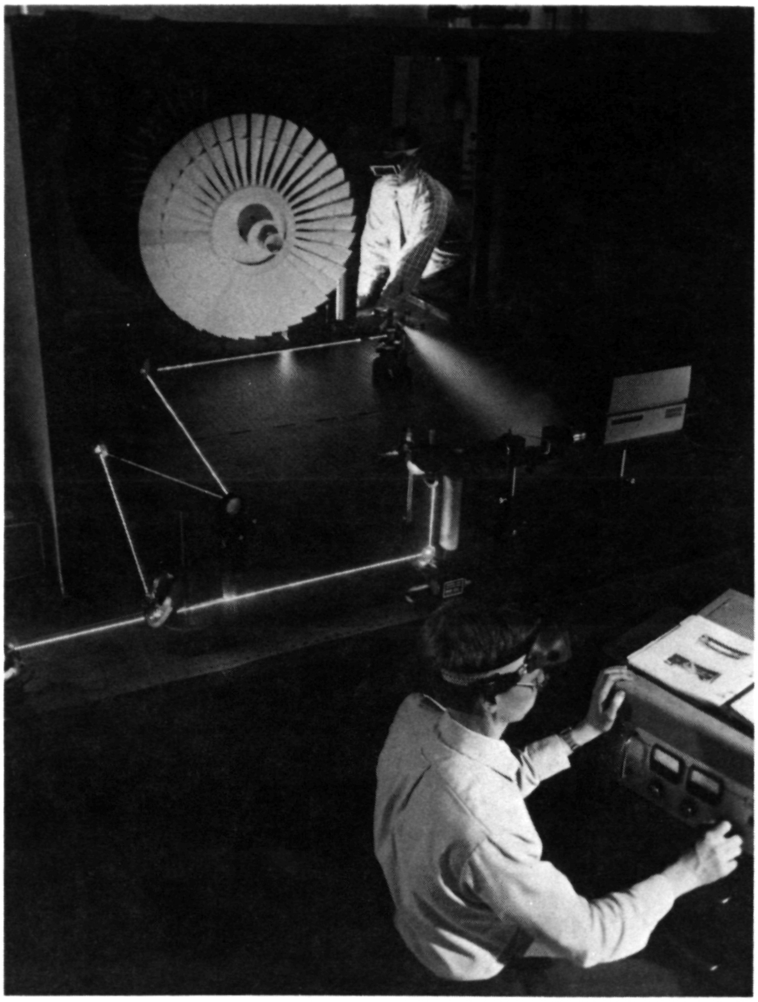


Figure 7

HOLOGRAPHIC CINEMATOGRAPHY SETUP WITH TRANSONIC CASCADE

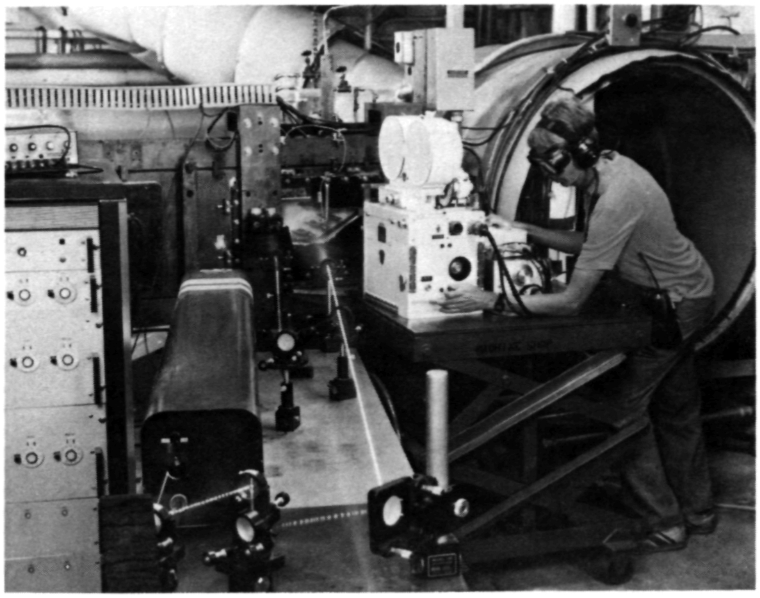


Figure 8

HOLOGRAPHIC MOTION PICTURE RECORDER IN TRANSONIC CASCADE

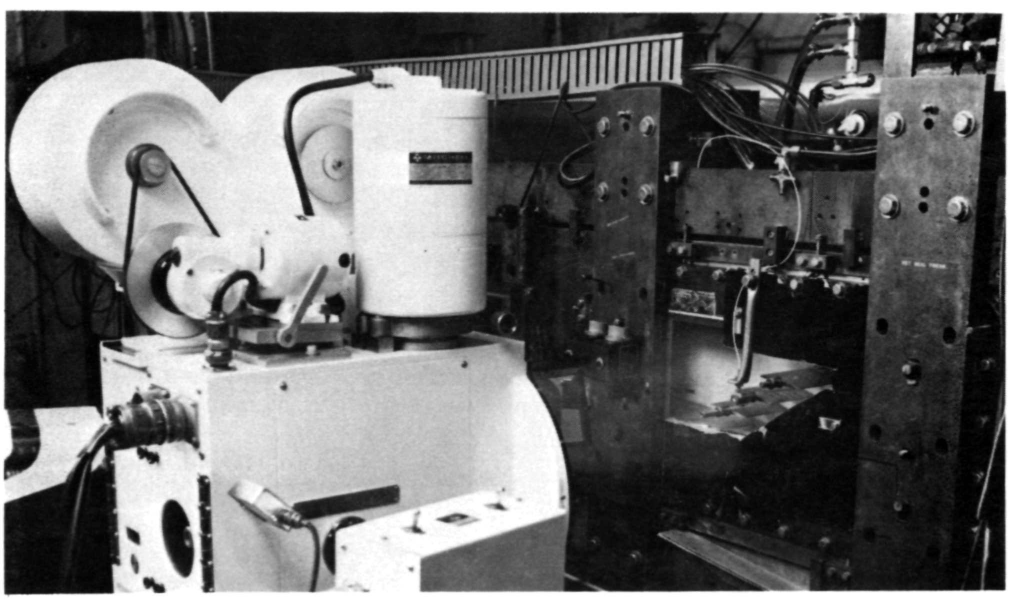
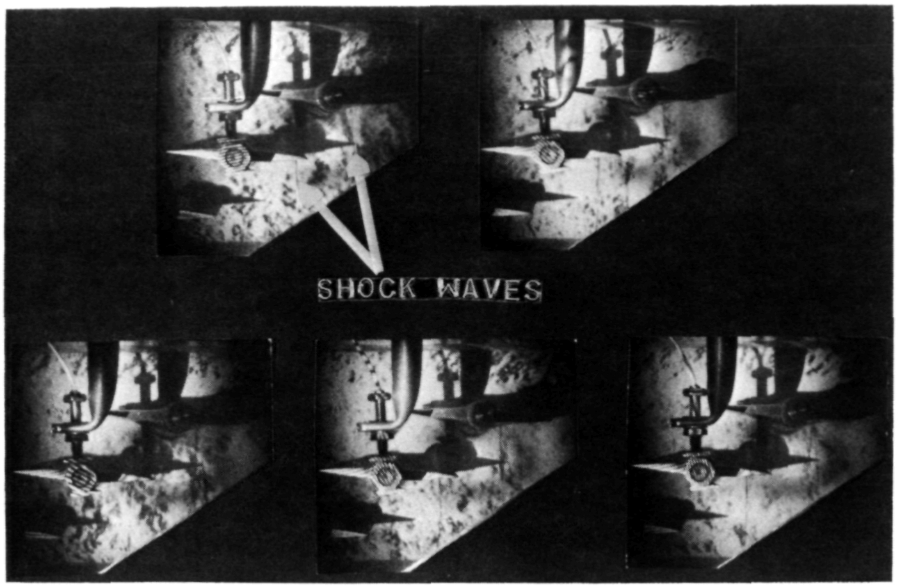


Figure 9

FIVE FRAMES FROM HOLOGRAPHIC MOVIE OF FLOW IN FLUTTER CASCADE



ALL AT CONSTANT ANGLE OF ATTACK

Figure 10

AIRFOIL UNSTEADY MEASUREMENTS IN A TRANSONIC OSCILLATING CASCADE

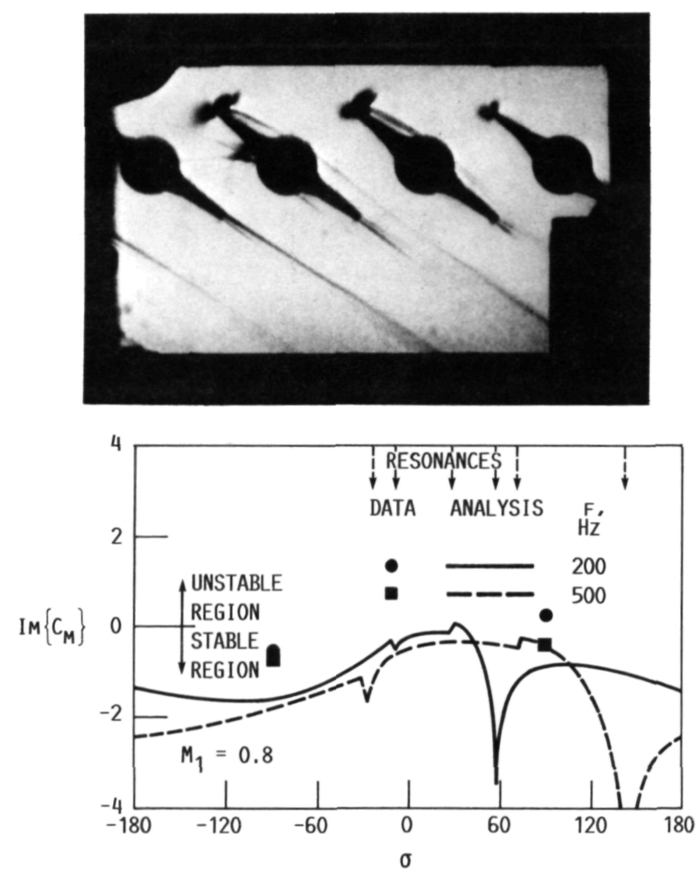


Figure 11

TURBINE BLADE TEMPERATURE RECORD

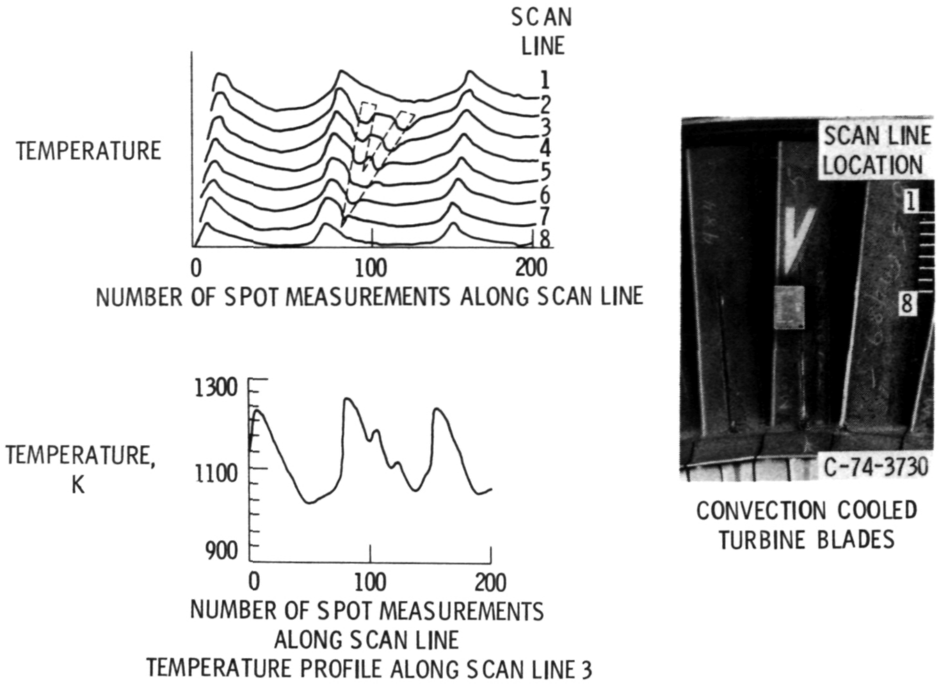


Figure 12

CASCADE CROSS-SECTION

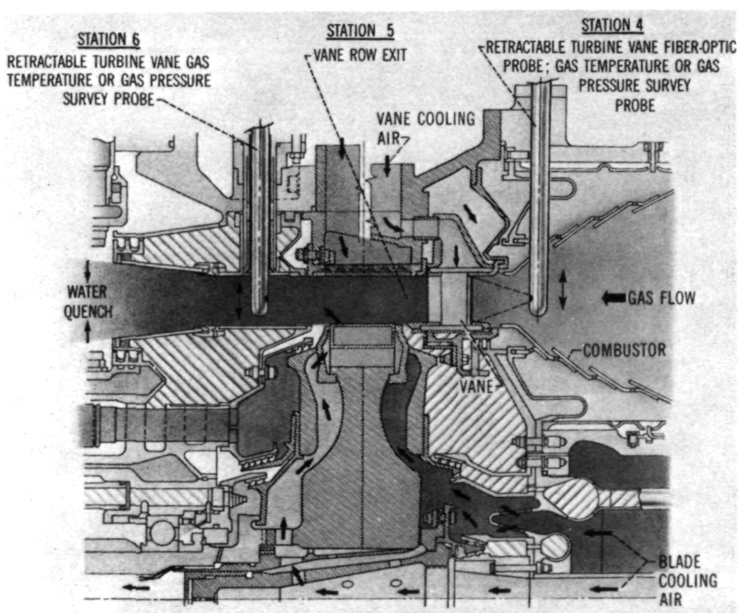


Figure 13

HEAT TRANSFER COEFFICIENTS FROM DYNAMIC SIGNAL ANALYSIS

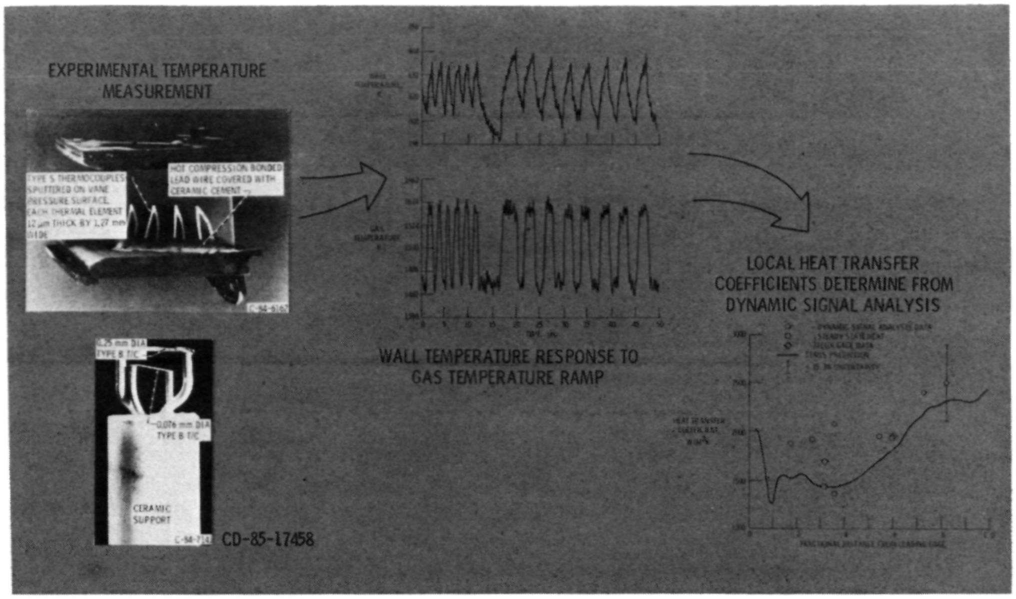


Figure 14

PHOTOELECTRIC SCANNING SYSTEM (PES) ELEMENTS

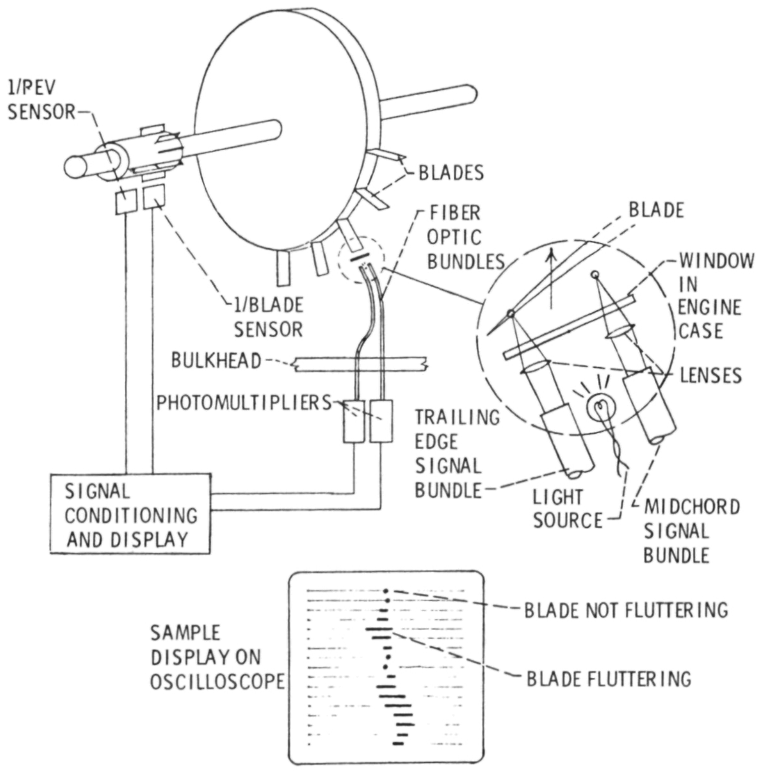


Figure 15

ENERGY EFFICIENT ENGINE ON STATIC TEST STAND

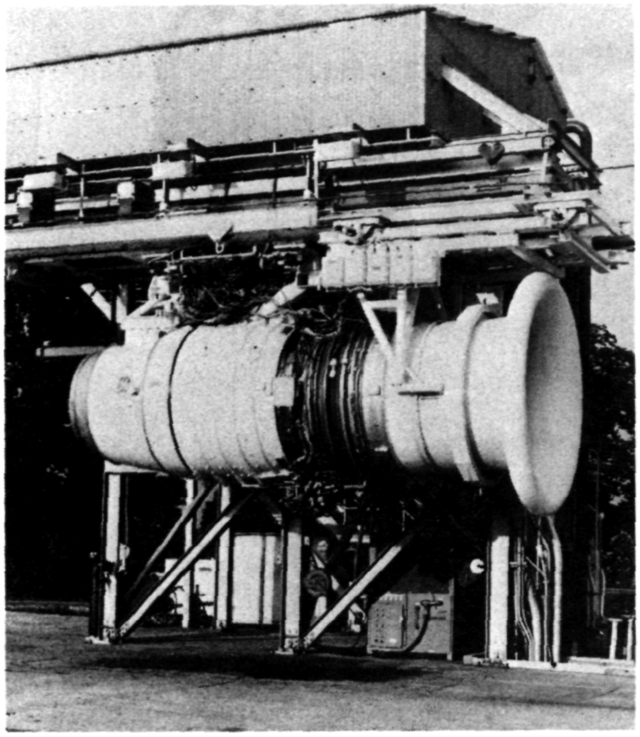


Figure 16

INSTRUMENTATION INSTALLED ON ENERGY EFFICIENT ENGINE

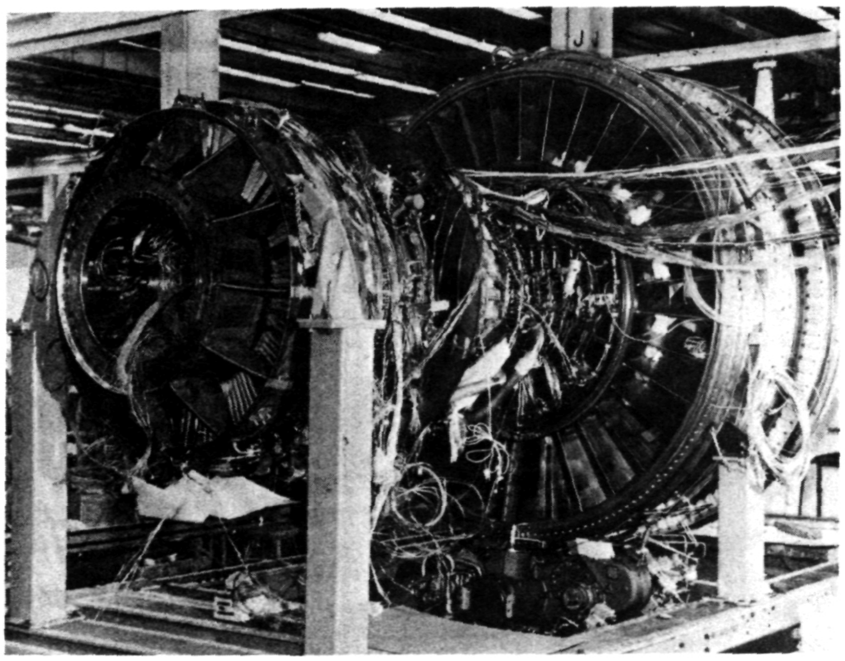


Figure 17

INSTRUMENTATION INSTALLED ON ENERGY EFFICIENT CORE TEST ENGINE

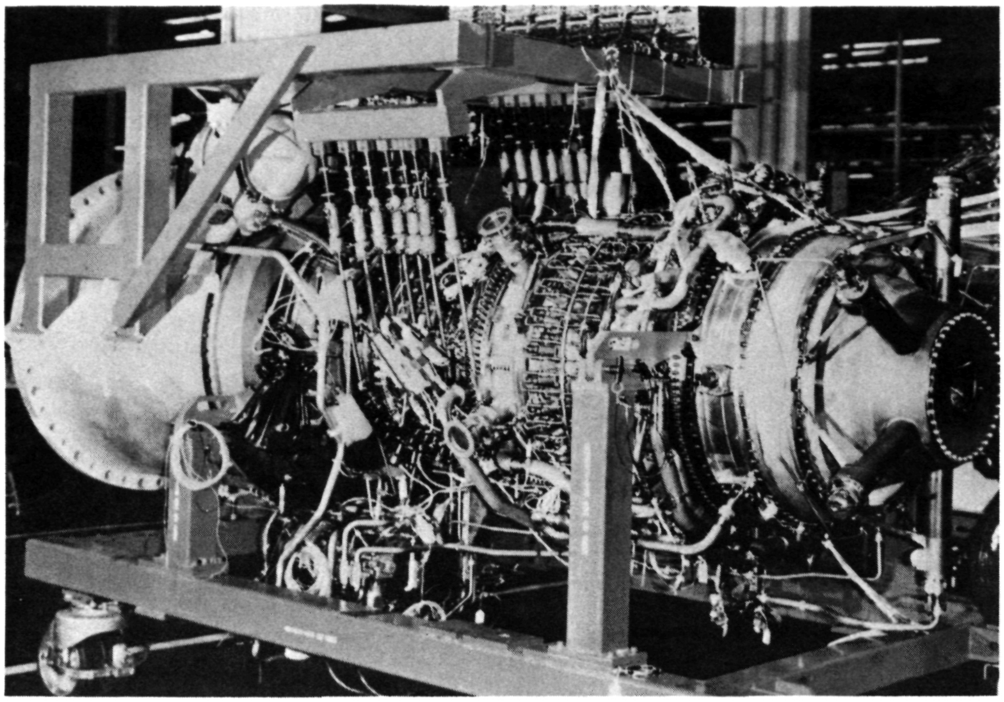


Figure 18

ENERGY EFFICIENT ENGINE - GENERAL ELECTRIC CONFIGURATION

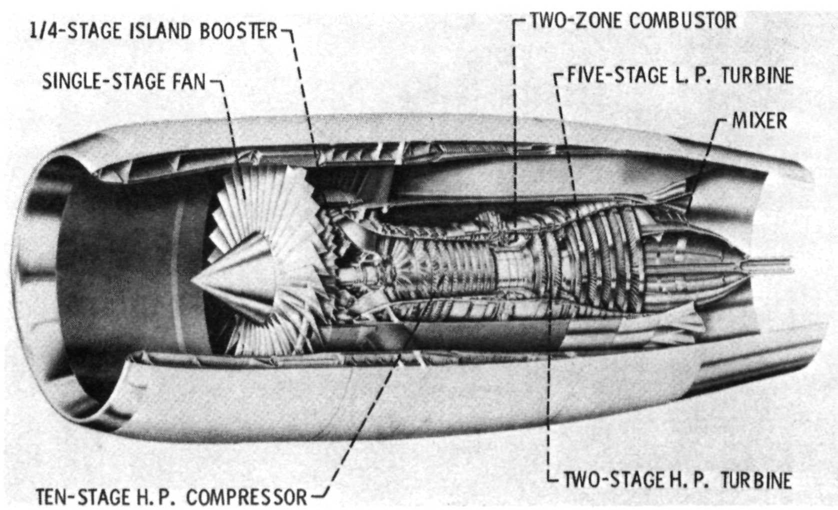


Figure 19

PROP FAN MODEL IN LEWIS TRANSONIC WIND TUNNEL

Figure 20

MULTIHEAD AERODYNAMIC SURVEY PROBE

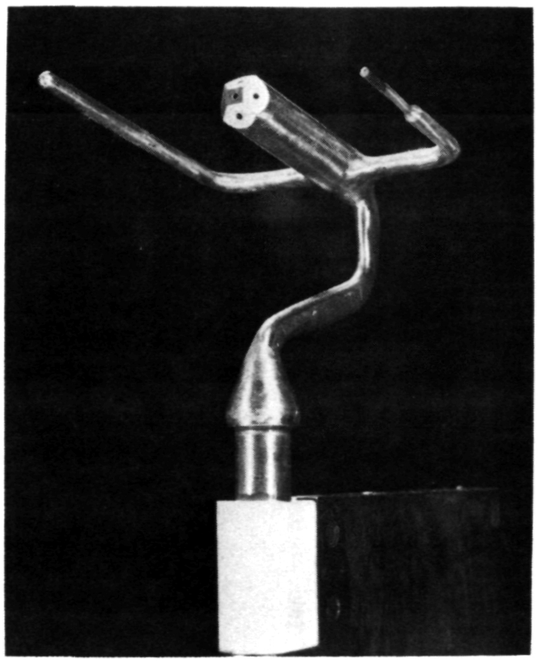


Figure 21

LASER VELOCIMETER MEASUREMENTS

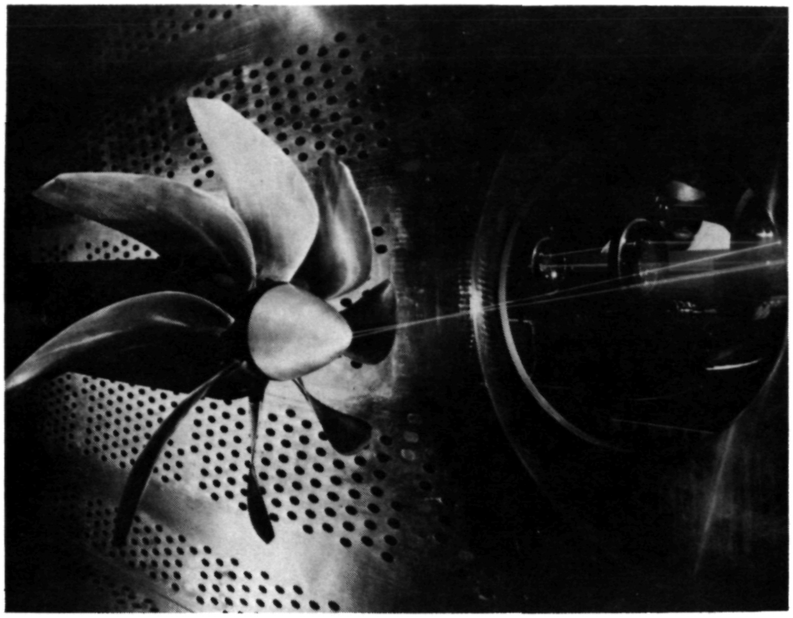


Figure 22

COMPONENTS OF LV SYSTEM

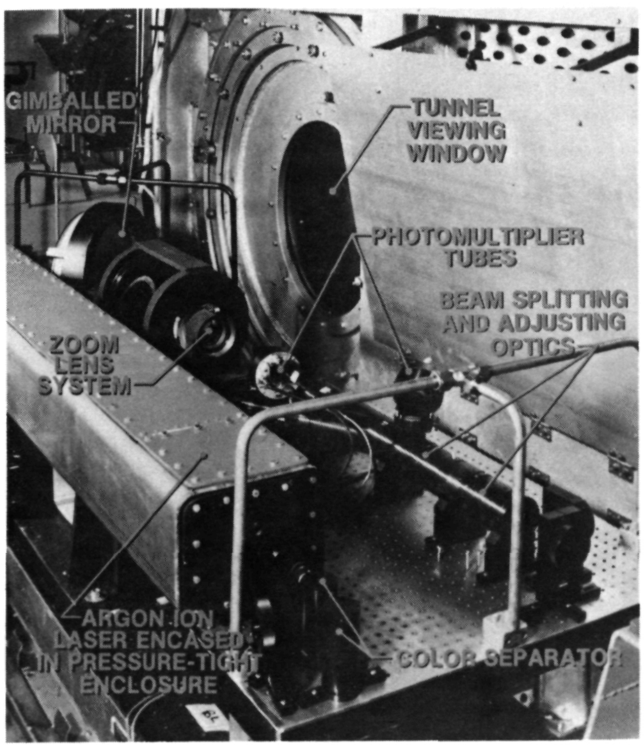


Figure 23

SR-3 INTERBLADE LV MEASUREMENTS

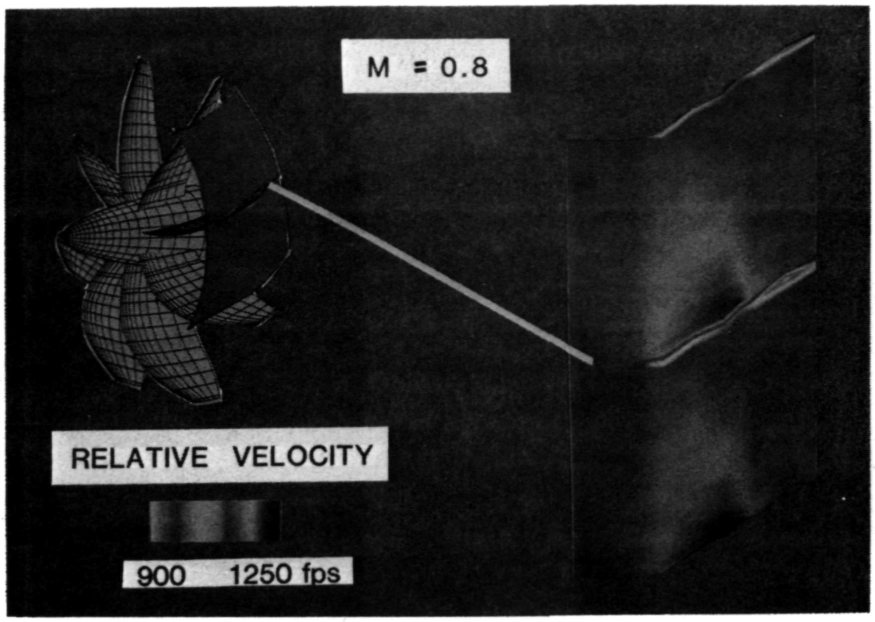


Figure 24

PROPELLER DIAGNOSTIC RESEARCH

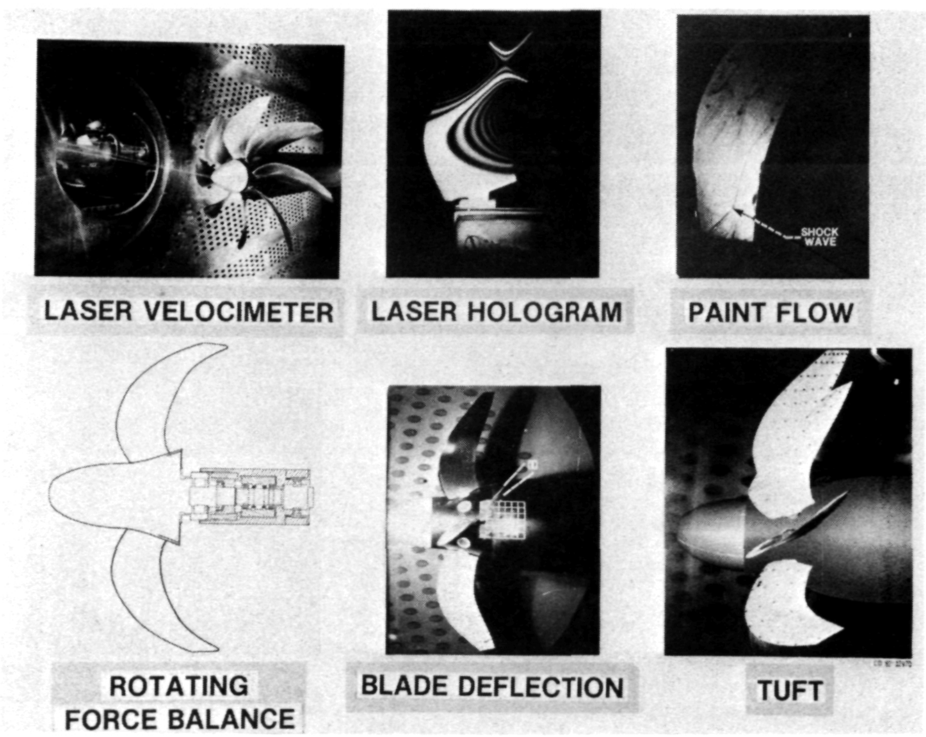


Figure 25

BLADE DEFLECTION MEASUREMENT SYSTEM

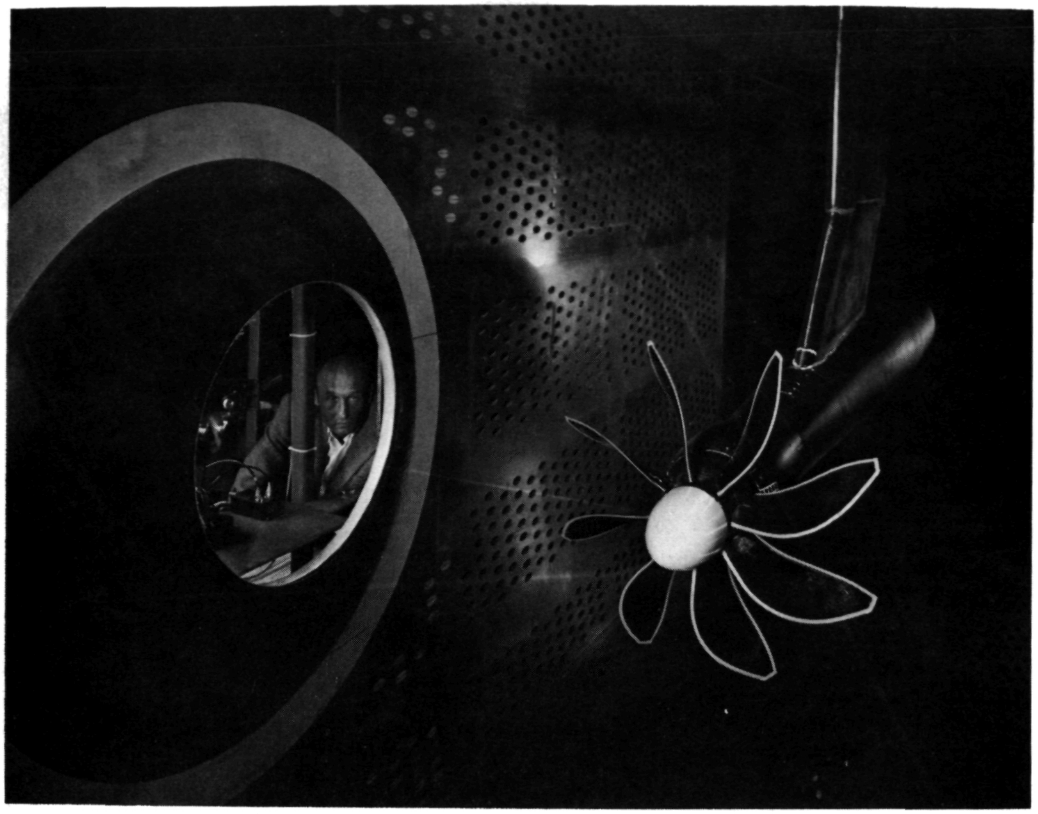


Figure 26

AEROPROPULSION RESEARCH INSTRUMENTATION
SUMMARY REMARKS

- A KEY FACTOR IN ADVANCING PROPULSION SYSTEMS
- REQUIREMENTS CONTINUE TO INCREASE
- INSTRUMENTATION RESEARCH IS MULTIDISCIPLINARY
- DEVELOPING AND VALILDATING NUMERICAL SIMULATIONS REQUIRE DETAILED MEASUREMENTS
- REQUIRED TO EXTEND THE TECHNOLOGIST EMPIRICAL UNDER-STANDING OF LIMITING PHENOMENA
- ADVANCED INSTRUMENTATION IS USED WITH TRADITIONAL METHODS

WITHIN EVERY AEROPROPULSION TECHNOLOGIST RESIDES AN INSTRUMENTATION ENGINEER

Figure 27

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-88853		

4. Title and Subtitle	5. Report Date
Advanced Instrumentation for Aeronautical Propulsion Research	
	6. Performing Organization Code 505-90-01
7. Author(s) Melvin J. Hartmann	8. Performing Organization Report No. E-3244
	10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the Symposium on Propulsion Instrumentation, cosponsored by the National Aeronautics and Space Adminstration and the Chinese Aeronautical Establishment, Jiangyou, People's Republic of China, October 6-10, 1986.

16. Abstract

The development and use of advanced instrumentation and measurement systems are key to extending the understanding of the physical phenomena that limit the advancement of aeropropulsion systems. The data collected by using these systems are necessary to verify numerical models and to increase the technologists' intuition into the physical phenomena. The systems must be versatile enough to allow their use with older technology measurement systems, with computer-based data reduction systems, and with existing test facilities. Researchers in all aeropropulsion fields contribute to the development of these systems.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Measuring instruments Mechanical measurement	Unclassified - unlimited STAR Category 35

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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