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INSTRUMENTATION FOR PROPULSION SYSTEMS DEVELOPMENT

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INSTRUMENTATION FOR PROPULSION

SYSTEMS DEVELOPMENT

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ABSTRACT. Examples are given of apparatus and techniques developed or used by NASA-Lewis to make steady-state or dynamic measurements of gas temperature, pressure, and velocity and of the temperature, tip clearance, and vibration of the blades of high-speed fans or turbines.

THE STAPLE PHYSICAL VARIABLES involved in studies of the engine cycle are temperature, pressure, and flow. Many primary elements and secondary instruments for measuring these variables have reached a high stage of development, but advanced techniques for using existing instruments are still needed as we seek to improve cycle efficiency through further experiment. This paper gives examples of measurement devices and techniques developed, improved, or used at this laboratory for propulsion system development or improvement.

STEADY-STATE MEASUREMENT OF LOCAL TEMPERATURE, PRESSURE, AND FLOW VELOCITY OF GASES

Multi-element probe - In surveys of local temperature, pressure, and flow direction, it is important that all of these quantities be measured at almost the same location. It is also important that any probes used do not block or perturb the flow excessively, lest the measurements yielded by the probes do not adequately represent the values of the variables that would exist if the probes were absent.

The combination probe shown in Fig. 1 has often met both requirements. It passes through a 6.4 mm (1/4 in.) hole in the supporting wall. The shielded thermocouple measures total temperature. The forward-facing tube measures total pressure. The two faces with side openings are at ±30 degrees to the centerline of the total-pressure tube. Measurement of the differential pressure between the two openings will provide an indication of flow direction; alternatively, the probe may be rotated until the differential pressure is zero, whereupon the angular position unequivocally represents the flow direction. When the probe is thus mechanically aligned with the flow, the mean pressure on the wedge surfaces almost represents the static pressure (there is a significant correction for the magnitude of flow velocity) so that flow speed, as well as direction, is deducible, though not always with high accuracy. Detailed dimensions and characteristics of probes of this type are given in (1) and (2).*

Calibrated thermocouple probes - The indication of a thermocouple probe intended to measure total or static gas temperature often

*Numbers in parentheses designate References at end of paper.

must be corrected for the effects of heat transfer through conduction and radiation, as well as for partial stagnation of the flowing gas at the thermocouple junction. These effects depend on gas pressure and velocity as well as on the probe design. Through appropriate design, some of these effects may be reduced to negligible magnitudes, but others must still be determined through laborious experiment.

For applications where the Mach number exceeds 0.1, a family of standardized designs of probes has been established, and their characteristics determined in sufficient detail to require no further experiment. They have been applicable in about 80 percent of all situations encountered. This series of probes is of the wedge type, shielded or unshielded. Design and performance data are reported in (3).

Thermocouple probes for use at very low gas velocities - For applications at Mach numbers below 0.1, where the rate of heat transfer by gas conduction may be as large as the rate of heat transfer by forced convection, the bare-wire crossflow design of probe is preferable. This consists of a fine thermocouple stretched between two prongs of the same thermocouple materials, the junction being midway between the prongs, and the length between prongs being sufficient to render negligible the effect of heat conduction along the wire or else to make possible a reasonable estimate of the conduction correction. A detailed treatment of conduction corrections has been presented in (4); however, since (4) emphasizes the case of high-velocity flow, some of the heat-transfer equations used therein must be replaced by equations for free-convective or low-velocity heat transfer, as presented in (5) and (6).

Pressure measurement on high-speed rotors - The availability of commercial pressure transducers only a few millimeters in diameter has made possible the measurement of pressure at the surfaces of compressor or turbine rotors turning at high speed. The rotor shaft must be hollow. The transducer, of the resistance-strain-gauge type, is mounted on the centerline of the shaft to minimize acceleration effects. It may be of either the absolute or the differential type. A typical transducer may be 2 mm diameter by 10 mm long. Tubing (about 1/2 to 1 mm i.d.) may be led from the pressure opening on the surface, radially to the shaft centerline, and then axially to the transducer. The method of electrical connection to the transducer is treated in the next section.

A restriction on the practicality of such pressure measurement is imposed by centrifugal effects, which make the pressure p_0 at the center of the rotor less than the pressure p_R at a radius R (7). For air,

$$\ln(p_R/p_0) = 1910\times10^{-12}(NR)^2/T_e \qquad (1)$$

where N is rotational speed in rpm, R is radius in cm, and T_e is an effective gas temperature, in kelvin, given by

$$\frac{1}{T_e} = \frac{2}{R^2}\int_0^R (r/T)\,dr \qquad (2)$$

where T is the gas temperature in the lead-in tubing at radius r. Figure 2 is a nomogram for the relation among N, R, and p_R/p_0 for several values of T_e; a straight line on the nomogram joins simultaneous values of the three quantities, where the scales chosen for N and p_R/p_0 are both for the same T_e. Linear horizontal interpolation may be used for other values of T_e.

For p_R/p_0 near to unity, the right-hand side of Eq. (1) represents the fractional correction that must be applied to the indication p_0. As p_R/p_0 increases, the inability to define T_e adequately, because of uncertainty in knowledge of T(r), may become excessive, so that adequately accurate deduction of p_R from the measured value of p_0 is no longer possible. The relation between the fractional uncertainty in T_e and the corresponding resultant uncertainty in p_R/p_0 is

$$|\delta(p_R/p_0)| = |\delta T_e/T_e|\,(p_R/p_0)\ln(p_R/p_0) \qquad (3)$$

Any inability to install the pressure transducer exactly on the shaft centerline raises the question of whether measurement of p_0 may be significantly impaired by centrifugal effects. The work of (8) indicates that these effects can be acceptably small for some transducers and provides quantitative data on this subject.

Data pickup from rotating members - Electrical connections to a transducer on a rotating member may be made in one of the following ways:

(a) Through sliprings and brushes. For very high speeds (many tens of thousands of rpm), both are usually of precious metal alloys, with the brushes harder than the sliprings. Slipring diameter may be only 6 mm. Brushes are of the multiple-contact type and not less than two brushes are used per ring. Forced cooling with a nonconducting fluid is common. For slower speeds, copper-graphite brushes have served well. Brush lifters are useful if data are to be extracted only intermittently.

(b) Through a multiple-winding rotary transformer, using a modulated-carrier system. Power enters through one pair of windings, the output signal leaves through another pair, and a third pair is used to monitor the power actually delivered to the strain-gauge bridge. Use of the ratio between output signal and monitor signal serves to eliminate many effects of imperfect coupling between transformer stator and rotor.

(c) Through a pulse-code-modulation method of data communication. This method is feasible if the rotor shaft is large enough to carry an electronics package about 5 cm diameter by 5 cm long (centered on the shaft axis) and is advantageous when the total number of channels is large, as when there is a multiplicity of thermocouples, pressure transducers, and strain gauges. A rotary transformer is used. The input power is rectified to operate the strain-gauge bridges (for both pressure and strain), but it is also used to operate amplifiers, multiplexers, and an analog-to-digital converter. The latter converts all outputs into digital form, so that the outputs leave the rotor, through a second pair of rotary-transformer windings, as a train of pulses. The advantage of this system is that losses in power transformation between stator and rotor do not impair accuracy. A restriction is that the electronic components must be carefully arranged and installed so that they will not be affected by acceleration. A 72-channel system of this type that handles only thermocouples has operated at speeds of 15 000 rpm (accelerations on the electronics up to 8000 g) and is reported in (9). An 80-channel system that will include 16 strain-gauge type circuits is scheduled for a future installation.

Both slipring assemblies and rotary transformers are listed by their commercial suppliers as being suitable for speeds up to 100 000 rpm.

DYNAMIC MEASUREMENT OF LOCAL TEMPERATURE, PRESSURE, AND FLOW VELOCITY OF GASES

Pressure measurement - The 2 mm-diameter pressure transducers mentioned in connection with steady-state measurements are also useful for measuring dynamic pressures in confined spaces. For example, flush-diaphragm transducers have been mounted at or near the end of a total-head tube, to permit study of eddying flow. These transducers have natural mechanical frequencies exceeding 100 kHz, so that, although they are undamped, they can follow pressure fluctuations up to at least 20 kHz with good fidelity. However, there are many potential applications where it is not practical to keep the transducer below 400 K, its maximum operating temperature. In such applications, the infinite-line technique, illustrated in Fig. 3, may be usable. In this technique, the transducer is located far enough from the source of pressure to permit a sufficiently low transducer temperature, and the pressure is transmitted to the transducer through capillary tubing of about 1.5 mm diameter.

In the more common form of transducer installation, wherein a transducer is located at the end of a tube and this end is closed off, there would be serious organ-pipe resonances that would obscure the dynamic pressure variations to be measured. These resonances derive from the fact that any pressure wave travelling down the tube is reflected from the end, and the buildup of successive reflections from both the open and closed ends produces standing waves in the tube. In the infinite-line technique, these reflections are prevented by making the tube of substantially "infinite" length and by mounting the transducer on the side of the tube, so that, ideally, there is no alteration of cross-sectional area or shape where the pressure wave passes the transducer. Hence there is no reflection.

The practical approach to the ideal situation involves the following expedients:

(a) A flush-diaphragm transducer, with active diaphragm area comparable to or slightly smaller than the tube diameter, is mounted so that the plane of the diaphragm is almost tangent to the inside cylindrical surface of the tube. The disturbance in cross-sectional area of the tube is held to a minimum. Thereby, reflections from this disturbance are relatively weak.

(b) The total length of tube is made great enough that the pressure wave is attenuated to only a few percent of its original amplitude by the time the wave reaches the end of the tube. (The end of the tube may be left open, or may be closed for safety, depending on the nature of the gas and on its average pressure.) Any reflection from the end will be doubly attenuated by the time it returns to the location of the transducer. The attenuation is exponential, obeying the equation

$$dp/p = -\alpha \cdot dx \qquad (4)$$

where x is distance along the tube. For air at 300 K, the attenuation factor α at 100 Hz in a 1.5 mm-diameter tube is on the order of 0.4 per meter. The factor α varies inversely with tube diameter and directly with the square root of the product of frequency and kinematic viscosity.

(c) The transducer is located as near to the source of pressure as feasible. This precaution provides three advantages: (1) the pressure wave is attenuated less by the time it reaches the transducer; (2) any resonant vibrations due to the weak reflections from the transducer are of higher frequency, hence have higher attenuation and obscure the desired dynamic information less; (3) if the pressure wave is of large amplitude, it will suffer less waveform distortion. This last feature derives from the fact that a high-amplitude sine wave, as it travels along a tube, suffers gradual distortion into an asymmetrical sawtooth wave with more nearly vertical forward wavefront. The distortion will have become severe in a distance $0.3\ \lambda/\beta$, where λ is wavelength and β is the ratio between sine-wave amplitude and mean pressure. (At 10 000 Hz and $\beta = 0.2$, this distance is 5 cm.)

An application of the infinite-line technique is described in (10).

Temperature measurement - Dynamic temperature data may sometimes be even more important than pressure data in characterizing a combustion process; for example, the concentration of minor gaseous combustion products may depend more on the peak temperatures reached than on the average temperature. A conventional method of following rapidly fluctuating gas temperature is to use a resistance thermometer or thermocouple, with low and predictable time constant, in conjunction with an electrical network that compensates for the thermal lag. An effective sensing element is the bare-wire crossflow design mentioned under Thermocouple Probes for Very Low Gas Velocities. The wire may be of 25-80 μm (1-mil to 3-mil) diameter, about 3 mm long, stretched between two needle-like prongs. The choice of materials depends on temperature level, gas composition, and whether catalysis is of concern. The choice of wire size depends on gas cleanliness and on the frequency response needed. To prepare a thermocouple, the two wires are crossed at about 120 degrees and the junction welded by capacitor discharge, laser, or the high-frequency starter arc of an arc welder. Resistance-thermometer wires may be made of Pt, Ni, W, or high-temperature-coefficient alloy wire.

Thermocouple time constant is given by

$$\tau_T = \rho c\, D/(4h) \qquad (5)$$

where D is wire diameter, ρc is the effective value of the product of density and specific heat of the wire material, and h is the heat transfer coefficient. The latter quantity depends on gas properties and stream conditions. For gas speeds exceeding Mach No. = 0.1, formulas in (4) may be useful; for lower speeds, the formulas in (5) or (6) may be used. The uncertainty in knowledge of h constitutes the principal limitation of the time-lag compensation technique.

Electrical techniques of time lag compensation have been detailed in (11). They involve making an electrical time constant τ_E equal to the thermal time constant τ_T.

Experience has shown that effective application of these techniques requires adequate attention to protection against the intrusion of power-line hum. Figure 4 shows how guarding is used to this purpose. Not shown in this figure, because it is often contained within the amplifier, is a shunt capacitor or other filter that attenuates all frequencies higher than these of interest; random noise and the possibility of oscillation are thereby minimized. The amplifier must satisfy some stringent requirements: its input and output should be floating and guarded; if it is operated from the power line, the power must be delivered through a double-shielded isolation transformer with negligible effective interwinding capacitance and negligible leakage current. As an alternative, a battery-operated amplifier may be used, if the battery is contained within an electrostatic shield. Similar shielding and isolation requirements apply to the power supply for a resistance thermometer.

Figure 4 illustrates the 100-fold improvement in frequency response obtained with the circuit shown in the figure. The effects when τ_E and τ_T are mismatched by a factor of two are also shown; despite the resultant twofold change in amplitude of the flat portion of the response curve, a considerable amount of useful information can be obtained concerning the wave shape of the temperature fluctuation.

Velocity measurement - A conventional technique of measuring the amplitude component of fluid velocity has been to measure the fluctuation in total pressure p_t by methods like those treated under Pressure Measurement and to assume that a concurrent steady-state measurement of static pressure p_s, say with a wall tap, will suffice to yield the velocity head $p_t - p_s$. Experience has shown this assumption and this technique to yield valid results in most applications.

When the directional component of velocity is also of interest, use of a similar pressure-measuring technique with inclined pressure probes like those shown in Fig. 1 is possible, but very difficult, because two pressure pickups must be installed (one on each inclined tube) and the two installations must be closely matched to ensure equality of both phase and amplitude of the pressures at each pickup when the flow angle is zero. Such a technique has been demonstrated (12) but a newer, easier method holds promise of providing dynamic measurement of either amplitude or direction.

This technique uses the same technology that made possible the miniature transducers mentioned under Pressure Measurement. A silicon crystal in the shape of a slab 0.25 mm thick by 1.5 mm square is used as an impact plate (Fig 5). A complete resistance strain gauge bridge is formed on the crystal surface by solid state diffusion; the bridge measures bending of the plate under impact of the airflow, when the plate is clamped along one edge. When the flow is normal to the plane of the plate (direction B, Fig. 5), the resultant simple bending is representative of the magnitude of the dynamic pressure. When the flow is against an edge of the plate, almost parallel to its plane (direction C, Fig. 5), there is a combination of bending and torsion representative of the angle between the airflow direction and the plane of the plate. (In a different configuration, not illustrated, flow can be directed against that edge of the plate which is opposite to the clamped edge; in this case simple bending results when the plane of the plate is inclined to the direction of the airflow.)

The beam has a natural frequency near 50 kHz, and negligible damping. Consequently, with simple filtering to suppress higher frequencies, fluctuations up to about 10 kHz can be followed with good fidelity. This device has been described in (13).

COMPRESSOR- AND TURBINE-BLADE INSTRUMENTATION

The commercial availability of fiber optic bundles which can transmit light from the immediate environment of the engine to a location where temperatures, vibration levels, and space limitations are less severe has made possible the development of several devices that permit measurements of greater accuracy, convenience, reliability, or detail than were previously possible. Some examples are given here.

<u>Turbine-blade temperature distributions</u> - Since propulsion cycle efficiency generally increases with operating gas temperature, turbines are generally operated at the highest blade temperature that will still allow adequate mechanical strength. In turbine

development, it therefore becomes necessary to know the temperature distribution over the blade surface at all operating conditions. An effective means has been the photography of the blade surface, using infrared radiation emitted by the surface. A densitometric analysis of the photograph can yield details of the temperature distributions, provided there is a single measurement of blade temperature at one point on the blade surface by some absolute means such as a thermocouple. Details of the application of this method to observation of stationary blades are in (14), which also lists earlier contributions. However, application to moving blades requires some stroboscopic method to provide a sufficient number of repetitive views of any blade to yield adequate signal-to-noise ratio.

A further limitation of this technique is that results are not available until the photographic film has been developed and scanned. This limitation is overcome by the method shown in Fig. 6. The technique provides virtually a real-time display to a test operator, so that warning of excessive temperature may be received in time to permit effective remedial action. A row of 80 optical fibers is oriented so as to receive radiation emanating from 80 contiguous areas on the blade, aligned in a radial direction. When the probe is about 100 mm from the blade, each fiber receives radiation from an area about 0.5 mm in diameter; thus, a total radial distance of 40 mm is observed. The length of the fiber bundle is generally limited to about 2 meters in order to minimize attenuation along the fiber. The fibers remain coherently aligned in a single row, at the far end. A microscope focused on the end of a single fiber delivers the outgoing radiation to a silicon-avalanche-type detector which produces an electrical signal representative of the radiation emitted by the corresponding element of area of the blade. As the blade passes by the probe, a continuous record of radiation intensity versus time appears on the screen of the monitor oscilloscope. By adjustment of sweep speed, a single sweep may represent a traverse of one or several blades. With appropriate mathematical processing, this signal is converted into a voltage that is proportional to temperature and that may be impressed on the vertical axis of a suitable recorder. Finally, the microscope may be mechanically shifted to observe each fiber in turn; with a corresponding slight vertical displacement of the oscilloscope spot each time this shift is made, one may obtain up to 80 curves of temperature distribution on the screen. Figure 7 shows such a group of scans, for seven radial locations; in this figure, each curve was displaced in the time direction, as well as vertically, to clarify the presentation by avoiding superposition of patterns.

The data processing, which is controlled by a minicomputer, permits averaging of any number of scans in order to improve accuracy. Additionally, the visual data that appear in Fig. 7 are also converted into a printout of temperature values that may be used for quantitative analysis. Details of this method are given in (15) and (16).

Blade clearance indication - Since the efficiency of any bladed fan is impaired by flow past the tips of the blades, tip clearance is made as small as feasible. It is therefore necessary to monitor this clearance as it changes because of temperature differentials, vibration, and, in the case of turbines, creep. Commercial instruments which have been popular for this purpose consist of a capacitance-type probe (Fig. 8(a)) in the form of a cylindrical center electrode separated by an appropriate tubular insulator from a grounded tube attached to the stator casing. As the blade tip passes under the probe, the capacitance between electrodes is increased. The capacitance is measured by a circuit (Fig. 8(b)) consisting of an oscillator of considerable internal impedance z_s in series with a tuned circuit of which the capacitance probe is a part. The voltage across the input of the tuned circuit is indicative of the blade clearance. When connected to an oscilloscope through an amplitude detector, the voltage appears as in Fig. 8(c). The trough represents the capacitance C_0 between probe electrodes when the blade is absent; the increase ΔC occurs when the blade tip is under the probe. The change ΔC varies inversely with blade clearance and is often only a small fraction of C_0. Variations in surface leakage between electrodes, principally because of changes in humidity, change the calibration of the probe. At this laboratory (17), we have found it feasible to correct for the change in calibration by providing a calibration impedance z_c that may be inserted into the circuit. The ratio of indications with switch S open and closed permits estimation of the sensitivity.

A stable and linear calibration, rather than a hyperbolic one, is provided by an optical technique for measuring the blade clearance; the principle is illustrated in Fig. 9. This system was originally developed by the Pratt and Whitney Aircraft Co. (18) but is being considerably expanded and improved under a NASA contract with this company.

An optical probe is attached to the stator casing in the mid-plane of the rotor blades. A beam of light from a point source impinges on the blade tip at point P_1, after being retracted by the prism. The illuminated spot at P_1, after return refraction by the prism, is imaged on to point Q_1. If the blade tip moves away from the prism, it becomes illuminated at point P_n and this point is imaged at Q_n. The point source is the end of a single optical fiber originating at a laser, which is used as a high-intensity source capable of being focused on a very small spot (about 0.1 mm diameter at the blade tip). The image plane $Q_1 \cdots Q_n$ is occupied by a row of 200 optical fibers. As the blade tip moves radially away from the prism, each of these fibers is illuminated in turn. The identification of the illuminated fiber defines the radial position of the blade tip. The separation between adjacent fibers represents an incremental blade deflection of 12μm (1/2 mil).

The fiber bundles are about 2.5 meters long. The image-transmitting bundle terminates in a coherent row; that is, the sequential order is exactly the same at both ends. After passage through an optical filter intended to remove all stray radiation and to pass only the laser radiation, the light from each fiber is imaged on to a photocathode. The emission from each image enters its own channel electronmultiplier that produces an amplified electron current. The electrons impinge on a phosphor, and the light from the phosphor impinges on an array of photodiodes, thereby producing an electrical signal. The photomultiplication process produces diode outputs at least one thousand times larger than would have been obtained directly from the optical fibers.

By use of a synchronizing signal which serves to identify the individual blades, the electrical signals thus generated may be processed in any of several ways. The clearance of a single blade, or of each blade in turn, may be followed from one revolution to the next; or the clearance may be averaged over any desired number of revolutions. The clearances may be displayed on a cathode-ray screen or converted to numerical form and printed out or recorded on tape for later processing.

Observation of blade vibration - An important mechanical problem that occurs in the use of fan rotors with relatively slender blades is blade vibration, generally induced by aerodynamic disturbances such as vortex shedding, shock impingement, or just the proximity of upstream struts or stator guide vanes. The problem can rarely be solved solely by analytical means. Each blade is just sufficiently unique so that experimental observation of each blade of the rotor is necessary. The entire range of normal and abnormal operating conditions must be covered before one can be assured that destructively large vibrations will not occur. Stroboscopic observation of the blade tips through a window in the stator casing has been used, but is time consuming because there are many blades; blade failure or fatigue may occur before the excessive vibration is detected.

A more effective method is illustrated in Fig. 10. The blade tip, as it passes the window in the stator, is illuminated by an appropriate light source. By means of lenses, each of two fiber optic bundles is focused on an appropriate point at the blade tip; for example, a focal point near the trailing edge and another focal point near the leading edge or near midchord. The light reflected from these points, after appropriate conversion by photomultipliers, produces pulses whose time of occurrence is representative of the time that the point being observed passed under the focal point of the respective lens. Let t_0 be the time when the blade would be expected to pass the line of sight if the blade were perfectly rigid and perfectly positioned. A pulse representing t_0 is available from a toothed wheel or equivalent pulse generator mounted on the shaft, as shown in Fig. 10 at the left-hand end of the shaft; the number of pulses generated per revolution is equal to the number of blades. Let x_1 be the distance from the neutral axis of the blade (in the fundamental torsion mode) to the focal point of the right-hand light beam, and $-x_2$ be the corresponding distance for the left-hand light beam. Let t_1, t_2 be the corresponding times when pulses are generated by the reflections from the two points on the blade tip. If the blades were perfectly rigid and synchronization were perfect, we would have $t_1 = t_2 = t_0$. If the blade is both bent and twisted at the time it passes under the lines of sight, then the amount of bending is proportional to

$$\frac{t_1 + t_2}{2} - t_0 - \frac{t_1 - t_2}{2} \cdot \frac{x_1 - x_2}{x_1 + x_2} \qquad (6)$$

and the angle of twist is proportional to $t_1 - t_2$. The distances x_1 and x_2 usually need not be known very accurately because if bending is predominant the third term of expression (6) is relatively small. The computation of the angle of twist depends only on the separation between the two lines of sight.

If the horizontal sweep of a cathode-ray oscilloscope is appropriately triggered by a signal at time $t_0 - \Delta t_0/2$, where Δt_0 is the time for one horizontal traverse of the oscilloscope screen, and the beam intensity is increased (Z-axis modulation) at time t_1, a bright dot will appear on the screen near midwidth. If t_1 varies with successive traverses, the dot will broaden into a line. Unless the blade vibrates synchronously with rotational speed, the vibration amplitude is proportional to the horizontal line width, if the latter has been integrated by phosphor persistence over many rotor revolutions. If, also, the oscilloscope beam is displaced vertically as each successive blade passes the line of sight, a separate display will be created for each blade. The nature of the complete display is illustrated in Fig. 10.

A single oscilloscope display will not reveal the mode of the vibration, but simultaneous measurements of the sums and differences of t_1 and t_2 will. These are performed by appropriate electrical circuits so that the results may be recorded and the data processed as required. However, the oscilloscope display provides to the test operator a real-time indication of the amplitude of vibration of each blade, so that warning of excessive amplitudes is received immediately. Furthermore, the vibrating blade is identified, so that it may be observed immediately by the stroboscopic method. Figure 11 is a photograph of an actual display representing a condition of negligible vibration. Because of mechanical and electronic imperfections, the spots are not perfect dots, nor are they perfectly aligned. However, Fig. 12, a photograph of the same screen under a condition where some of the blades are vibrating, serves to indicate that the vibration is clearly recognizable.

This technique of vibration detection was conceived and demonstrated by Hohenburg (19). Its further development at this laboratory is described in (20). Despite its limitation to vibrations not synchronous with rotor rotation, its use is considered essential to insure against engine failure during development; its cost is only a few percent of the cost of the engine being tested.

CONCLUDING REMARKS

The examples of instrumentation that have been given are intended to illustrate techniques that, with appropriate modification, may be useful in research on and development of a variety of propulsion systems. The present availability of excellent commercial instruments, computers, and data processors makes the assembly of even a complex instrumentation system possible in considerably less time than was possible a few years ago. The use of such systems not only provides a better understanding of a prototype system, but also may insure against costly mistakes or failures in production.

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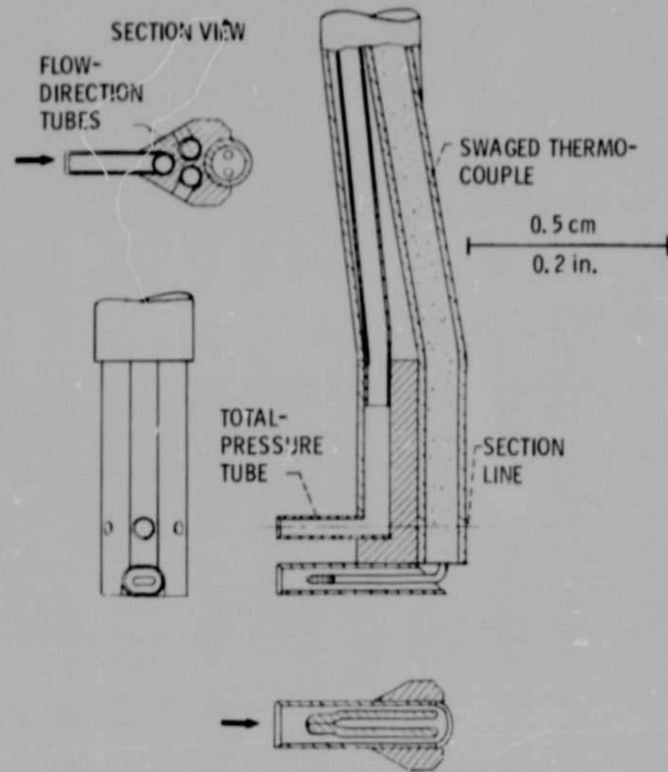

Figure 1. - Miniature combination probe for temperature, total pressure, and flow direction.

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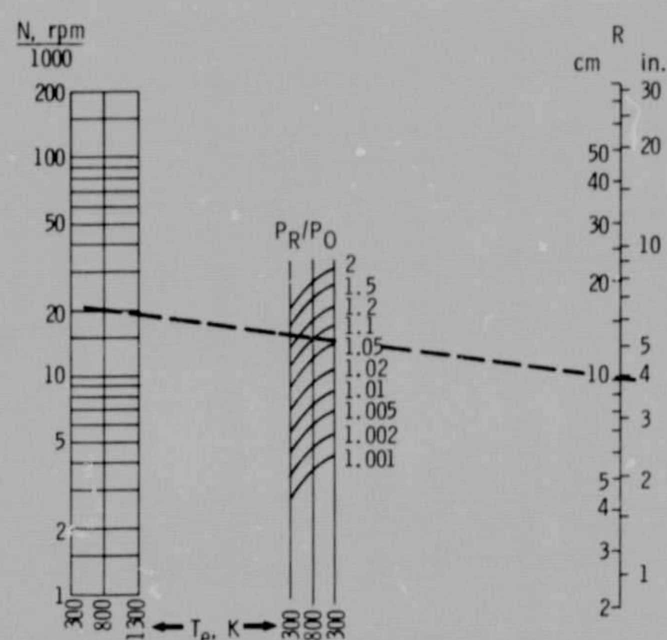

Figure 2. - Centrifugal effect on high-speed-rotor pressure measurement. The dashed line illustrates the case T_e = 800 K, N = 20 000 rpm, R = 10 cm, P_R/P_O = 1.10.

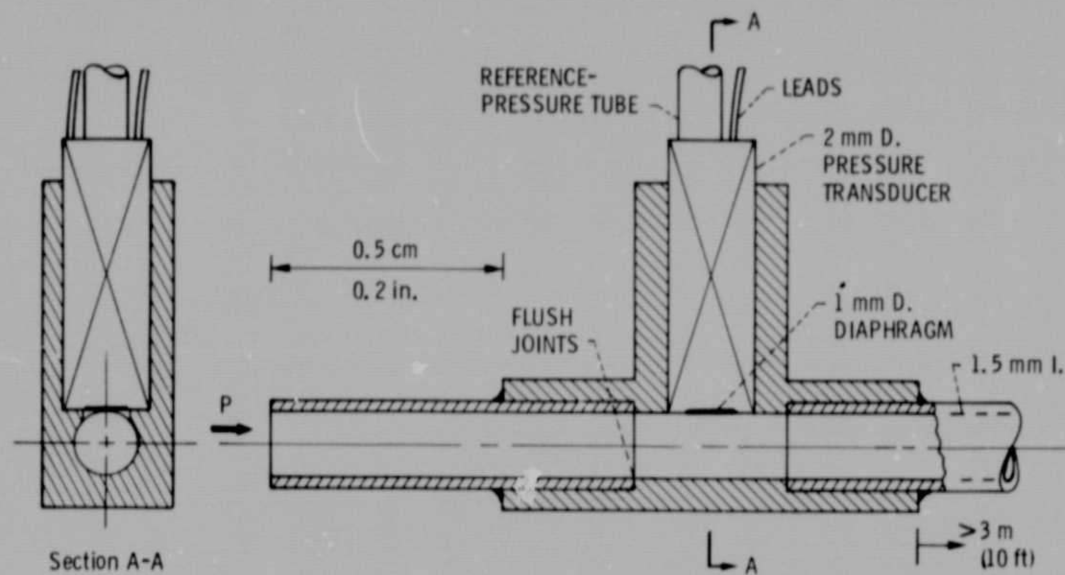

Figure 3. - Infinite-line technique of dynamic pressure measurement.

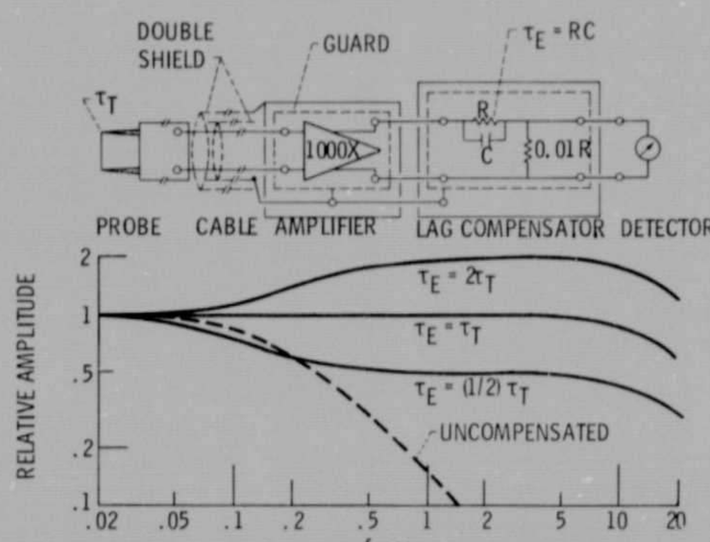

Figure 4. - Illustration of electrical compensation of thermal time lag.

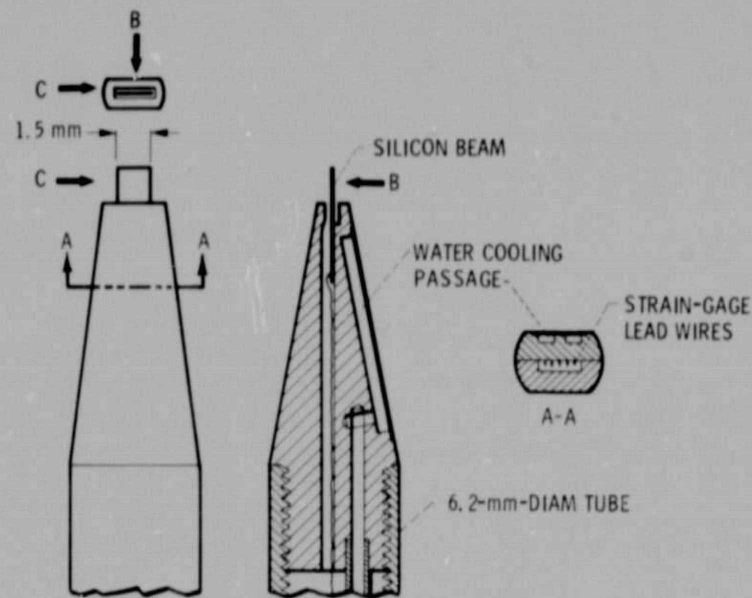

Figure 5. - Impact-plate probe for air velocity measurement.

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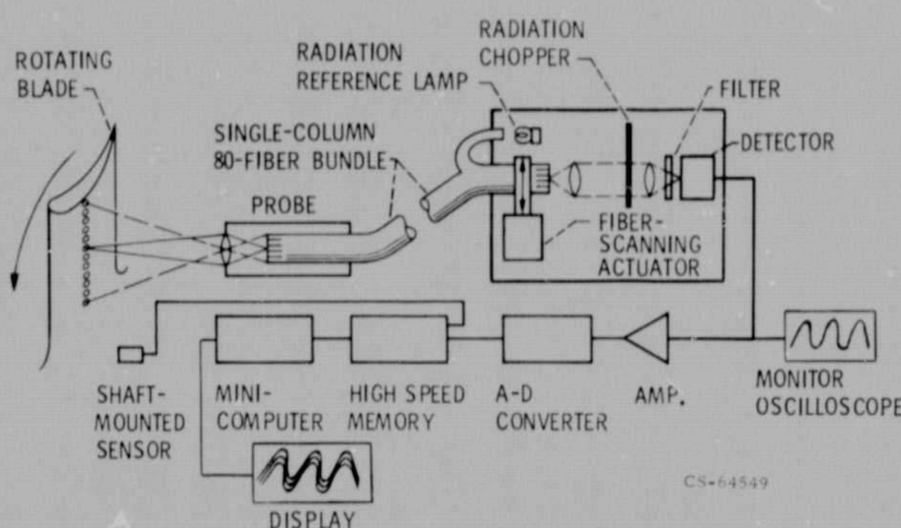

Figure 6. - Pyrometer for mapping turbine-blade surface temperature.

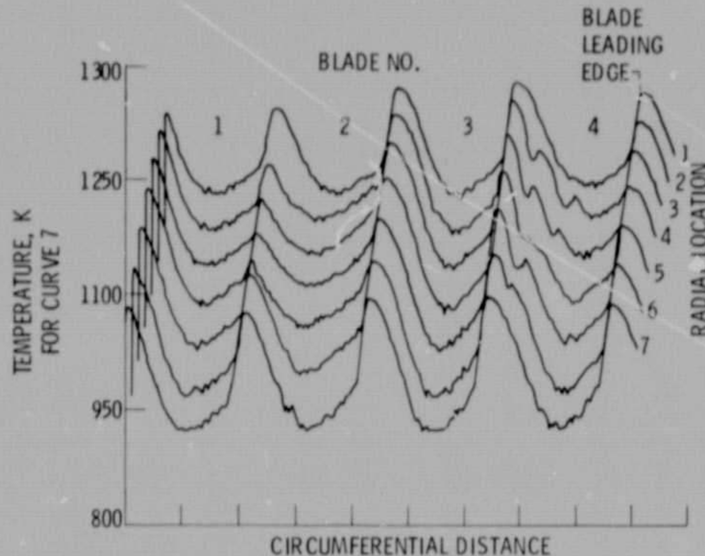

Figure 7. - Illustration of turbine-blade surface temperature distributions.

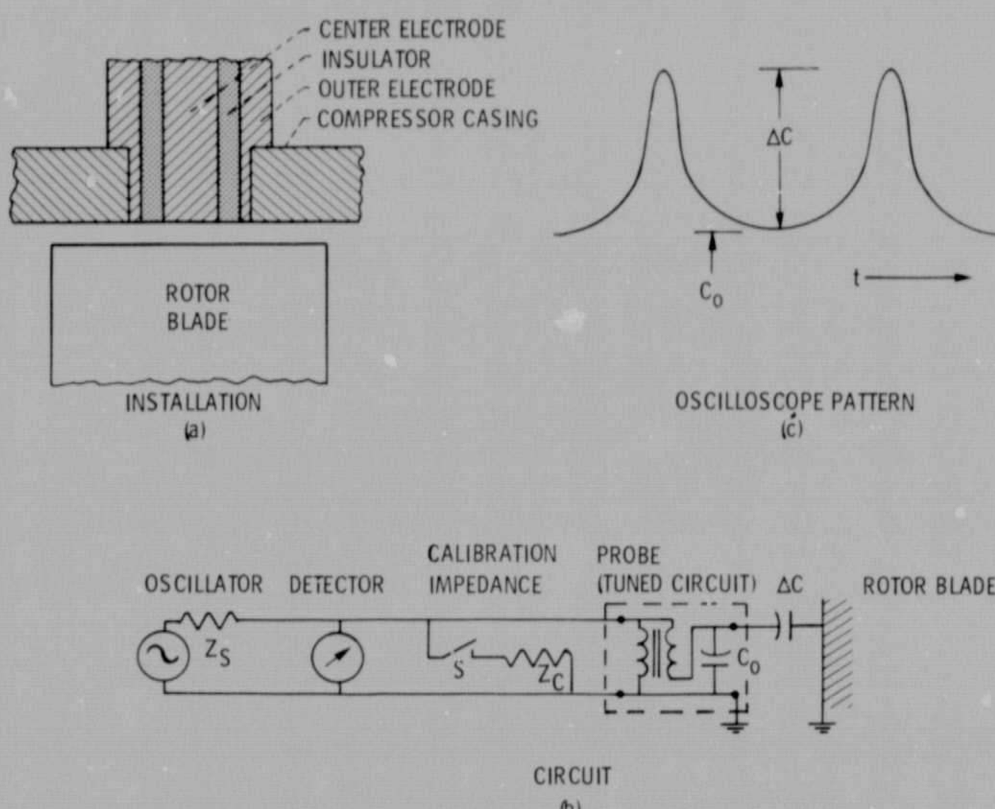

Figure 8. - Capacitance method of rotor clearance measurement.

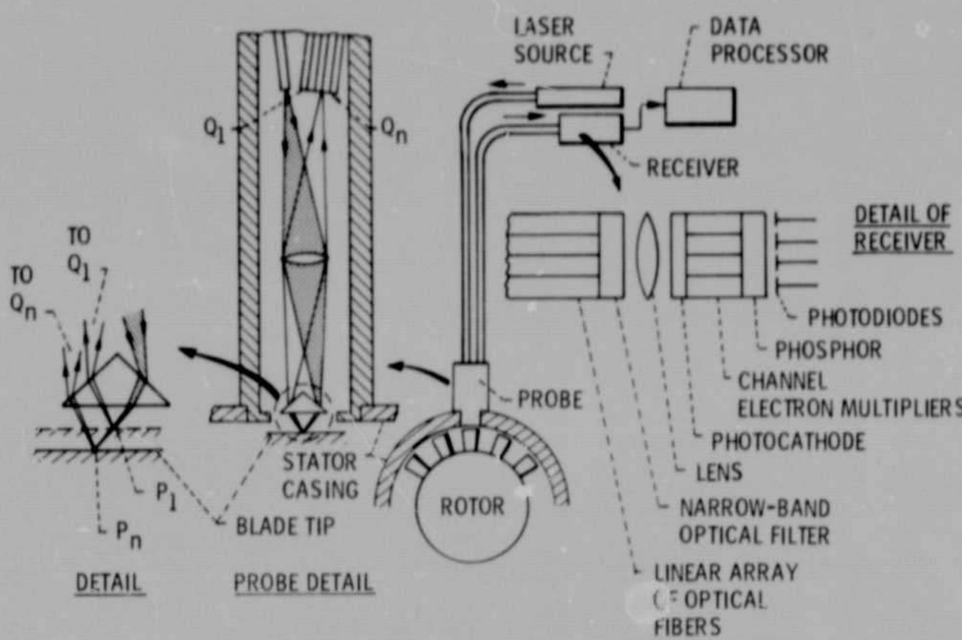

Figure 9. - Optical method of rotor clearance measurement.

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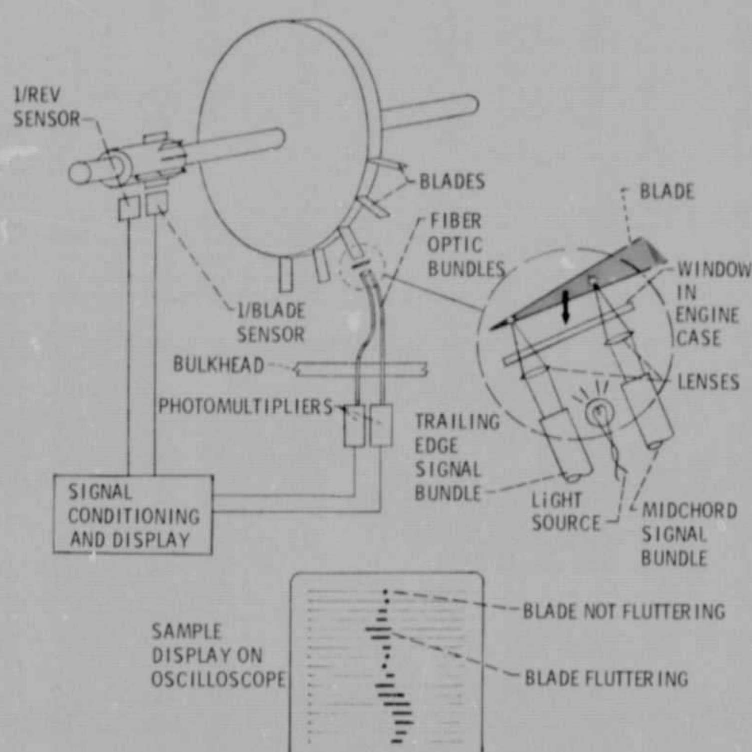

Figure 10. - Optical detection of blade vibration amplitude.

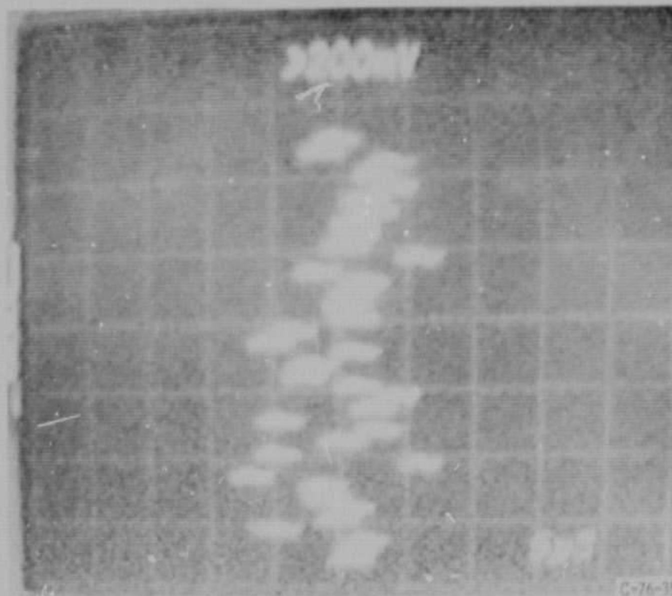

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Figure 11. - Oscilloscope display of quiescent condition.

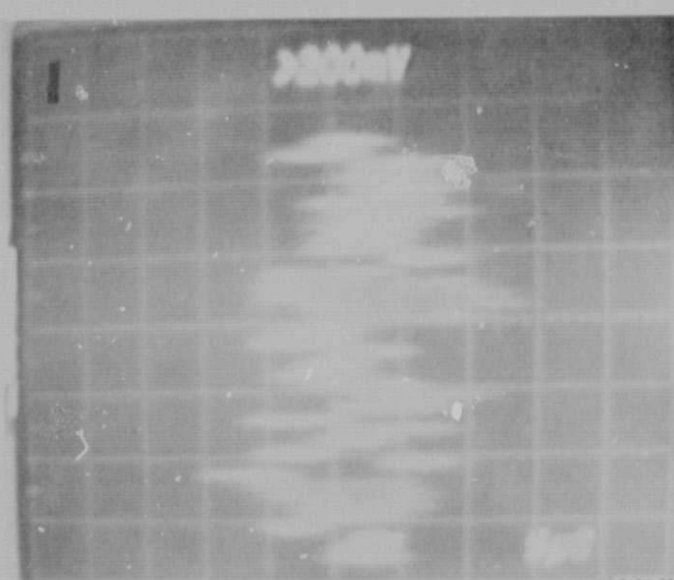

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Figure 12. - Oscilloscope display of flutter condition.

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