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The Design and Use of a Temperature-Compensated Hot-Film Anemometer System for Boundary-Layer Flow Transition Detection on Supersonic Aircraft

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ABSTRACT

An airborne temperature-compensated hot-film anemometer system has been designed, fabricated, and used to obtain in-flight airfoil boundary-layer flow transition data by the NASA Ames-Dryden Flight Research Facility. Salient features of the anemometer include near constant sensitivity over the full flight envelope, installation without coaxial wiring, low-noise outputs, and self-contained signal conditioning with dynamic and steady-state outputs. The small size, low-power dissipation, and modular design make the anemometer suitable for use in modern high-performance research aircraft.

Design of the temperature-compensated hot-film anemometer and its use for flow transition detection on a laminar flow flight research project are described. Also presented are data gathered in-flight which is representative of the temperature-compensated hot-film anemometer operation at subsonic, transonic, and supersonic flight conditions.

INTRODUCTION

Measurement of the boundary-layer flow has become increasingly important in the testing of advanced aircraft because a turbulent boundary-layer flow will increase the aerodynamic drag and reduce the lift of an airfoil. Future aircraft that are designed to achieve a greater amount of laminar flow will have improved performance and greater fuel efficiency.

For several decades, constant-temperature hot-film anemometers have been used in wind tunnel testing of airfoils to detect boundary-layer flow transition. The anemometer output also supplies power to a whetstone bridge configuration (Figure 1) which has the hot-film sensor and a temperature control resistor with a variable inductor as two of the legs of the bridge. The temperature control resistor sets the hot-film operating temperature, and the variable inductor maximizes the frequency response for a given hot-film sensor and wiring installation. A change in the airflow over the sensor will cause a corresponding change in the bridge power required to maintain the set temperature. Laminar, transitional, or turbulent flow can be determined easily by analyzing the dynamic portion of the voltage level required to maintain the hot-film sensor temperature.

In recent years, constant-temperature hot-film anemometers have been used for boundary-layer flow transition detection on several low-speed aircraft (Reference 1), but the anemometers were large and required adjustment to maintain proper operation if the speed or altitude of the test aircraft changed significantly.

The need for a hot-film anemometer that can be used on a high-performance supersonic aircraft, where large speed and altitude changes occur and unattended operation is required, has led to the development of a temperature-compensated hot-film anemometer.

In preparation for a natural laminar flow flight research project at the NASA Ames-Dryden Flight Research Facility (ADFRF), an investigation of the use of hot-film anemometry for boundary-layer flow transition detection on high-performance aircraft was performed. During the investigation, two commercially available constant-temperature hot-film anemometers were evaluated using the ADFRF F-104G/FTF airplane (Figure 2), a modified F-104G aircraft with an instrumented ventral fin known as the "flight test fixture" (Reference 2). When the systems were flown at various flight conditions, it was found that the voltage of the output varied greatly, saturating the output at some flight conditions. Compensation for the local stagnation temperature was required to achieve proper operation of the anemometers throughout the aircraft flight envelope. A temperature compensation scheme was developed, and the anemometers were modified and flight tested (Reference 3). Design requirements for a temperature-compensated hot-film anemometer were formulated, and a design effort was begun.

DESIGN CONSIDERATIONS

Operational Requirements

The most important consideration for the design of the temperature-compensated hot-film anemometer is that it must provide high quality, noise free boundary-layer flow transition data throughout the entire operating envelope of any existing and near future aircraft.

In order to provide high quality flow transition data, the temperature-compensated hot-film anemometer

- Must exhibit low noise. The anemometer should be designed to provide low noise outputs without special installation or wiring provisions, such as the use of coaxial wiring.
- Should have telemetry output. The anemometer has a high frequency response (10 kHz) containing flow transition, disturbance wave, and crossflow information and must be recorded onboard the test vehicle. A low frequency output for real-time monitoring of flow condition (laminar, turbulent or transition) can save flight time as well as data analysis time.
- Should contain internal signal conditioning. Signal conditioning is often at a premium on modern research aircraft in which the anemometer system may be installed.
- Should use readily available parts. Special order parts, for repair or changing the hot-film operating temperature, often have a long delivery time which can cause costly program delays.

Environmental Requirements

In defining the environment to which the temperature-compensated hot-film anemometer will be exposed, the most demanding application at the ADFRF is that of the modern fighter aircraft. Modern fighter aircraft are characterized by little available space for added instrumentation electronics and a test bay environment in which large extremes of temperature and vibration are considered normal.

To survive the environment outside the environmentally controlled test bays, the temperature-compensated hot-film anemometer

- Must be rugged. The vibration to which the anemometer may be exposed in many modern aircraft can destroy fragile equipment. The design must satisfy the environmental requirements of all NASA and military specifications for airborne electronics.
- Must be small. In many modern high-performance aircraft, space is limited, and several anemometers will usually be required, making size a critical parameter.
- Should be a modular design. A modular construction allows packaging to be tailored to the specific size and shape of the available mounting location.
- Should have low-power dissipation. Since operation without cooling at high ambient temperatures is required, self-heating of the electronics should be minimized to avoid exceeding the manufacturer's specifications on any of the components.

ANEMOMETER DESIGN

Functional Design

As can be seen in the functional block diagram of the temperature-compensated hot-film anemometer (Figure 3), temperature is compensated by the temperature sensor and two resistors, R_s in series with the temperature sensor and R_p in parallel with the temperature sensor and the R_s resistor. The temperature sensor used has a much greater temperature coefficient than that of the hot-film sensor, allowing the network to provide the desired hot-film heating throughout the operating temperature range.

The variable inductor (frequency trim) allows optimizing the frequency response of the anemometer to the resistance of the sensor and capacitance of the wiring for each individual installation.

The anemometer also contains separate signal conditioning with active filters for the dynamic and steady-state outputs. This allows independent changes in the gain and frequency response of each output to accommodate differing recording system requirements or special tests, such as measurements of low-amplitude high-frequency disturbance waves.

The side of the whetstone bridge that contains the temperature sensors and compensation resistors R_s and R_p is five times the resistance of the side containing the hot-film sensor. This ratio has been selected to accommodate the nominal resistance of the hot-film and temperature sensors being used and can be easily changed to accommodate other sensor resistance values.

Detailed Design

With the sensors wired as shown in the functional block diagram (Figure 3), most noise signals induced in the sensor wiring will appear as common mode noise and can be rejected by a well-designed anemometer. The amplifier used in the temperature-compensated hot-film anemometer is comprised of a high gain (gain = 1000) instrumentation amplifier followed by a single transistor power amplifier to provide the current required to maintain the hot-film temperature. The amplifier output offset is fixed at 1.6 V, the approximate output level for laminar flow. The use of the instrumentation amplifier provides a large common mode rejection

(110 dB), giving the anemometer a very low noise, high quality output.

The signal conditioning contained within the anemometer is comprised of separate active filters with buffered outputs so that the frequency or gain of one output can be altered without affecting the other output. The dynamic output signal conditioning filter is band pass with output sensitivity being single resistor selectable, and the steady-state output signal conditioning filter is low pass with single resistor selectable sensitivity and a trimming potentiometer for offset control.

The temperature-compensated hot-film anemometer is contained on a 2.5 × 3.3 in. (6.3 × 8.3 cm) printed circuit card 0.53 in. (1.3 cm) thick (Figure 4), with a power consumption of < 3 W. Since the temperature compensation resistors Rs and R_p may be required to be any value, the anemometer allows the use of two paralleled resistors in each of these positions to facilitate nonstandard resistance values. The printed circuit card can be installed within an enclosure tailored to the number of anemometers required and any restrictions in geometry imposed by the mounting location. Examples are shown for five channel and fifteen channel (Figure 5) hot-film anemometer boxes that have been used on two different flight research projects.

The temperature-compensated hot-film anemometer sensor wiring in the test vehicle uses two conductor-shielded wires (as is commonly used in aircraft instrumentation and avionics systems), with one conductor each to the hot-film and temperature sensors and the shield (anemometer ground) to a common junction of both sensors. The design allows portions of the wiring, which must be run on the external surface of the test vehicle, to use three conductor flat ribbon wire or three single conductor wires which can be spliced onto the two conductor-shielded wire.

To satisfy the requirements of small size and low-winding resistance for airborne use, the variable inductor was specially designed and fabricated in-house for the anemometer. All other parts are commercially available and were selected for performance specification in an airborne environment, availability, and cost.

USE OF THE ANEMOMETER

The hot-film and temperature sensors should be bonded to the test surface with an adhesive compatible with the airfoil surface and the sensors. The hot-film sensor should be aligned such that the active element of the sensor is nearly perpendicular to the expected direction of the airflow, and the temperature sensor should be bonded adjacent to and slightly aft of the hot-film sensor (Figure 6) to avoid any possible flow disturbance over the hot-film sensor active element. Flight data on an F-14 aircraft with a variable sweep wing has shown that an alignment error of 15° to the true airflow direction is acceptable for proper anemometer operation.

The wiring on the external surface from the sensors to an entry through the aircraft skin may use flat ribbon or single conductor wires, but should be spliced onto two conductor-shielded wires for long wire lengths inside the aircraft. As a result, the induced noise will be reduced by the shielded wire. The external wiring should be routed in the direction of airflow and may be secured to the surface and covered with a suitable tape or potting material, depending on the severity of the environment it will be exposed to.

When the temperature-compensated hot-film anemometer system is installed on a test vehicle, it is important that the resistance of the wiring from the anemometers to the sensors is known. The wiring resistance is required in the calculation for the two temperature compensation resistors. An error in the value of the wiring resistance can cause a large change in the hot-film operating temperature, since the hot-film operating resistance will normally be between 10 and 20 ohms.

The hot-film operating resistance can be calculated by analyzing the sensor and resistor circuitry (Figure 3) for the amplifier inputs. Because of the offset of the amplifier, the inputs may be assumed to be equal, simplifying the calculation. The error caused by the assumption is less than the error from the accuracy of the resistors (0.1 percent) and can be ignored. The values of the two resistors within the anemometer that are required for temperature compensation then can be calculated using the relationship derived for the hot-film operating resistance as follows:

$$(R_f + R_w) = \frac{(R_t + R_w + R_s)(R_p - 5R_{sh})}{5(R_t + R_w + R_s + R_p) + R_{sh}}$$

where

R_f is hot-film operating resistance,
R_t temperature sensor resistance,
R_s value of series resistor,
R_p value of parallel resistor,
R_w resistance of sensor wire, and
R_{sh} resistance of sensor common wire (shield).

Because the value of R_p will normally be several hundred to several thousand ohms, if the resistance of the sensor common wire R_{sh} is made small (by the use of short wire length or large gage wire), then R_{sh} will be insignificant and may be deleted. This simplifies the calculation of R_s and R_p, giving the relationship

$$R_s = \frac{\sqrt{(R_{th} - R_{tl})^2 + (R_{fh} + R_w)(R_{fl} + R_w)\frac{(R_{th} - R_{tl})}{(R_{fh} - R_{fl})}}}{2} - \frac{(R_{th} + R_{tl} + 2R_w)}{2}$$

$$R_p = \frac{5(R_{fh} + R_w)(R_{th} + R_w + R_s)}{(R_{th} + R_w + R_s - 5R_{fh} - 4R_w)}$$

where

R_{fh} is hot-film operating resistance at high temperature,

R_{th} temperature sensor resistance at high temperature,

R_{fl} hot-film operating resistance at low temperature, and

R_{tl} temperature sensor resistance at low temperature.

The calculated resistance values may be obtained through the use of two resistors in parallel to avoid the need of a special purchase for nonstandard resistance values.

After the system is installed, the anemometer requires adjustment of the frequency compensation variable inductor and steady-state output offset to provide proper operation. The variable inductor may be adjusted for maximum frequency response (without oscillating) when air is being blown over the hot-film sensor. After the anemometer is properly adjusted, no further adjustments are required unless the hot-film sensor is replaced because of damage, or the measurement location is changed.

ANEMOMETER FLIGHT USAGE

Anemometer Installation

At the present time the temperature-compensated hot-film anemometer has been used to obtain boundary-layer flow transition data on F-14 and F-15 flight research aircraft. The hot-film and temperature sensors were bonded to the wings which had been covered with a fiberglass glove. Single conductor wiring was run to the aft end of the glove. On the F-14 installation (Figure 7a), the wiring entered an access location aft of the glove and was spliced onto the two conductor-shielded wiring. On the F-15 installation (Figure 7b), the wiring was spliced onto the two conductor-shielded wires and then covered with a potting material, run to the inboard side of the glove, and forward to an access panel.

Because of limitations imposed by the fiberglass glove used on the F-14 aircraft, the maximum speed flown was Mach 0.82. However, on the F-15 research aircraft, the temperature-compensated hot-film anemometer successfully provided airflow transition data at airspeeds up to Mach 1.4 (the Mach number on this aircraft was limited by an unrelated experiment) and up to 40,000 ft (12,192 m) altitude. An airspeed up to Mach 1.8 was flown during the development flights using a modified constant-temperature anemometer on the F-104G/FTF aircraft (Reference 2).

The dynamic output of the temperature-compensated hot-film anemometer was recorded using an onboard airborne tape recorder with a wideband frequency modulation record amplifier. The steady-state output was recorded on the aircraft instrumentation system for telemetry to the ground station for real-time analysis.

A problem of hot-film sensor failure was encountered during the F-14 flight research project, but no sensors were damaged on the F-15 flight research project. Initially, on the F-14 project, the sensors were purchased from a new manufacturer and some were defective. The manufacturer eventually solved the production problem and replaced the defective sensors. The only other sensor failure occurred when a grain of sand hit the active portion of the hot-film sensor and cut the active element.

For both of the projects, the operating temperature of the hot-film sensor was set for 90°C above the sensed local stagnation temperature. This is the same temperature that was used during the development flights for the compensation scheme being used. Since the anemometer works well at this condition, and the F-14 and F-15 flights were for gathering research data rather than anemometer development, the decision was made not to change the operating temperature at that time. A flight test project for anemometer enhancement is planned at present. Along with optimizing the signal conditioning for disturbance wave detection, the optimum operating temperature will be investigated and reported.

Dynamic Output

The onboard instrumentation tape recorder was replayed and analyzed to evaluate the signal quality of the dynamic output of the anemometer by measuring the noise during pure laminar flow where the anemometer output should have very low noise. For these tests, the noise was found to be below the noise threshold of the tape recorder for all anemometer channels. On a later flight, with a high gain on the dynamic outputs, the noise was measured and the signal-to-noise ratio found to be greater than 65 dB.

The gain of the dynamic outputs recorded on the five tape recorder tracks was increased to 25 times normal for one flight and analyzed for low-amplitude, high-frequency content. The analysis showed high-frequency disturbance waves during several test points. Time history and frequency spectrum plots (Figure 8) are shown for one test point.

Steady-State Output

The steady-state output from the anemometer provided such an excellent flow transition indication (Figure 9) that on one of the projects with only five tape recorder tracks available, fifteen anemometers were installed, and the real-time steady-state outputs were used for all flight planning. The five dynamic outputs that were tape recorded were used only for detailed analysis, and the tape was not replayed for flow analysis until after all flights for the project had been flown.

A problem encountered during analysis of the steady-state output was that the output did not give a good indication of the initial onset of flow transition, which is desirable if the flow transition occurs slowly. The output filter frequency response has now been changed (Figure 10a) to pass the anemometer flow transition spikes (Figure 10b) at a reduced amplitude. The improved steady-state output has not yet flown, but should be used on a flight test project by mid-1988.

CONCLUSIONS

The temperature-compensated hot-film anemometer has been shown to provide excellent high quality boundary-layer flow transition data through subsonic, transonic, and supersonic flight. No adjustment of the anemometer was required during or between flights of greatly differing airspeed and altitude profiles. Once the system was installed, no further changes were required except when the hot-film sensor was damaged. The steady-state output of the anemometer is of sufficient quality to provide a real-time indication of the boundary-layer flow transition. Analysis of the dynamic output is limited only to the time segments where the real-time data indicates a need to do so. The anemometer exhibits very low noise, making possible the detection of high-frequency disturbance waves in addition to the normal flow transition for which it was designed.

The lightweight of the selected components and the small printed circuit board size contribute to the ability to withstand large levels of vibration, making the anemometer suitable for use in the severe environments encountered in modern high-performance aircraft.

On the F-14 project, the small size and low power consumption of the anemometer has allowed fifteen anemometers to be installed with less space requirement and lower power consumption than the five miniature constant-temperature hot-film anemometers for which the mounting location had been originally designed. This reduced the number of flights required to obtain the flow transition measurements, saving considerable cost and time.

Future projects planned to use the temperature-compensated hot-film anemometer include one project proposed for mid-1988 to optimize the anemometer for disturbance wave detection and hot-film operating temperature. Other possible future projects include extending the operating speed range and investigating natural laminar flow at speeds up to Mach 3. Results of future work will be reported as they become available.

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2. Meyer, R.R., Jr., "A Unique Flight Test Facility: Description and Results," NASA TM-84900, 1982.

3. Chiles, H.R. and Johnson, J.B., "Development of a Temperature-Compensated Hot-Film Anemometer System for Boundary-Layer Transition Detection on High-Performance Aircraft," NASA TM-86732, 1985.

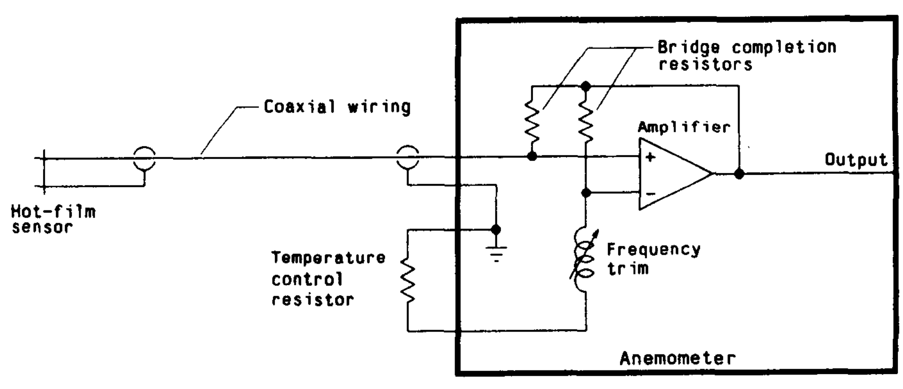

Figure 1. Block diagram of constant-temperature anemometer.

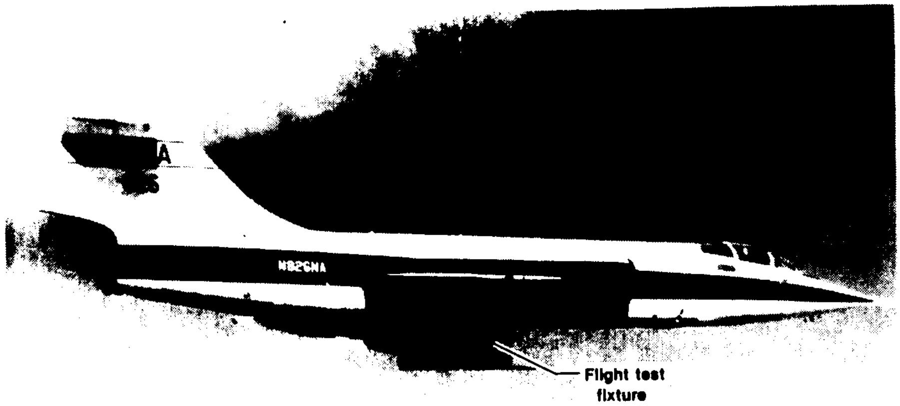

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Figure 2. F-104G aircraft with flight test fixture.

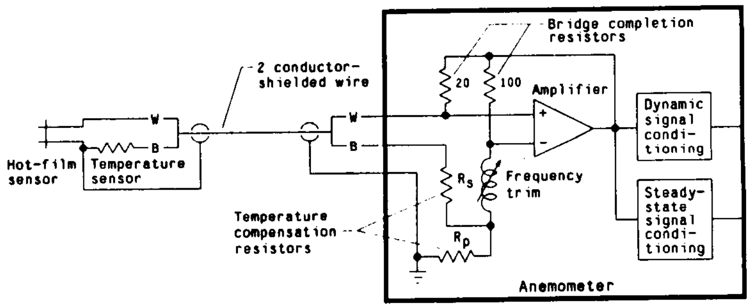

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Figure 3. Functional block diagram.

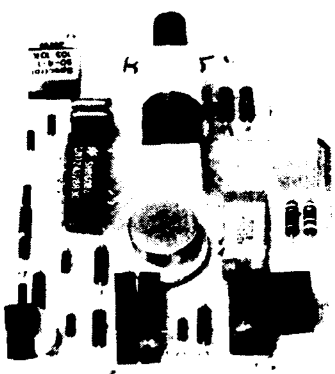

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Figure 4. Temperature-compensated hot-film anemometer.

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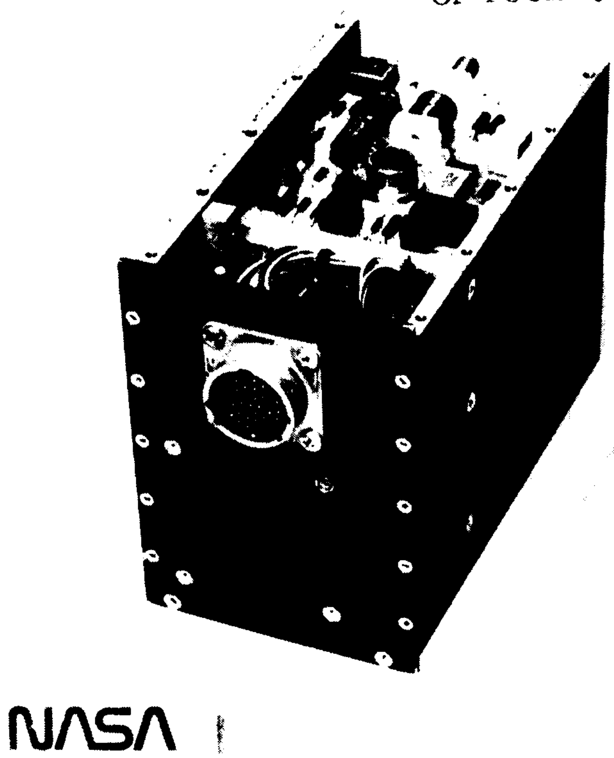

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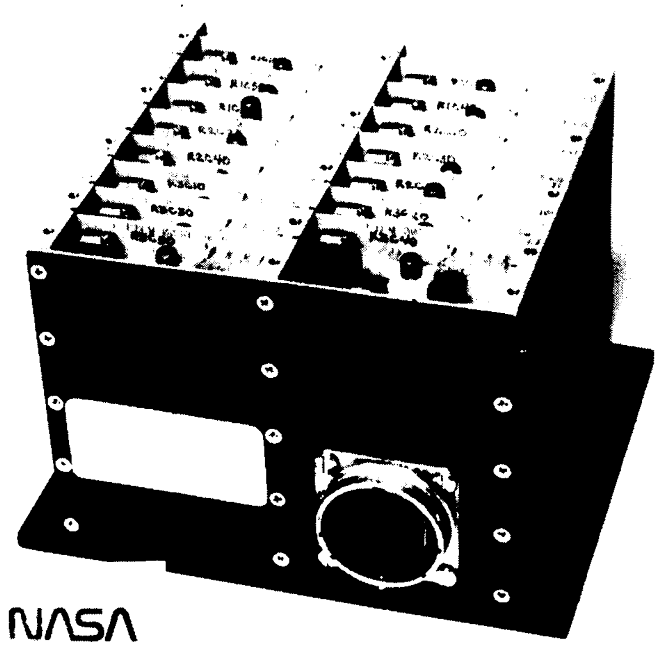
(a) 5-channel anemometer box.



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(b) 15-channel anemometer box.

Figure 5. Hot-film anemometer boxes.

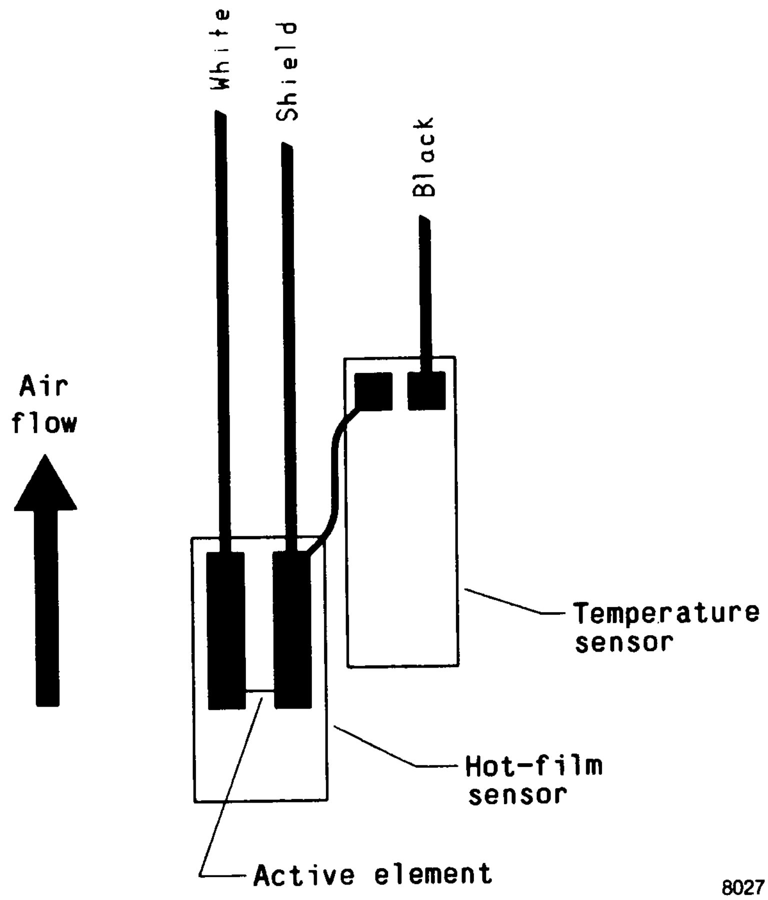

Figure 6. Hot-film and temperature sensor installation.

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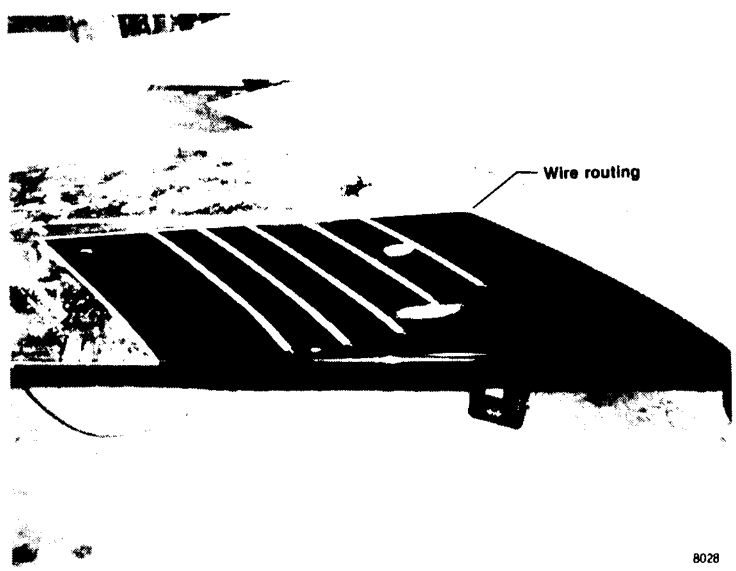
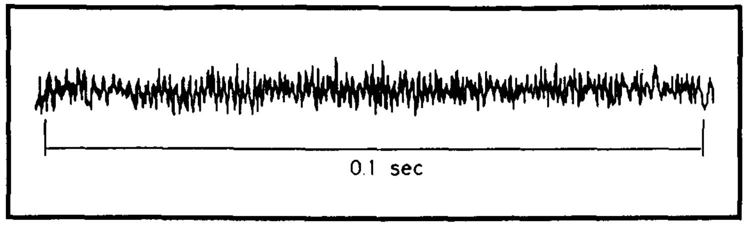
(a) F-14 right wing sensor installation.

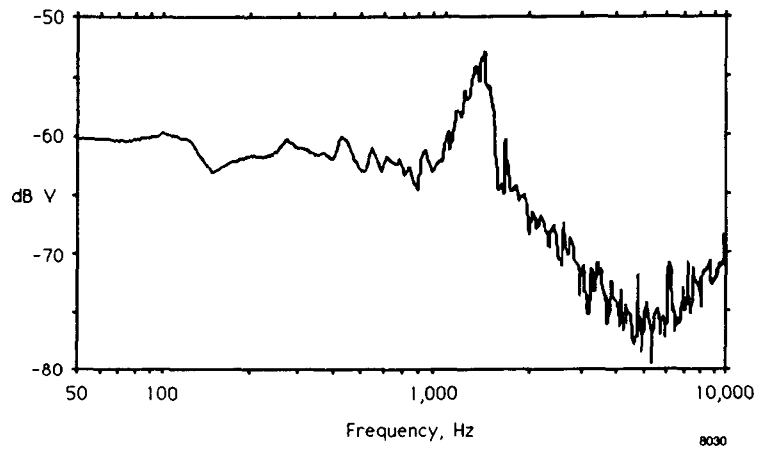


(b) F-15 right wing sensor installation.

Figure 7. Sensor installation on wing.



(a) Time history plot.



(b) Frequency spectrum plot.

Figure 8. Flight data.

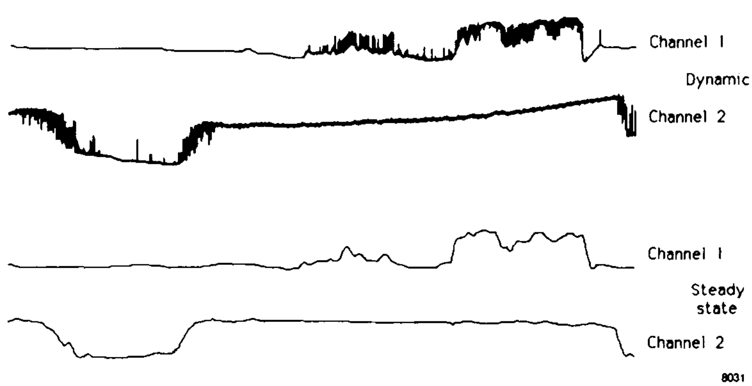
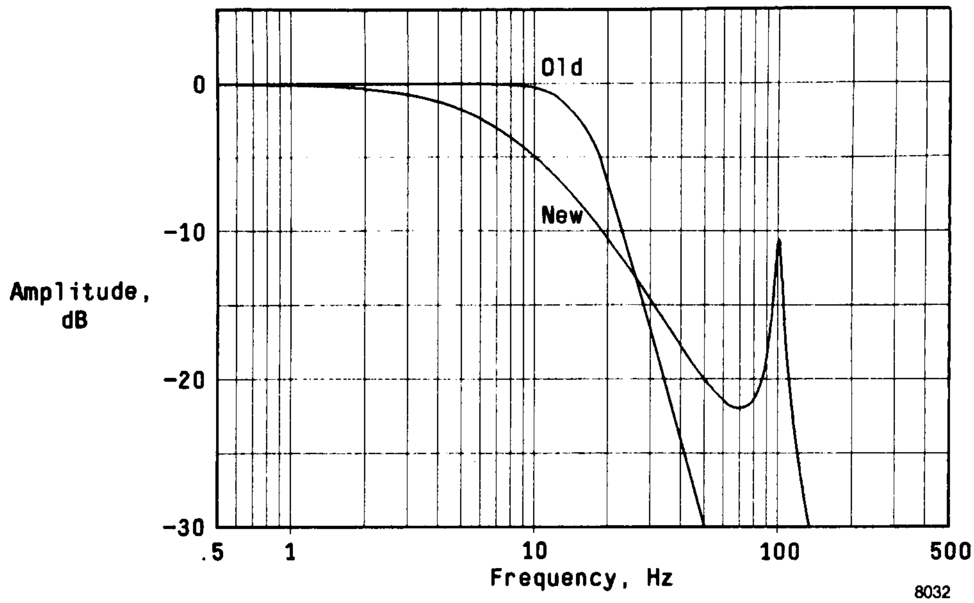
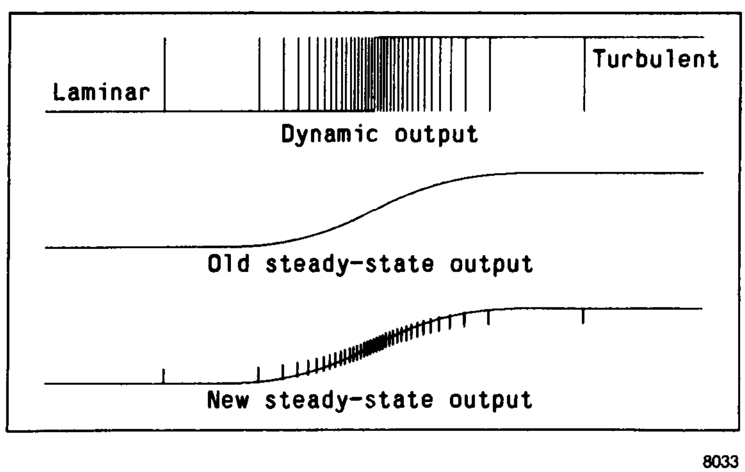


Figure 9. Flight data comparing dynamic and steady-state data.



(a) Frequency spectrum plot.



(b) Steady-state time history plot.

Figure 10. Steady-state output filter.

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15. Supplementary Notes

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16. Abstract

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