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Flight Experience with Lightweight, Low-Power Miniaturized Instrumentation Systems

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Engineers at the NASA Dryden Flight Research Facility (NASA-Dryden) have conducted two flight research programs with lightweight, low-power miniaturized instrumentation systems built around commercial data loggers. One program quantified the performance of a radio-controlled model airplane. The other program was a laminar boundary-layer transition experiment on a manned sailplane. The purpose of this article is to report NASA-Dryden personnel's flight experience with the miniaturized instrumentation systems used on these two programs. This article will describe the data loggers, the sensors, and the hardware and software developed to complete the systems. It also describes how the systems were used and covers the challenges encountered to make them work. Examples of raw data and derived results will be shown as well. For some flight research applications where miniaturized instrumentation is a requirement, the authors conclude that commercially available data loggers and sensors are viable alternatives. In fact, the data loggers and sensors make it possible to gather research-quality data in a timely and cost-effective manner.

Nomenclature

a_n = normal acceleration, g
a_x = axial acceleration, g
C_D = vehicle drag coefficient
C_L = vehicle lift coefficient
L/D = lift-to-drag ratio
$\bar{q}$ = dynamic pressure, psf
T = total thrust, lb
V_{true} = true airspeed, ft/s
α = angle of attack, deg
α_0 = angle-of-attack breakpoint, deg
Δ_{p_l} = left-engine static pressure rise, psi
Δ_{p_r} = right-engine static pressure rise, psi
δ_e = symmetric elevon deflection, deg
δ_{e_l} = left-elevon deflection, deg
δ_{e_r} = right-elevon deflection, deg

Introduction

ENGINEERS at NASA Dryden Flight Research Facility (NASA-Dryden) fly radio-controlled model aircraft for preliminary validation of risky design concepts. For programs with limited budgets, the engineers also operate a manned, self-launching sailplane as a low-speed flight research platform. Although the two research efforts are quite different, their instrumentation system requirements are similar. Each system requires up to 24 channels of data acquisition, onboard recording, and operation using batteries, in addition to small size, weight, and price.

The instrumentation systems currently in use at NASA-Dryden are overly complex for these applications. A class of instruments, commonly called data loggers, was investigated as an alternative. Data loggers are commercially available data acquisition units with onboard storage. From the Tattletale® line of data loggers, model 4 was selected for the radio-controlled model aircraft. (Tattletale is a registered trademark of Onset Computer Corp., North Falmouth, Massachusetts.) Later, when model 7 became available, it was selected for the manned sailplane.

This article describes the flight experience gained with miniaturized instrumentation systems built around the model 4 and model 7 data loggers. The report will cover the transducers the data loggers were interfaced to and how they were used. Additional discussions include the software and hardware developed to complete the systems, and the challenges faced in getting the systems to work properly. Examples of raw and derived data will be shown.

Flight Experience with a Radio-Controlled Model Aircraft

Test Objective

Model 4 (see Table 1) has been used on several model aircraft flight programs where research-quality data were required for quantitative analysis. An objective of one of these flight programs was to measure the performance of the test aircraft, which was powered by two ducted-fan engines. Performance parameters of interest were the lift-curve slope, the lift-to-drag ratio, and the trim curve.

Maneuver Design

A flight test maneuver commonly used to quantify aircraft performance is a quasistatic pushover-pullup (POPU). Properly executed, a single POPU maneuver can simultaneously characterize the lift curve, the lift-to-drag ratio, and the trim curve over a large angle-of-attack range.[1] For its simplicity, the POPU maneuver was initially selected as the primary maneuver for performance measurement.

Measurement Requirements and Sensor Selection

Minimum measurement requirements for the test program were determined from the test requirements and maneuver selection. Measurement of the aerodynamic forces (lift and drag) and their nondimensional coefficients required measurement of a_x and a_n, α, $\bar{q}$, and T.

Accurate measurement of the thrust produced by the ducted-fan engines was central to obtaining accurate drag measurements. An engine and fan assembly was calibrated in a wind-tunnel test program. Then, a model of engine thrust as a linear function of dynamic pressure and static pressure rise across the fan assembly was obtained. Measurement of in-flight thrust also required measurement of the static pressure rise across

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Table 1 Comparison of Tattletale date loggers

Specification	Model 4	Model 7
Microprocessor	6301	68332
Onboard memory	32 kbytes	2 Mbytes
A/D converter resolution, bits	10	12
Maximum sample rate, samples/s	600 (approximate)	100,000
Host computer	PC compatible	Macintosh (PC interface planned)
Language	TTBASIC	C
RS-232 port	Yes	Yes
Parallel port	No	Yes
Battery-backed RAM	Yes	No
Hard drive	No	Yes (up to 80 Mbytes)
Real-time clock	No	Yes
Size, in.	3.725 by 2.25 by 0.8	4.0 by 2.75 by 0.44
Weight, oz	2.2	2.5
Weight including hard drive, oz	——	8
Maximum power consumption, mW	100	500
Typical power with hard drive, W	——	3
Approximate cost with startup materials	$500	$3300

Table 2 Sensor specifications

Variable	Model number	Range	Resolution	Accuracy
α, deg	NASA-Dryden noseboom	-5–40	0.04	0.25
$\bar{q}$, psf	SenSym 142SC01D[a]	0–55	0.058	0.144
δ_{e_l}, deg; δ_{e_r}, deg	NASA-Dryden control position transducer	-40–20	0.06	0.20
Δ_{p_l}, psi; Δ_{p_r}, psi	SenSym 142SC01D[a]	0.0–0.6	0.0006	0.001
a_x, g	IC sensors 3110-002[b]	-1–1	0.002	0.015
a_n, g	IC sensors 3110-005[b]	-0.5–2.5	0.003	0.02

[a]SenSym Inc., Sunnyvale, California. [b]IC Senors, Milpitas, California.

the left- and right-fan assembly, Δ_{pl} and Δ_{pr}, respectively. Measurement of the trim curve also required measurements of the elevon control surface deflections δ_{el} and δ_{er}.

Because of size and weight constraints, no lateral- or directional-axis variables were measured. All test maneuvers were flown while minimizing cross-axis motion; the analysis assumed purely longitudinal motion.

The selection of sensors for the test program was driven primarily by weight and power considerations. Table 2 presents sources and specifications for the sensors used in the test program.

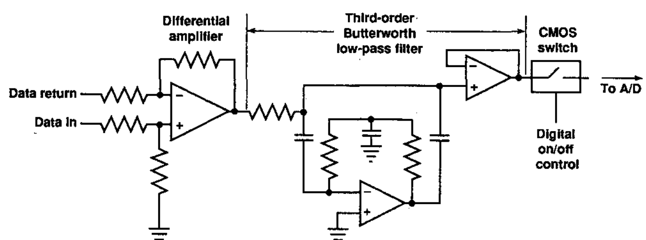

Fig. 1 One channel of analog multiplexer board used with model 4.

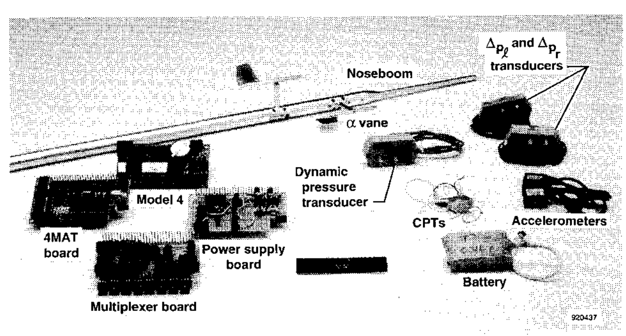

Fig. 2 Model 4 onboard data acquisition components.

Instrumentation System

Model 4 was the core of the instrumentation system used on the model aircraft. A 128-kbyte memory expansion board was added to increase data storage capability to approximately 150 kbytes. Two application boards were also needed to complete the hardware. These were designed at NASA-Dryden and consisted of an analog multiplexer board and a power supply board. The circuitry for each channel on the multiplexer board consisted of a differential amplifier, a third-order Butterworth low-pass filter, and a complementary metal oxide semiconductor (CMOS) switch. The schematic is shown in Fig. 1. The power supply board provided voltage regulation and excitation to the sensors, and contained a voltage reference for the analog to digital (A/D) converter. Figure 2 shows the complete data acquisition system including the model 4, the memory expansion board, application boards, battery pack, and all sensors. These components weighed 1.7 lb and consumed 500 mW of power. Figure 3 shows the model 4 package installed in the nose section of the model aircraft.

Software written at NASA-Dryden controlled model 4 in flight. It was uploaded from the PC compatible before flight and was left in standby mode. At the runway, a ground operator threw a switch to start data logging and released the aircraft for takeoff. Model 4 recorded eight channels of data continuously at 25 samples/s. Data logging stopped automatically in approximately 6 min when random access memory (RAM) was full.

By using an 8086 class PC compatible, a flight's data set (150 kbytes) could be downloaded in approximately 6 min and converted to engineering format in approximately 30 min. Although the total time is comparatively long, it was adequate for the project needs. The total time can be shortened by using a more powerful PC compatible.

Implementation Challenges

In anticipation of potential interference between the avionics and instrumentation systems, the power switch for the instrumentation system was attached to a servoactuator of the avionics system. This gave the pilot the ability to turn the instrumentation system on or off in flight. Likewise, the model aircraft receiver was programmed to turn off the instrumentation system automatically upon loss of the transmitter signal. The logger program and any data gathered would not be lost upon shutdown because of the 3-V backup battery.

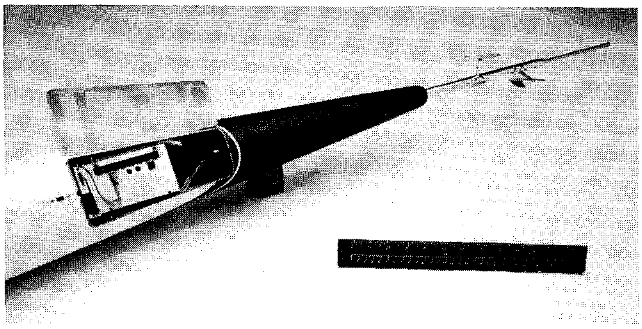

Fig. 3 Model 4 package installed in model aircraft.

There was never any interference between the systems in flight. However, getting the systems to work together on the ground was a major challenge initially.

From successful noninstrumented flights it was clear that the avionics system worked. From practice flights using a different model airplane it was also clear that the instrumentation worked. However, for an unknown reason, the preflight checks sometimes failed with the instrumentation system in place and turned on. Different transmitters, receivers, uplink frequencies, and antenna orientations were tried without success. Boosting uplink power from 0.5 to 5 W provided some improvement; however, upon elimination of an intermittent ground loop in the instrumentation the preflight checks succeeded consistently. With the problem solved, the extra uplink power was probably not needed, but was used anyway.

The high-vibration environment in the model aircraft provided another challenge. At high-power settings, the structural vibration from the reciprocating engines was in excess of 5 g. This overwhelmed the lower level acceleration signals from the lift and drag forces during the test maneuver. Different mounting techniques and locations for the engines and accelerometers were attempted, but failed to alleviate the

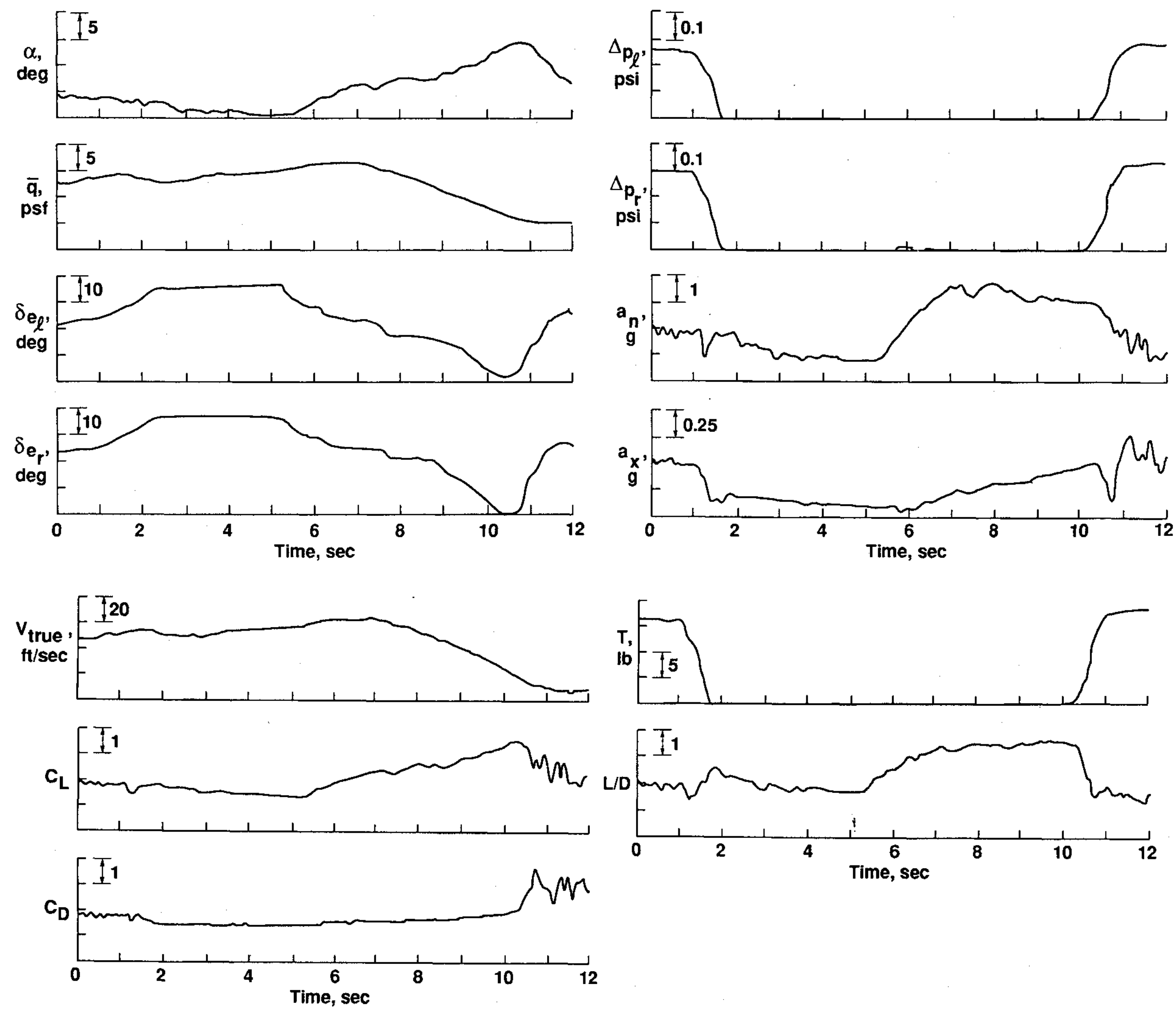

Fig. 4 Time history of pullup maneuver for model aircraft.

problem. Ultimately, a "pullup" maneuver was developed that could be flown with the engines at an idle power setting. Under these conditions the accelerometer data were suitable for analysis.

Results of Model Aircraft Flights

Figure 4 shows a time history of a representative pullup maneuver. Included are the raw measured variables, α, $\bar{q}$, δ_{el}, δ_{er}, Δ_{pl}, Δ_{pr}, a_n, and a_x, as well as the derived variables V_{true}, C_L, C_D, T, and L/D. Light turbulence is evident in α, a_n, and a_x.

Figures 5–7 show results derived from the time history data shown in Fig. 4. The turbulence-induced and other noises were removed from a subset of the raw data using a digital low-pass filter, and these data were used in the following results.

Figure 5 shows the flight-determined lift curve for the aircraft. The small symbols represent the C_L and angle-of-attack measurements at each sample point, and the solid line is a piecewise linear fit to the data points. There is a change in slope at $\alpha = \alpha_0$ where the aerodynamics of the aircraft change character. Both above and below $\alpha = \alpha_0$ the slope is consistent.

Figure 6 shows the flight-determined L/D for the aircraft. The small symbols represent the L/D measurements at each sample point, and the solid line is a hand-faired estimate through the data points. The dotted lines above and below the solid lines are estimates of the error bounds for the data based on instrumentation error estimates, data repeatability, maneuver quality, and signal-to-noise ratio.

Figure 7 shows the flight-determined trim curve for the aircraft. The small symbols represent the δ_e and angle-of-attack measurements at each sample point, and the solid line is a piecewise linear fit to the data points. As with the lift curve shown in Fig. 5, there is definite change in the trim curve at approximately $\alpha = \alpha_0$, where there is a measurable change in the aircraft aerodynamics.

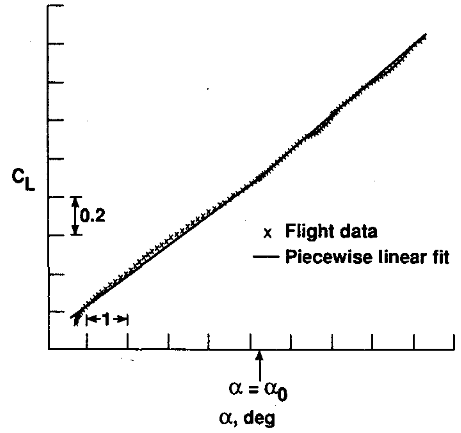

Fig. 5 Flight-determined lift curve for model aircraft.

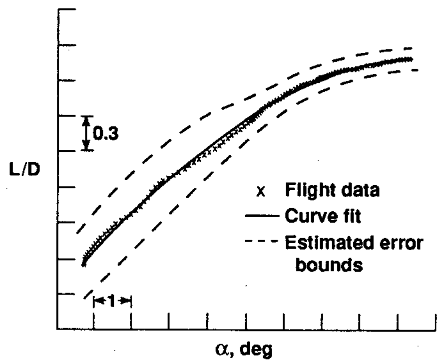

Fig. 6 Flight-determined lift-to-drag ratio for model aircraft.

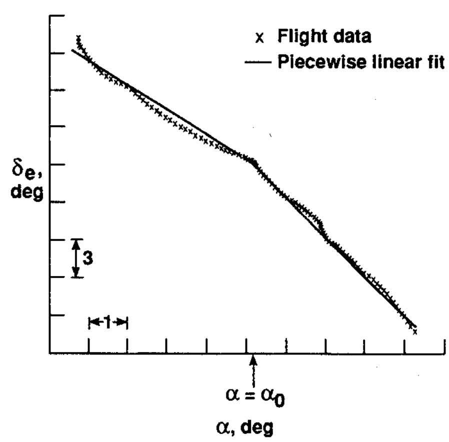

Fig. 7 Flight-determined trim curve for model aircraft.

Flight Experience with a Manned Sailplane

Test Objective

For programs with limited budgets, a self-launching sailplane (shown in Fig. 8) serves as a low-speed flight research platform. The objective of one flight program was to determine the maximum size of excrescence tolerable on a laminar-flow wing before boundary-layer transition occurs. Excrescences are rough spots on a surface.

Experiment Design

A set of calibration flights determined the natural boundary-layer transition location on the wing. In subsequent flights, excrescenses of varying thickness were applied to the wing, and changes in the boundary-layer transition location were observed. The excrescences were simulated by using vinyl sheets 0.032 in. or less in thickness. The sheets were wrapped around the leading edge of the wing leaving an aft-facing step as shown in Fig. 9. Maneuvers were flown 5000–10,000 ft above sea level, and straight and level flight was used to obtain stabilized data.

Measurement Requirements

To pinpoint transition location, an array of hot films (shown in Fig. 10) was laid on the wing such that part of the array

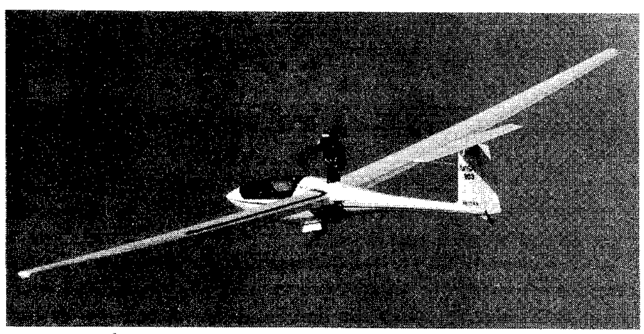

Fig. 8 PIK 20E self-launching sailplane.

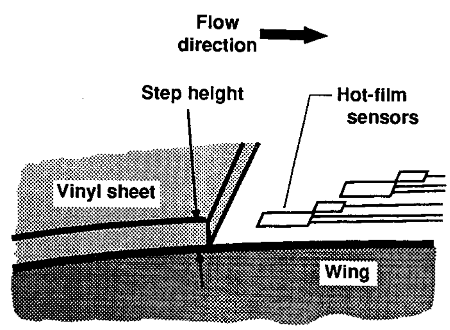

Fig. 9 Cross-sectional view of the test excrescence.

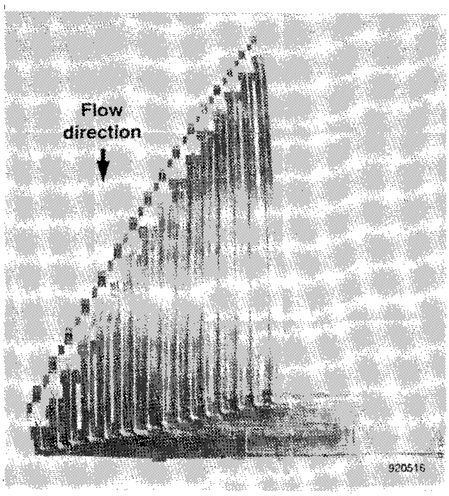

Fig. 10 Hot-film sensor array on wing.

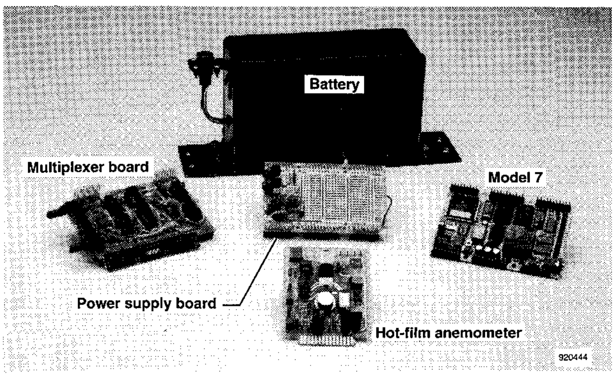

Fig. 11 Signal conditioning, data logging, and power components of model 7-based data acquisition system.

would see laminar flow, and part would see turbulent flow. Hot-film anemometers developed at NASA-Dryden[2] provided signal conditioning for the hot films. Figure 10 shows the hot-film array on the wing. It was a requirement to record eight of the hot-film signals at 1500 samples/s.

Air-data parameters such as outside air temperature, airspeed, and altitude were also measured. For expediency, these measurements were not recorded electronically. Rather, the pilot read the measurements from the cockpit instrument panel and noted them on the flight card. The pilot also noted the time for correlation to the electronic data.

Instrumentation System

Model 7 (see Table 1) was the core of this instrumentation system. Model 7 was selected for its high sampling rate capability and greater data storage capacity.

Two application boards were stacked on model 7 to complete the system. One was an eight-channel analog multiplexer board, and the other was a power supply board. Both were designed at NASA-Dryden. The circuitry for each channel on the multiplexer board consisted of a differential amplifier and a complementary metal oxide semiconductor (CMOS) switch. Overvoltage protection for the A/D converter inputs, a lamp driver, and triggering circuitry were included on this board as well. No antialiasing was included because it existed on the anemometers. A patch panel between the anemometers and the multiplexer board provided easy selection of hot films between flights. The power supply board provided voltage regulation and a voltage reference for the system, as well as a voltage offset for the differential amplifiers on the multiplexer board.

Figure 11 shows model 7, the analog multiplexer board, and power supply board. Also shown is one of the anemometers and the 72-Wh nickel-cadmium battery pack that powered the entire system. The size of the battery pack was driven by three factors: 1) the power requirements of the anemometers, 2) the flight time, and 3) the need to provide reserve capacity to power instrumentation added in the future. The anemometer chassis consumed up to 23 W when fully stocked, and flights generally lasted 1 h. The model 7 package alone consumed only 0.9 W. Figure 12 shows the battery pack, model 7 chassis, and anemometer chassis installed in the cockpit.

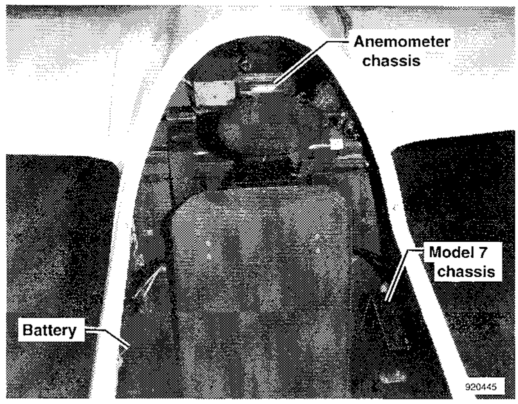

Fig. 12 Instrumentation installation in sailplane cockpit.

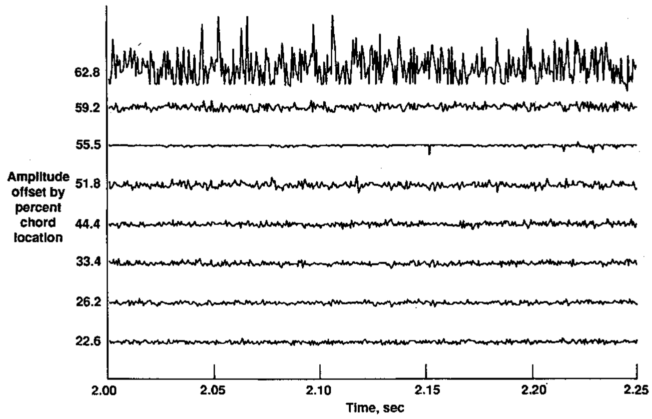

Fig. 13 Time history of hot films on smooth wing at 70 kt.

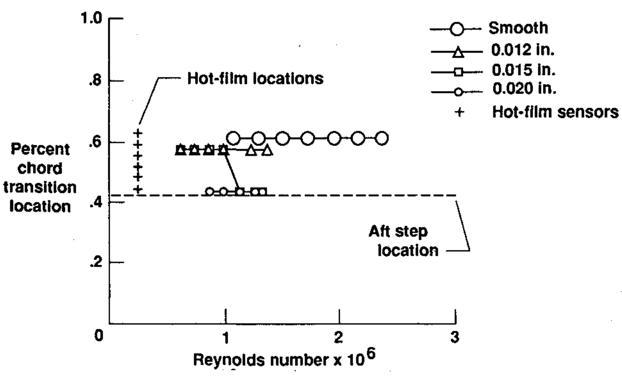

Fig. 14 Transition location for aft step configuration at 42.6% chord.

Software written at NASA-Dryden controlled model 7 in flight. It was uploaded from the Macintosh computer before flight and it remained in standby mode. When triggered by the pilot, it turned on a lamp in the cockpit, gathered eight channels of hot-film data at a rate of 1500 samples/s for 4 s, turned off the lamp, and waited for the next trigger. Data for up to 10 maneuvers could be captured in this manner during 1 flight.

A flight's data set (1 Mbyte) could be downloaded in approximately 3 min, and conversion of the data from binary format to engineering units only required a few minutes. Hence, flight data were available quickly after landing.

Implementation Challenges

The major challenge involved triggering the system. Initially, the triggering circuitry consisted of a digital input pin on model 7, a 100-kΩ pullup resistor, and a 6-ft wire to a switch on the control stick. This circuitry was susceptible to false triggering upon engine startup.

To solve the triggering problem, a 1-μF capacitor was attached to the digital input pin, and the pullup resistor was reduced to 1 kΩ. However, for added robustness, the software was changed to look for a trigger pulse lasting at least 0.25 s. Previously it had only looked for a momentary trigger. Furthermore, a lamp in the cockpit, previously illuminated only while data were being gathered, was programmed to blink once every 10 s after the memory was filled. This provided some visible indication of the system's state.

Results of Sailplane Flights

Figure 13 shows a time history of eight hot films for one maneuver conducted at 70 kt during a smooth-wing flight; i.e., a flight without excrescences. The signals are offset by chord location measured in percent chord. The lower amplitude signals, such as those from 22.6 to 59.2% chord, indicate laminar flow. The large amplitude signal at 62.8% chord indicates turbulent flow. Thus, the transition location for this maneuver was between 59.2–62.8% chord.

Figure 14 shows results derived from flights with aft-facing steps located at 42.6% chord. The transition location resulting from step heights of 0.012, 0.015, and 0.020 in. are compared with the transition location of the smooth wing. Notice that with all step heights the transition location moves forward. Whereas, the location resulting from step heights 0.012 and 0.020 in. appear to be independent of Reynolds number, the location resulting from the 0.015-in. step moves forward at Reynolds numbers greater than 10^6.

Concluding Remarks

The flight programs described acquired research-quality data in a timely and cost-effective manner using instrumentation systems built around commercially available data loggers and sensors. Data loggers are well-suited for applications requiring miniaturized instrumentation and onboard recording.

The data loggers provide large bandwidth and onboard storage capabilities in a small-sized and low-power package. In the case of the sailplane program, eight channels of data were acquired at 1500 samples/s for 40 s with 12-bit (0.024%) resolution. The package measured approximately 4 by 2.75 by 2.5 in., weighed approximately 8 oz, and consumed approximately 900 mW of power.

References

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[2]Chiles, H. R., "The Design and Use of a Temperature-Compensated Hot-Film Anemometer System for Boundary-Layer Transition Detection on Supersonic Aircraft," NASA TM-100421, 1988.