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DESIGN AND FLIGHT TESTING OF A NULLABLE COMPRESSOR FACE RAKE

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INTRODUCTION

Dynamic flow in the inlets of jet aircraft has been studied at the NASA Flight Research Center during supersonic flight to gain an understanding of inlet flow conditions related to engine compressor stalls and other problems encountered in flight. This information is required in order to advance current inlet-design technology for application to future high-performance airplanes.

One important facet of this type of inlet research is surveying the pressures across an aircraft engine compressor face by using fixed, multiprobe, total-pressure rakes. Inlet research programs have been conducted on an XB-70 airplane (ref. 1) and an F-111 airplane (ref. 2), and more advanced studies are in progress with a YF-12 airplane. For these programs, rakes with very high frequency response were required to measure the rapidly fluctuating (dynamic) pressures experienced by the engine compressors. Thus frequency response was a key consideration in the inlet rake design. To avoid excessive duct blockage by the rakes and line attenuation of the rapid pressure pulses that would occur if the transducers were remote from the rakes, miniature pressure transducers were placed close to the probes in the bodies of the rakes. Experience with such transducers had revealed that they were subject to severe calibration shifts with even moderate temperature changes. Thus in the F-111 investigation (ref. 3) these miniature transducers were used only for dynamic pressure measurements. A second sensing system in which precision transducers were remote from the rakes was used to measure steady-state pressures. The two types of rakes were installed alternately around the compressor face.

To avoid such installation complexity and duplication of sensing channels, a compressor face rake was developed with an internal valve arrangement to null the pressure across each differential pressure transducer and, hence, permit the determination of zero shifts at frequent intervals during flight. This design made it possible to measure both dynamic and steady-state pressures with only one sensing system.

This report describes the nullable compressor face rake, the method of construction, and the principle of operation. Proof tests to insure structural integrity and operational reliability are also described. Data showing the performance of the rake in flight are presented, and flight experience with the rake is discussed. Techniques for implementing the zero-shift calculation and corrections to the data using automatic data processing equipment are described.

Physical quantities are given in the International System of Units (SI) and parenthetically in U.S. Customary Units. The measurements were taken in U.S. Customary Units. Factors relating the two systems are presented in reference 4.

NULLABLE RAKE SYSTEM

Description of the Rake

A photograph of the nullable compressor face rake is presented in figure 1. Figure 2 is a photograph of the rake partially disassembled to show interior details of the rake body, transducer cavities, the valve rod assembly with O-rings, the actuator assembly with piston, the piston O-ring and cylinder, and the protective rear cover plate. The pressure transducer used is shown in the inset photograph. Physical dimensions of the rake are shown in the assembly drawing of figure 3.

Each rake was designed to accommodate five probes, which were close-coupled to a small differential transducer (inset, fig. 2) approximately 3 millimeters (0.125 inch) in diameter by 3 millimeters (0.125 inch) high with a frequency response of 5000 hertz and a natural resonance in excess of 60,000 hertz. Each transducer was isolated from adjacent orifices by rubber O-rings on each side of the transducer-probe assembly, and reference pressure was supplied to each transducer through the center of the valve rod which had a small orifice for each section. Reference pressure air was supplied to each valve rod from a manifold ring which encircled the engine. The valve rod, which was moved by the actuator piston, controlled pressure routing by sliding inside the rake. The actuator piston was supplied with high-pressure air from two manifold rings which encircled the engine.

The rakes were designed to be mounted in front of the engine compressor face. Teflon blocks and pads were used to attenuate mechanical shock and vibration. The rake mounting was fastened and secured with aircraft quality bolts and safety wire.

Fabrication of the Rake

Type 416 stainless steel was chosen for the rake body because of its machinability. A rifle drill was used to bore the 0.635-centimeter (0.250-inch) hole the full length of the rake body (35.56 centimeters (14.00 inches)). Adequate flushing was very necessary to prevent sharp metal chips from damaging the smooth internal surface of the hole, and, more importantly, to keep chips from building up on the drill and thereby forcing it off center. After right-angle holes had been drilled into the rake body for insertion of the probes and transducers and the reference pressure ports had been drilled, sharp edges were found internally which damaged the O-rings. These edges were removed by smoothing the internal cylinder surface with a metal rod covered with very fine emery paper.

Miniature transducers were installed and potted in place with a commercial room-temperature curing silicone rubber potting compound. A slight vacuum was applied to the probes to draw the compound into, and thereby seal, existing leaks. Signal wires from the transducers were connected to small terminal strips, on the rear of the rake body, to which longer output signal wires were connected. The wires, reference pressure tubes, and transducers were protected by a rear cover plate. Inconel 600 alloy was selected for the rear cover plate because it could be bent sharply without cracking.

Principle of Operation

During normal operation, pressures were measured by differential pressure transducers because they permitted better resolution of the dynamic fluctuations in the data. The reference pressure to the transducers was measured by precision transducers so that the absolute level could be determined accurately. During nulling actuation, zero shift was determined by simultaneously applying reference pressure to both sides of each differential transducer, thus nulling the transducer input to zero.

A partial cross-sectional schematic view of the rake showing the actuator piston and a typical rake probe, transducer, valve, and the internal porting arrangement is shown in figure 4(a) for the rake in the null position and in figure 4(b) in the data position. When the valve rod was in the null position, the transducer face (front of its diaphragm) was closed to incoming probe pressure and was simultaneously vented to the reference pressure source. Any difference between the electrical output from the transducer and the ground calibration value during this time was considered to be a zero shift and was corrected for later. When the valve rod was in the data position, the transducer face was closed to reference pressure, but was reopened to measure incoming probe pressure data.

Nulling was accomplished on command from the cockpit by a switch connected to two solenoid valves which routed the high-pressure air to the proper side of the actuator piston. Both the switch and the solenoids were spring-loaded in the data position as a fail-operate measure.

FLIGHT QUALIFICATION TESTS

Before the rakes were installed for flight tests, one rake was constructed for use as a test specimen to evaluate its susceptibility to fatigue caused by vibration and to evaluate the frequency-response characteristics of the transducer-probe combination.

Vibration Test

The rake was vibration tested along each of its three major axes. The tests were conducted for 3 hours on each axis at fixed or varying frequencies from 10 hertz to 2000 hertz at levels of 1.5g to 10g according to the vibration test schedule in figure 5. Before tests were made on each axis, the rake was mounted on a shaker table in a manner similar to the intended airplane installation. A miniature accelerometer was glued to the rake to monitor vibration levels encountered during the test. A preliminary frequency sweep was then made at reduced input levels to determine the major resonant frequencies of the rake for that axis. If four or more severe resonances were found, the rake was dwell tested for one-half hour at each of the four most severe major resonant frequencies for a total of 2 hours of dwell testing. The third hour of testing was composed of sweeps up and down the schedule spectrum limits. If less than four major resonances were observed, an additional half hour of sweeping was substituted for each resonant peak dwell to meet the 3-hour-per-axis requirement.

The rake was dye checked after each axis test to detect fatigue cracks. No cracks were found, and X-ray photographs of the rakes indicated no internal damage. As a result, the rake, as designed, was judged suitable for aircraft installation for the flight-test program. The test rake was not used for the flight tests because of the severity of the preflight testing; instead, a set of identical rakes was constructed for installation in the airplane.

Frequency-Response Tests

To determine the frequency-response characteristics of the installed transducer-probe combination, a miniature transducer was placed in the test rake. The rake was then mounted on and connected to a dynamic sinusoidal pressure generator. Pressure in the chamber and frequency of modulation were both varied, and the electrical output of the transducer being tested was compared to the output of a precision, flush-mounted transducer inside the chamber. The rake and transducer were tested from 5 hertz to 1000 hertz at pressure levels of 35, 105, and 175 kN/m^2 (5, 15, and 25 psia) to simulate the nominal total-pressure levels of the flight-test envelope.

Nominal test results shown in figure 6 indicate that the frequency-response characteristic of the probe at all pressures tested was essentially flat out to 300 hertz. Because the maximum frequency of interest for all probes was 200 hertz, the probes were considered to be acceptable for the flight-test program.

DATA REDUCTION PROCEDURES

All flight data, including the pressures measured during rake nulling actuations, were sampled and digitized by a pulse code modulation system and recorded on an onboard magnetic-tape recorder during flight. To aid in the digital zero-shift calculation, the position of the switch used to null the rakes and the time of day from the onboard time-code generator were recorded.

Three computer programs were written to calculate the hundreds of zero-shift measurements taken in flight and apply them to the data.

Zero-Shift Calculations

Zero shifts in the data were calculated by the first computer program, which scanned the flight tape for null switch actuations and calculated the zero-shift value when nulling was detected. The program incorporated a time lag to compensate for the short mechanical system delay and to allow subsequent pressure transients to subside. The time-averaged output level of each transducer, excluding erroneous points, was then compared with the value obtained from the original ground calibration. Any difference between the values was the zero-shift correction value.

Each zero-shift correction value obtained during flight for each pressure transducer and associated times was listed and stored magnetically for later application. The output listing was carefully examined for erroneous values. If erroneous values were found, the correct values were calculated manually and then used to correct the stored values by means of a second computer program.

Zero-Shift Correction

A third computer program was used to remove the zero shifts from the final data. The zero-shift corrections for each pressure transducer were contained in the stored time histories of all zero-shift correction data. Therefore it was possible to determine zero-shift values for all transducers during the required run time intervals by using linear interpolation. Once determined, the zero shifts were then corrected for during the final data reduction process.

FLIGHT EXPERIENCE

During the flight-test program, approximately 1000 nulling actuations were performed during 25 hours of operation under actual environmental flight conditions and temperatures from less than 230° K (-46° F) to greater than 430° K (314° F). The rakes functioned reliably and as expected. The measured pressure levels were consistent and repeatable as a result of the correction of the zero shifts determined in flight. The need for zero-shift determination in flight is shown in figure 7, a time history of two typical pressures, free-stream total temperature, and airplane Mach number during a 3-minute portion of a data flight. This figure illustrates the severity of the zero shifts in moderate supersonic flight. As the airplane decelerated from Mach 1.9 to 1.2, then accelerated back to Mach 1.5, six nulling actuations were performed. A fairing between the zero actuations (dashed line), which shows the trends of the shifts, can be compared with the total-temperature variation. During the deceleration, as total temperature varied between 280° K (44° F) and 390° K (242° F), the magnitude of the zero shifts ranged from about 10 percent of the transducer full-scale output to about 65 percent of the full-scale output above the ground calibration level. At higher Mach numbers and temperatures, even larger zero shifts were observed. However, because nulling actuations were performed frequently during flight, and especially before and after data runs, the zero shifts were determined accurately and corrected for during data reduction. Thus temperature and other environmental effects were eliminated in the final data.

In addition to providing greater data accuracy, the nullable rakes were capable of measuring both dynamic and steady-state pressure levels with the same sensor; therefore, dual sensing systems were unnecessary. Instead of using four rakes for measuring dynamic data and four rakes for steady-state data, all eight rakes were used for both types of data. Since the quantity of both dynamic and steady-state data was doubled, a more comprehensive and meaningful survey was obtained than with separate systems.

During the flight-test program, three problems occasionally caused some loss of data. First, the rake actuation tended to be sluggish if the valve assembly was not lubricated or actuated periodically. Second, two of the 40 transducers were unusable because of leaks caused by O-ring damage. This was resolved by modifying the data reduction procedures. Third, a few transducers showed some attenuation at higher frequencies, which was believed to be due to partial obstruction of the internal ports by foreign matter, possibly excess lubricant. The anomaly was occasional, but would appear or disappear immediately after rake nulling occurred; however, the data were usable except for the dynamic analysis. Despite these problems, more than 90 percent of the data were usable at all times. It should be noted, too, that no maintenance was performed on the rakes during the program because the engine would have had to be removed.

Because of its successful operation in flight and its inherent advantages, the nullable rake system should be useful in future flight applications. Moreover, the basic design concept and associated correction technique could be adapted for use in other applications where uncontrollable environmental effects cause data errors, or where dynamic and steady-state data must be measured with a single probe.

CONCLUDING REMARKS

A compressor face rake with an internal valve arrangement that permitted nulling was tested in flight. The rake functioned reliably and as expected under the flight environmental temperature and vibration conditions without structural failure. Rake sensor zero shifts in flight proved to be large and unpredictable because of the high temperature sensitivity of the miniature transducers used. The subsequent accounting for the zero shifts during the data reduction process permitted the steady-state pressure levels to be accurately determined. Thus the technique of improving data accuracy by in-flight determination of zero shifts and subsequent removal of these shifts during data reduction was proved to be feasible and sound. Use of a single sensing system to measure both steady-state and dynamic pressure doubled the quantity of data obtained, thus making the compressor face survey more comprehensive than with separate sensing systems. Because of the proved advantages of the nullable rake, the basic design concept and correction technique could be used in other applications where combined steady-state and dynamic pressures must be measured with a single transducer or where uncontrollable environmental effects adversely affect the accuracy of measured pressure data.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., September 8, 1972.

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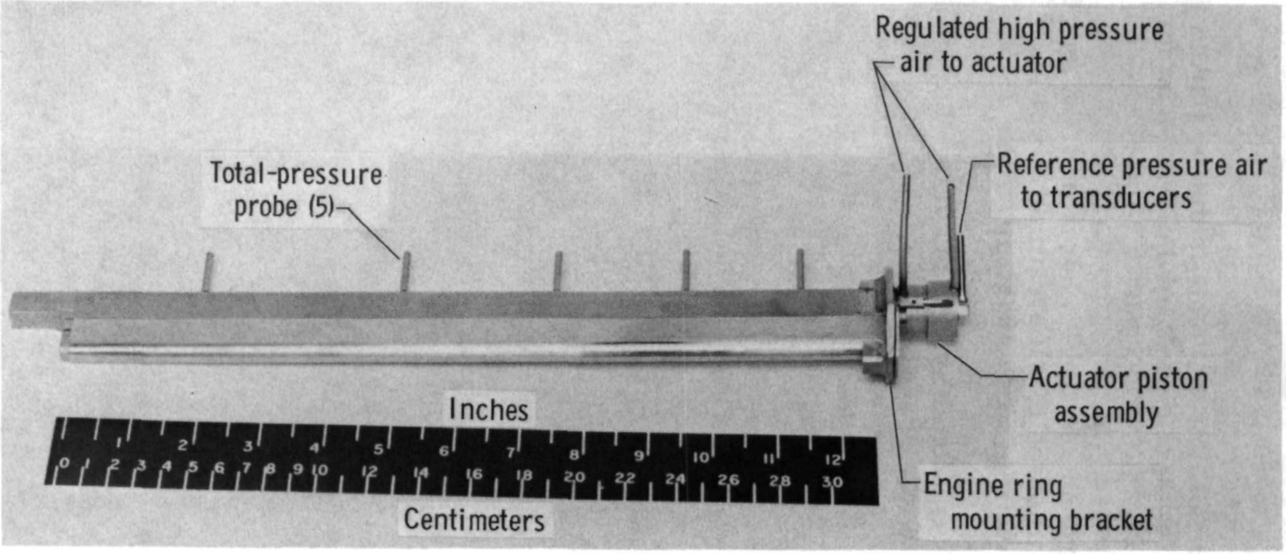


Figure 1. Nullable compressor-face total pressure rake.

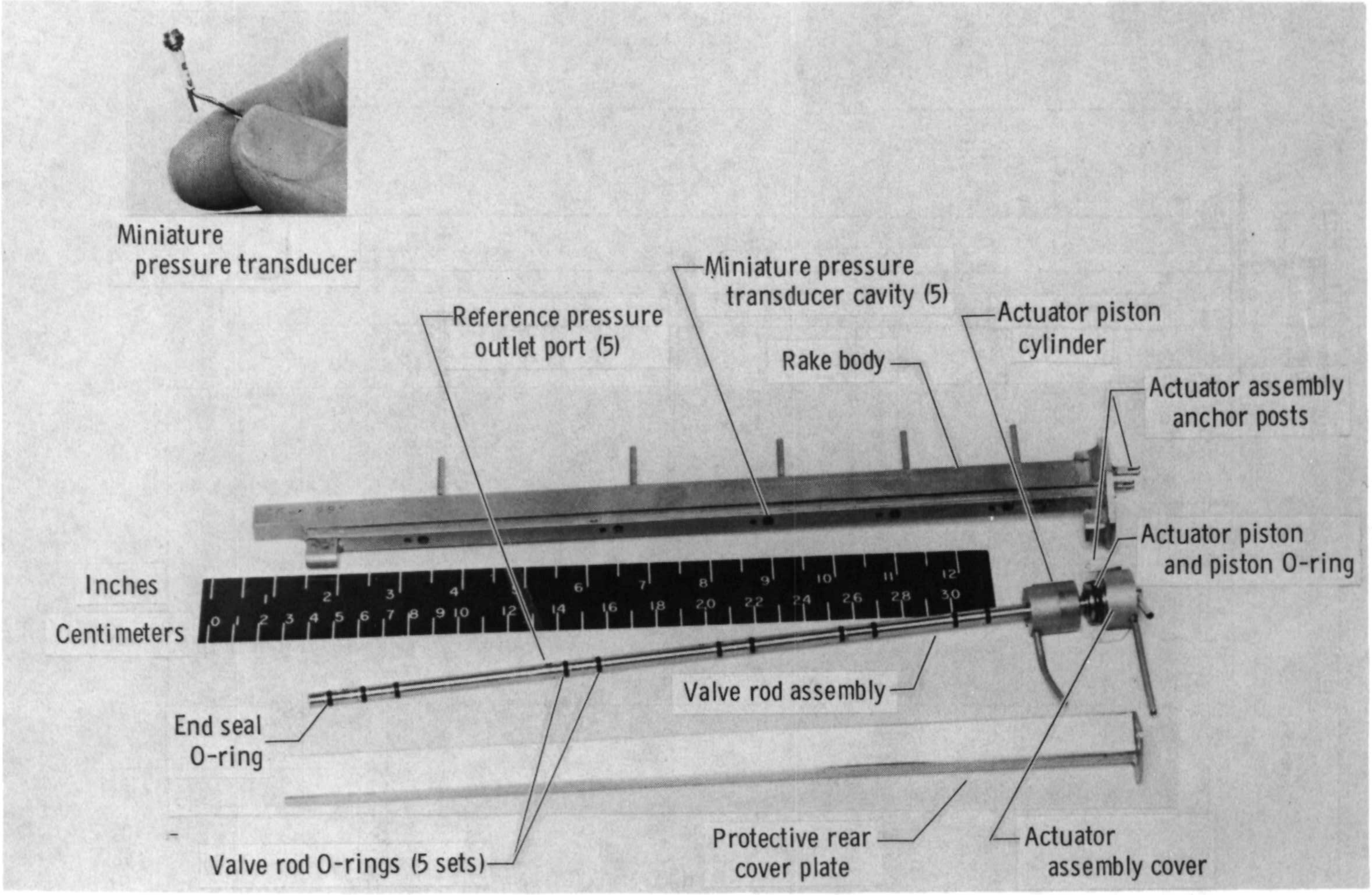


Figure 2. Partially disassembled nullable compressor-face rake showing details of the internal configuration.

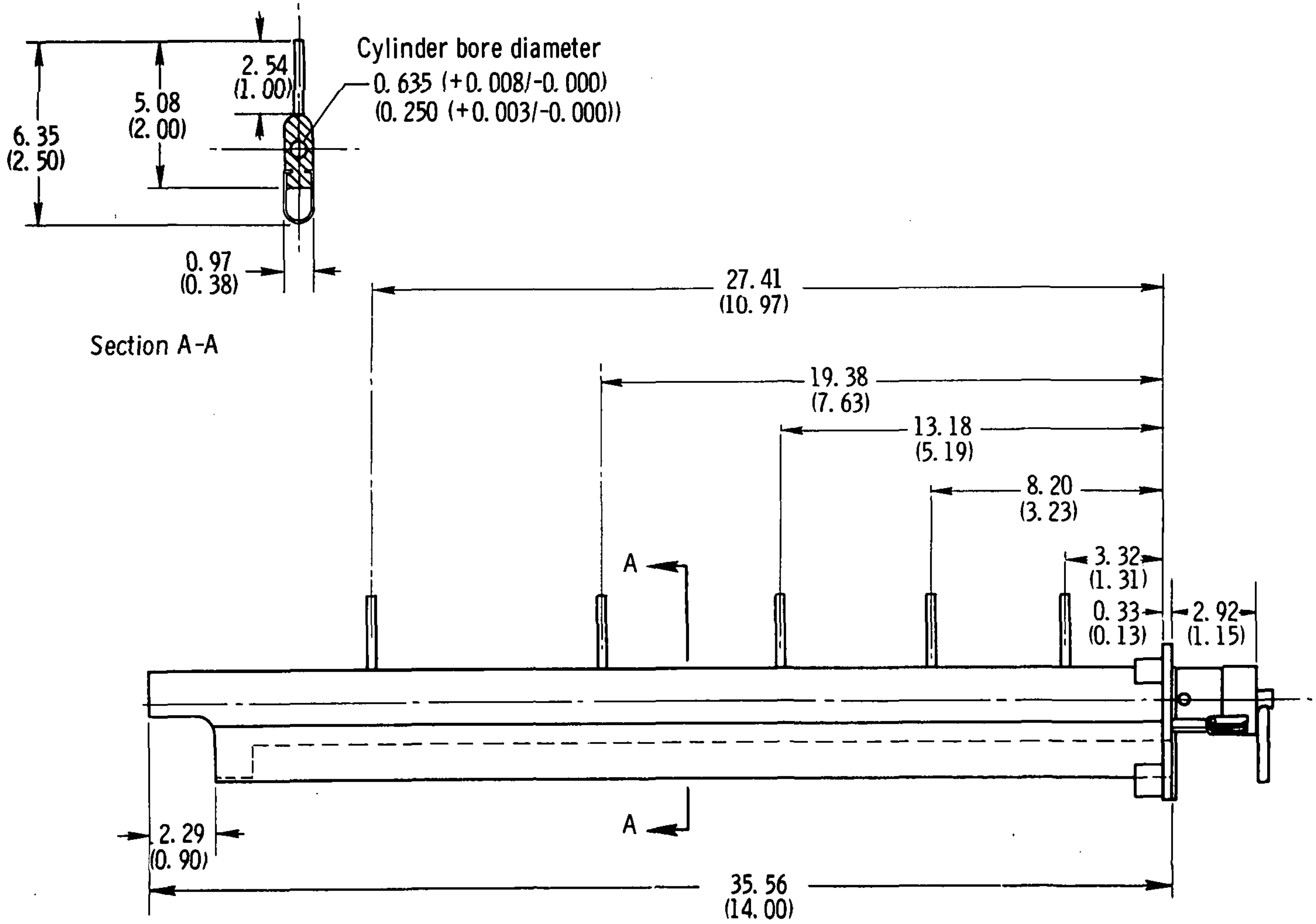
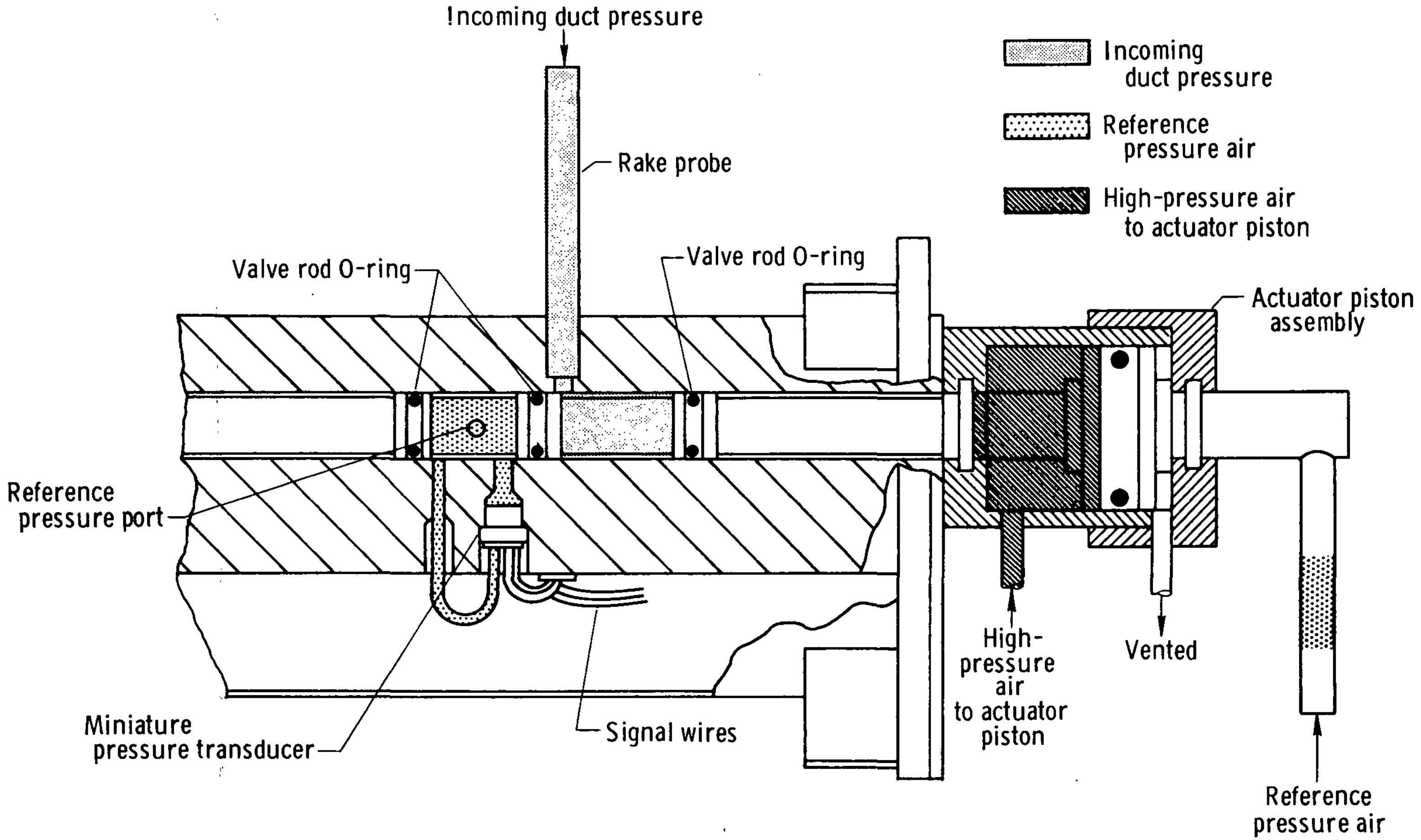
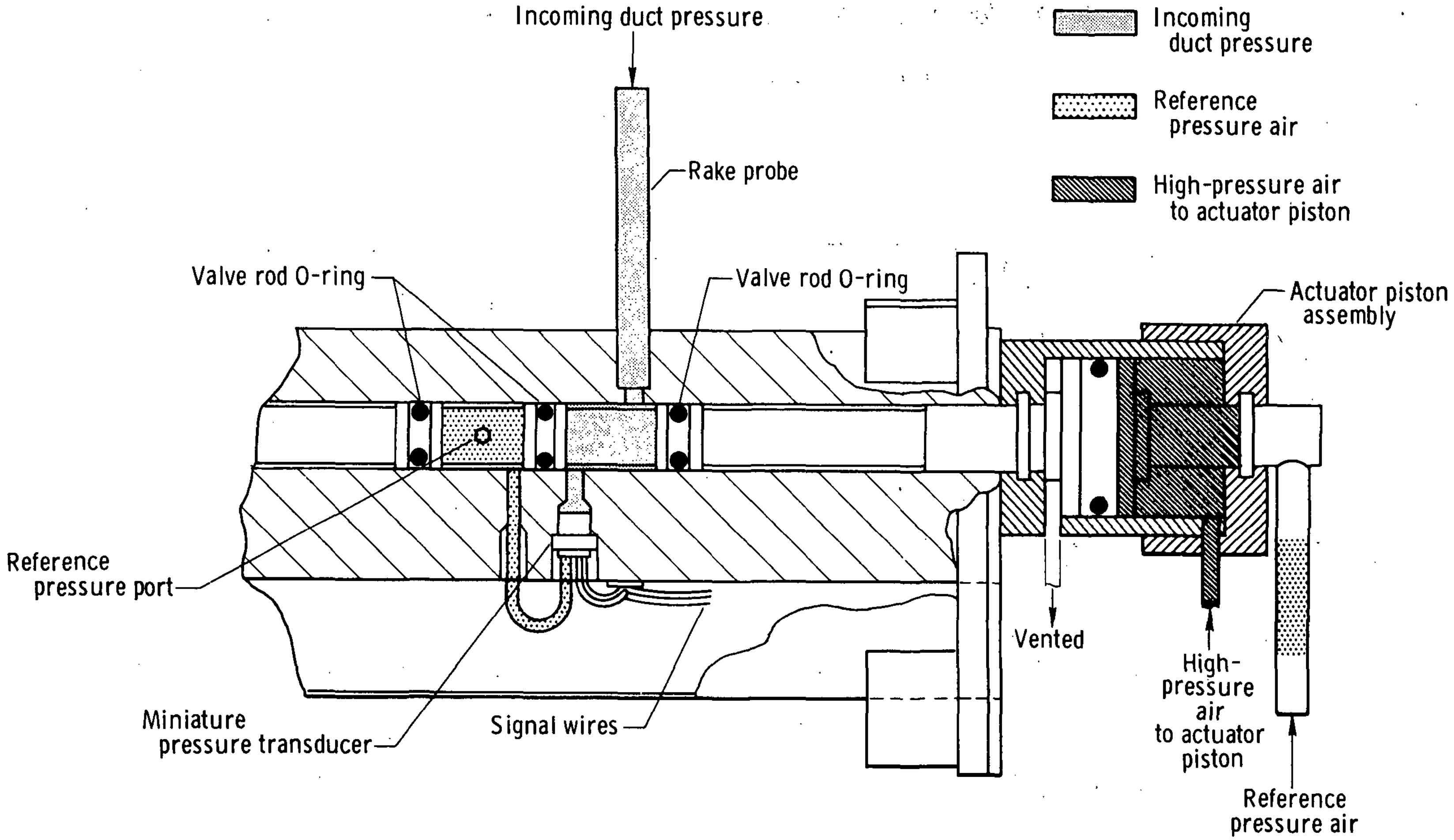


Figure 3. Assembly drawing of nullable compressor-face rake. All dimensions in centimeters (inches).



(a) Rake in the null position.

Figure 4. Schematic partial cross-sectional diagram of nullable compressor-face rake.



(b) Rake in the data position.

Figure 4. Concluded.

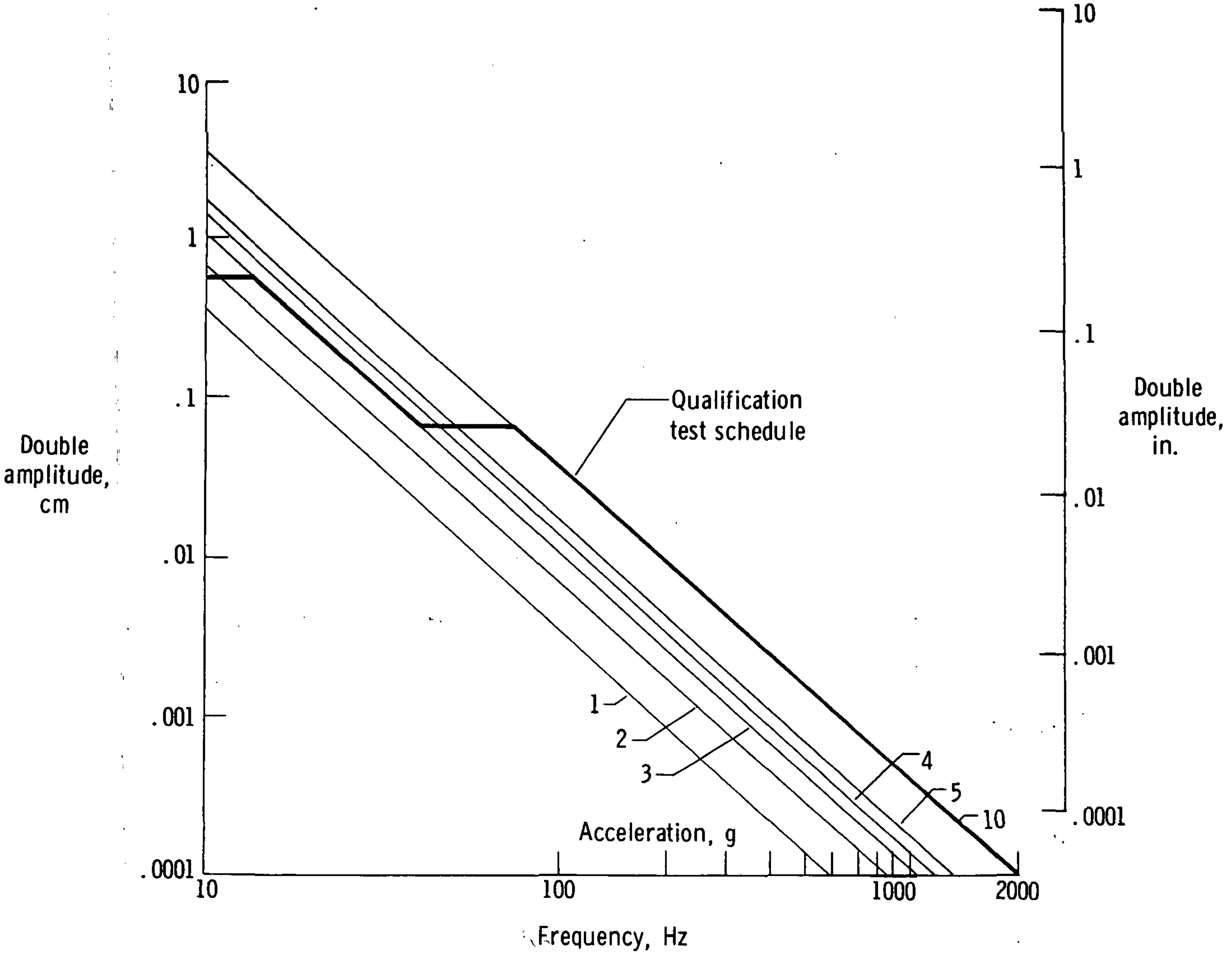


Figure 5. Rake vibration test schedule.

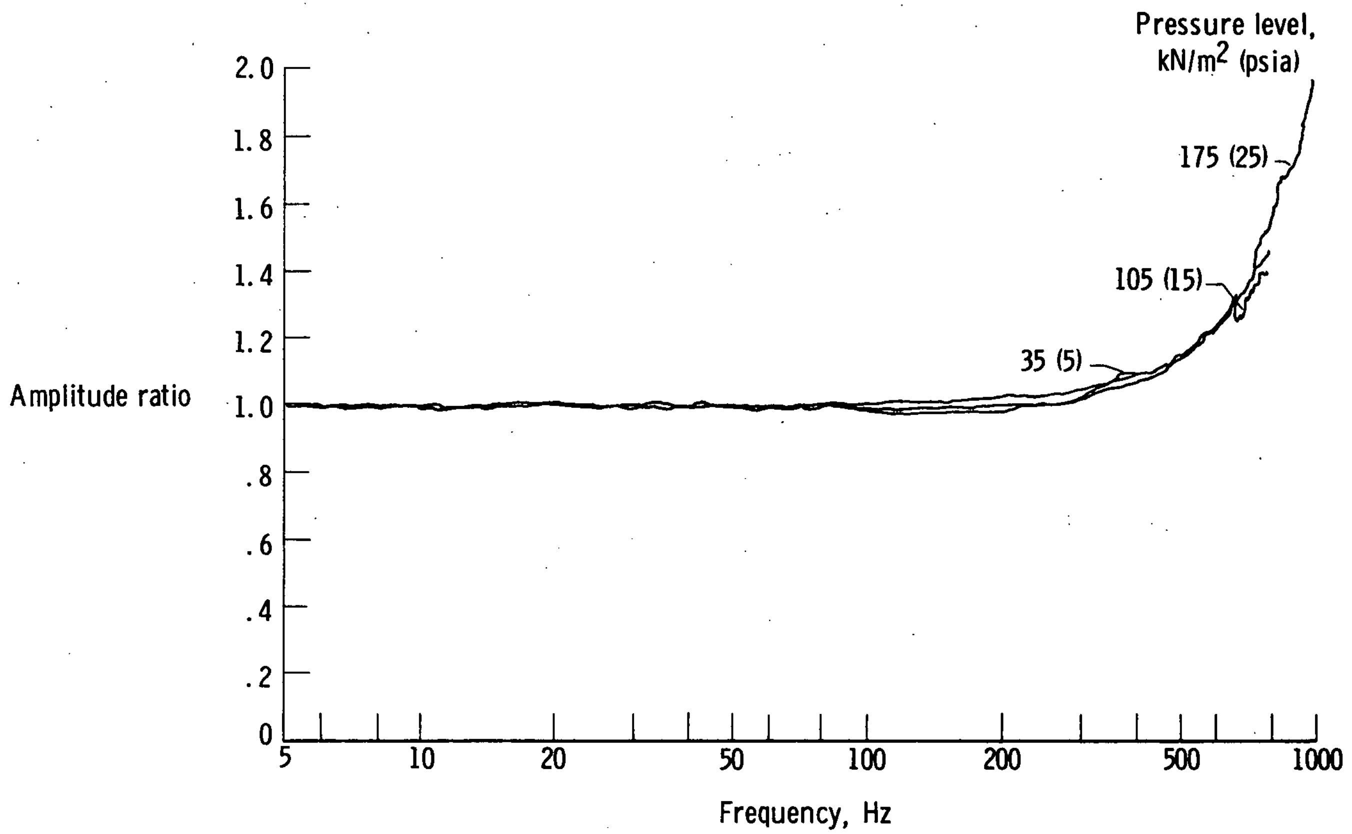


Figure 6. Frequency response of the nullable compressor-face rake with transducer installed at pressure levels of 35, 105, and 175 kN/m^2 (5, 15, 25 psia), ±7 kN/m^2 (±1 psia) modulation.

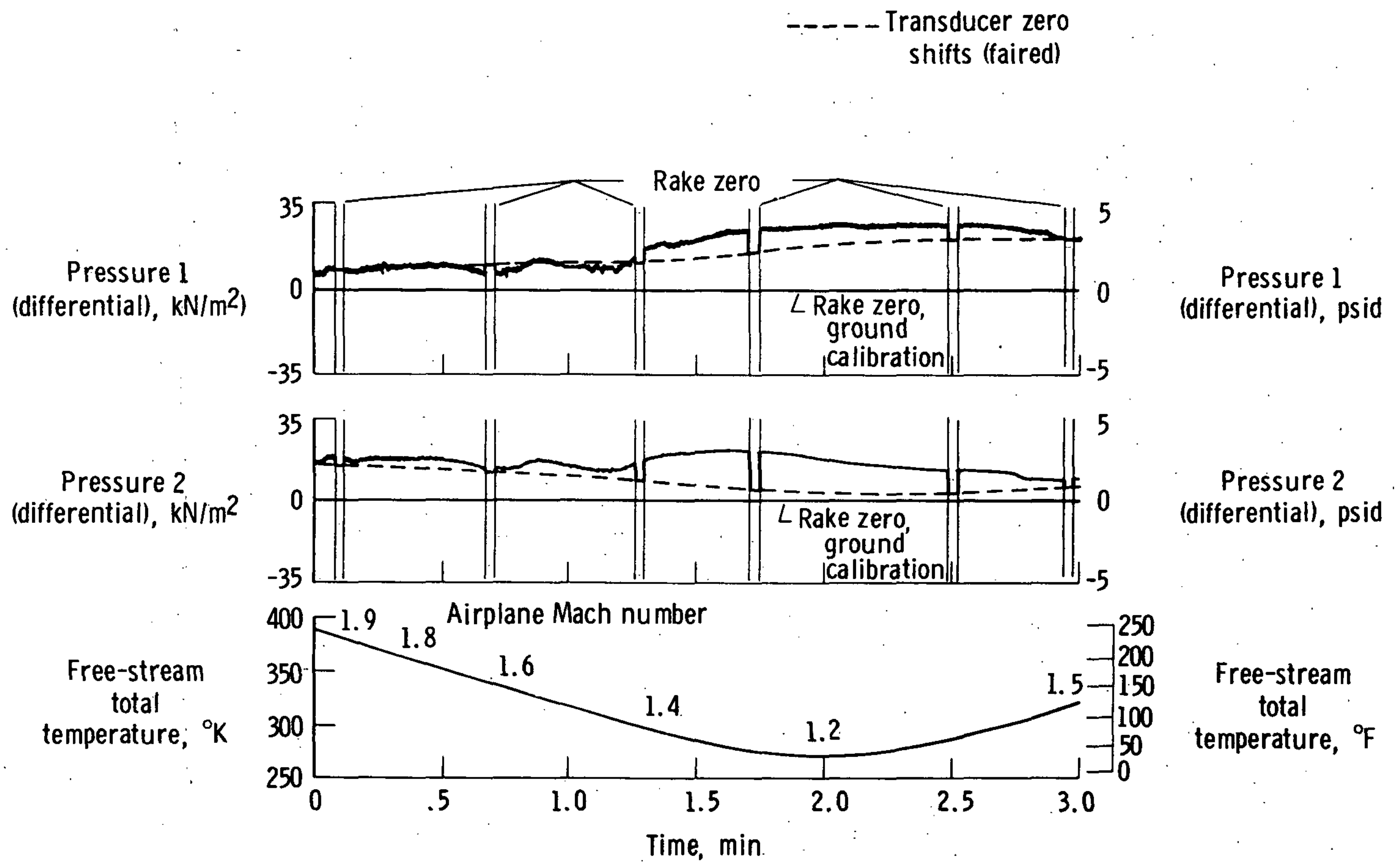


Figure 7. Typical flight-measured dynamic pressure data showing the changing zero-shift levels of the transducer output, free-stream total temperature, and airplane Mach number with time.

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16. Abstract

A compressor face rake with an internal valve arrangement to permit nulling was designed, constructed, and tested in the laboratory and in flight at the NASA Flight Research Center. When actuated by the pilot in flight, the nullable rake allowed the transducer zero shifts to be determined and then subsequently removed during data reduction. Design details, the fabrication technique, the principle of operation, brief descriptions of associated digital zero-correction programs and the qualification tests, and test results are included. Sample flight data show that the zero shifts were large and unpredictable but could be measured in flight with the rake.

The rake functioned reliably and as expected during 25 hours of operation under flight environmental conditions and temperatures from 230° K (-46° F) to greater than 430° K (314° F). The rake was nulled approximately 1000 times. The in-flight zero-shift measurement technique, as well as the rake design, was successful and should be useful in future applications, particularly where accurate measurements of both steady-state and dynamic pressures are required under adverse environmental conditions.

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