Use of a Navigation Platform for Performance Instrumentation on the YF-16

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An instrumentation package that makes use of an inertial navigation platform to obtain aerodynamic and performance flight test data has been developed. This package is being used quite successfully to obtain timely and accurate data during the General Dynamics YF-16 flight test program. This paper discusses the theoretical basis and practical aspects of using this instrumentation inertial reference set (IIRS) along with selected results obtained to date. Specific topics addressed include use of the IIRS to obtain flight path acceleration, α, β, normal load factor, rate of climb, airspeed, takeoff and landing velocities and distances, position error calibration through the Mach jump region, and wind information. This system has proved to be invaluable on the YF-16 program and has demonstrated many benefits over previously used performance instrumentation.

I. Introduction

IN aircraft performance flight testing, the engineer always is constrained in his selection of the onboard instrumentation systems by the need to get the maximum information in a minimum of flight time while insuring that the data derived are accurate enough for his needs. All of this must be done within the framework of allowable instrumentation, maintenance, and data reduction costs. In most cases, these constraints result in an instrumentation system tailored to the particular aircraft or type of testing being done. The system usually does not quite do the desired task, and yet costs more than what management or the customer would like.

The adaption of an inertial navigation platform to the task of gathering flight test information has been discussed for many years[1] but has not, with limited exceptions, been implemented because of a combination of factors. These include high initial cost, marginal long-term accuracy in unaided modes of operation, questionable day-to-day reliability in a flight test environment, and the fact that other instrumentation, such as the flight path accelerometer, could yield most of the desired information with acceptable accuracy for most aircraft for a much lower total cost.

A combination of recent developments has made the inertial platform more attractive for flight test use. First, the cost/accuracy ratio of these systems has begun to decrease dramatically with the introduction of new high-accuracy platforms. Secondly, over the same period of time, the mean time between failures of some of these systems has passed the 1000-hr mark. Finally, flight testing of the new generation of high-performance air-to-air combat aircraft is making demands that the instrumentation system yield more information than was required in the past. In addition, it must be able to determine accurately performance data over a large Mach, altitude, and load factor envelope under highly dynamic conditions. These data will be vitally important in determining the performance of the aircraft in the air-to-air role.

This paper makes some comments on the theoretical and practical aspects of using inertial navigation platforms as instrumentation inertial reference sets (IIRS) for performance flight testing, with emphasis on their use in the General Dynamics YF-16 Lightweight Fighter Prototype flight test program.

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II. IIRS Advantages

The IIRS has several basic advantages over other types of flight test instrumentation used for performance work. Most of these advantages are of particular interest when it is necessary to obtain accurate data during highly dynamic maneuvers or when the aircraft is following an arbitrary flight path.

The IIRS is a self-contained system that supplies all data needed to define the motion of an aircraft in three-dimensional space. Therefore, it serves as a unified data source for the majority of information needed to define the performance capabilities of an aircraft. This feature of the IIRS can reduce greatly time correlation problems that develop when four or five separate instruments are required to determine aircraft orientation, angular rates, accelerations, and velocities. In addition, the IIRS is not subject to inertial, aerodynamic, or pneumatic lags and is insensitive to moderate and high-frequency vibration. Since the unit is mounted internally in the aircraft, it is not subjected to weather, rough handling, temperature variations, etc.

A modified Delco Carousel V inertial platform was chosen for use as the YF-16 IIRS. This unit has a demonstrated mean time between failures of over 1000 hr, an average navigation accuracy of less than 1 n.mi./hr, and an extensive self-test/fault isolation capability. All of these features have contributed greatly to the overall success of the YF-16 test program and the demonstrated ability to run two or three data flights per day on each of two aircraft on a routine basis.

III. IIRS Mechanization

The Delco platform used on the YF-16 flight test program operates on the same principles and, in general, is mechanized the same as most other high-accuracy three-axis inertial platforms. For a detailed discussion of its characteristics, see Ref. 2. A schematic of the IIRS platform is shown in Fig. 1.

The YF-16 IIRS accepts true airspeed and pressure altitude inputs from the aircraft Central Air Data Computer (CADC). The CADC data are derived from nose probe static and total pressure sources. The IIRS North and East Earth-referenced velocities are vectorially added, and the result is subtracted from the true airspeed vector to compute horizontal wind speed and direction with respect to true North. These parameters, as well as true airspeed, are output from the IIRS, along with the inertial accelerations, velocities, angles, etc.

The CADC pressure altitude is used in the IIRS to damp the IIRS Earth-referenced vertical velocity and altitude on a long-term basis. This damping is necessary because of local variations in the Earth's gravitational field, but it has essen-

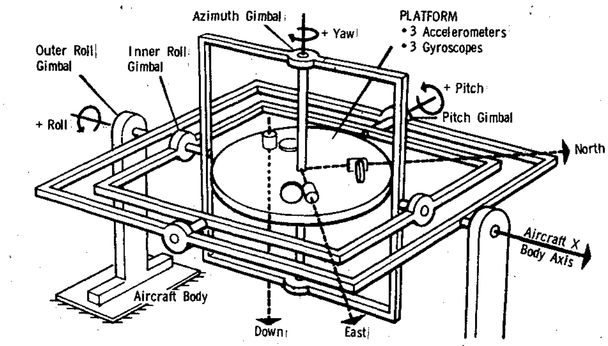

Fig. 1 Schematic of IIRS platform.

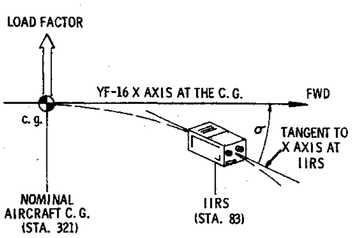

Fig. 2 Fuselage deflection.

tially no effect on sensed vertical acceleration, nor does it affect the validity of sensed short-term rates of climb during most types of testing.

The YF-16 IIRS has an extensive self-check system that monitors the platform instruments and the performance of the computer. These checks are performed many times a second, and the results are formed into a status word that is output along with the other IIRS-computed parameters. This word can be monitored on the ground real-time via telemetry to insure that the IIRS is functioning properly. A partial list of the YF-16 IIRS outputs is shown in Table 1.

IV. Data Reduction

The YF-16 data reduction procedures are designed to convert the IIRS information in the North, East, and down reference frame into performance parameters along and normal to the instantaneous flight path of the aircraft. This conversion is done in seven distinct steps that are discussed in detail in the following subsections.

Data Synchronization

In a highly maneuvering aircraft, time correlation within milliseconds is necessary to achieve the desired performance

Table 1 IIRS outputs

Parameter	Range	Accuracy
Baroinertial altitude	−1060 to 80,338 ft	[a]
True airspeed	425 to 2500 fps	[a]
Ground speed	±4096 fps	±2.8 fps
Latitude	±90°	0.0055[b]
Longitude	±180°	0.0055[b]
Wind direction	±180°	[a]
Wind speed	0 to 500 fps	[a]
Track angle	±180°	0.0055[b]
Drift angle	±180°	0.0055[b]
North velocity	±2500 fps	2.0 fps
East velocity	±2500 fps	2.0 fps
Down velocity	±2500 fps	2.0 fps
North acceleration	±9.0 g	0.002 g
East acceleration	±9.0 g	0.002 g
Down acceleration	±9.0 g	0.002 g
True heading	±180°	0.1°
Pitch	±180°	0.1°
Roll	±180°	0.1°
Status word	...	...

[a] Dependent on CADC accuracy. [b] Output resolution.

data accuracies. Therefore, synchronizaton of IIRS acceleration, velocity, and angular outputs is required because all of these parameters are not updated in the IIRS computer at the same instant of time. Since the accelerations are the most critical from an accuracy standpoint, the velocities and angles are adjusted in the data reduction procedure to represent their respective values at the exact time that the accelerations were updated in the IIRS computer. This is done, for each parameter, by using a fifth-order curve fit routine to represent the variation of that parameter with time and by picking off the curve function value at the desired correlation time. This correction procedure has essentially no effect on velocity accuracy but can, under certain circumstances, adversely affect the accuracy of computed angular values. This is discussed in more detail in Sec. V.

Fuselage Bending Correction

The IIRS is located in the forward avionics bay of the YF-16 and thus experiences motions slightly different from those that are sensed at the aircraft center of gravity (c.g.) during maneuvering flight. Part of this difference is due to forward fuselage bending as a result of aerodynamic and inertial forces. This deflection can be determined by analysis of the aircraft structural characteristics and pressure model tests in the wind tunnel at various Mach, altitude, and angle-of-attack conditions. Once the bending angle has been determined, it can be used to convert platform angles to true angles of the body axes at the c.g. with respect to the North, East, and down reference frame. The only deflection that the YF-16 normally experiences is in the pitch axis, and thus the following equations represent the complete orientation angle correction applied during steady or maneuvering flight. A diagram of the forward fuselage deflection is shown in Fig. 2.

$$\sigma = f\,(\text{Mach, load factor, dynamic pressure, angle of attack, and fuel weight}) \tag{1}$$

$$\psi = \theta_Y + \sigma \sin\theta_R \tag{2}$$

$$\theta = \theta_P + \sigma \cos\theta_R \tag{3}$$

$$\phi = \theta_R \tag{4}$$

where:
σ = forward fuselage bending angle
θ_P = platform pitch angle
θ_R = platform roll angle
θ_Y = platform yaw angle
ψ,θ,ϕ = true angles of the aircraft body axes at the c.g. with respect to the reference North, East, and down.

Center-of-Gravity Correction

In order to correct out IIRS sensed accelerations and velocities induced by aircraft rotation, it is necessary to know the location of the IIRS platform relative to the aircraft c.g. in three axes and the rotation rate and angular accelerations that the IIRS is experiencing. Since the c.g. travel with fuel consumption of the YF-16 is fairly small, the location of the IIRS relative to it is essentially constant.

The body axes' angular rates and accelerations can be determined by differentiating the corrected platform angles to obtain angular rates, transforming these to body axes' angular rates, and differentiating them with respect to time to obtain angular accelerations. This is done using a moving 20-point curve-fitting procedure to track the angles as a function of time and then differentiating the curve-fitted lines to obtain angular rates and accelerations time-synchronized with the IIRS linear acceleration outputs. Once this information has been obtained, it is a matter of determining what accelerations and velocities the angular motion of the aircraft would produce at the IIRS location and subtracting these components from the IIRS outputs. A schematic of the IIRS location relative to the c.g. is shown in Fig. 3, and the transformation equations are

$$\dot{\psi} = d\psi/dt \tag{5}$$

$$\dot{\theta} = d\theta/dt \tag{6}$$

$$\dot{\phi} = d\theta/dt \tag{7}$$

$$p = \dot{\phi} - \dot{\psi}\sin\theta \tag{8}$$

$$q = \dot{\theta}\cos\phi + \dot{\psi}\cos\theta\sin\phi \tag{9}$$

$$r = \dot{\psi}\cos\theta\cos\phi - \dot{\theta}\sin\phi \tag{10}$$

$$\dot{p} = dp/dt \tag{11}$$

$$\dot{q} = dq/dt \tag{12}$$

$$\dot{r} = dr/dt \tag{13}$$

$$\Delta v_x = -q l_y + r l_p \tag{14}$$

$$\Delta v_y = -r l_r + p l_y \tag{15}$$

$$\Delta v_z = -p l_p + q l_r \tag{16}$$

$$\Delta a_x = \dot{r} l_p - \dot{q} l_y + l_r (q^2 + r^2) - p(q l_p + r l_y) \tag{17}$$

$$\Delta a_y = \dot{p} l_y - \dot{r} l_r + l_p (p^2 + r^2) - q(r l_y + p l_r) \tag{18}$$

$$\Delta a_z = \dot{q} l_r - \dot{p} l_p + l_y (p^2 + q^2) - r(p l_r + q l_p) \tag{19}$$

where

p, q, r = true angular rates of the aircraft about its own body axes (see Fig. 3)
l_r, l_p, l_y = distances from the c.g. of the aircraft to the IIRS in a body-axis coordinate system (see Fig. 3)
$\Delta v_x, \Delta v_y, \Delta v_z$ = increments in sensed body axes' velocities at the IIRS due to aircraft rotation
$\Delta a_x, \Delta a_y, \Delta a_z$ = increments in sensed body axes' accelerations at the IIRS due to aircraft rotation

These increments in body axes' velocities and accelerations are subtracted from the corrected IIRS motion data once the IIRS outputs have been transformed to body axes, as discussed in the next subsection.

The results of the previous analyses are accelerations, velocities, and angles with respect to the IIRS reference axes system and represent the motion and orientation of the aircraft c.g. as compared to the Earth reference system. The previous two data reduction sections have been required to correct the effect of having the IIRS away from the nominal c.g. of the aircraft. This displacement was necessary because of lack of space for the IIRS at the c.g. Obviously, the ability to locate the IIRS at the c.g. would reduce greatly the data reduction complexity and eliminate a potential source of error.

Transformation to Body Axes

The transformation of the IIRS Earth-referenced data to body axes' data usable for performance work is done in two steps. The first is to convert Earth inertial velocities to velocities relative to the air mass. This is done by subtracting vectorially the North and East components of wind from the

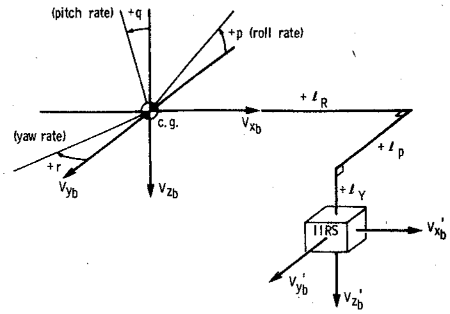

Fig. 3 Geometry definition.

North and East inertial speeds, as shown in Eqs. (20) and (21). The wind speed is determined in straight and level flight and is added to the inertial velocities during maneuvering flight to decouple the performance determination from the need to have a continuous output of pitot-statically derived true airspeed. This is necessary to prevent pneumatic line lags from degrading the overall picture of aircraft capabilities in very highly dynamic flight. It is assumed that the wind lies entirely in the horizontal plane

$$V_x = V_{x_I} + V_w \cos\psi_w \tag{20}$$

$$V_y = V_{y_I} + V_w \sin\psi_w \tag{21}$$

where

V_{x_I}, V_{y_I} = horizontal inertial velocity components in the Earth reference frame
V_w = wind speed
ψ_w = direction from which wind is coming with respect to true North
V_x, V_y = horizontal air mass velocity components in the Earth reference frame

The transformation of velocities and accelerations to aircraft body axes is done once the wind correction has been made. The transform matrix is shown in Table 2. The increments calculated in Eqs. (14-19) now can be used to correct the sensed body axes motion for aircraft rotation, as shown by

$$V_{xb} = V'_{xb} + \Delta v_x \tag{22}$$

$$V_{yb} = V'_{yb} + \Delta v_y \tag{23}$$

$$V_{zb} = V'_{zb} + \Delta v_z \tag{24}$$

$$A_{xb} = A'_{xb} + \Delta a_x \tag{25}$$

$$A_{yb} = A'_{yb} + \Delta a_y \tag{26}$$

$$A_{zb} = A'_{zb} + \Delta a_z \tag{27}$$

where

$V'_{xb}, V'_{yb}, V'_{zb}$ = uncorrected body axes' air-mass velocities
$A'_{xb}, A'_{yb}, A'_{zb}$ = uncorrected body axes' accelerations
V_{xb}, V_{yb}, V_{zb} = air-mass body axes' velocities at the c.g. of the aircraft
A_{xb}, A_{yb}, A_{zb} = body axes' accelerations at the c.g. of the aircraft

α, β, γ Determination

Angle of attack α, sideslip angle β, and flight path angle γ, are determined directly from the corrected air mass body axes' velocities using the equations presented below. Note that none of these angles is dependent on upwash angle determination, nor are they necessarily less accurate during highly dynamic

Table 2 Body axes' transformation

Aircraft axes					IIRS axes
V'_{x_b}, A'_{x_b}		$\cos\theta \cos\psi$	$\cos\theta \sin\psi$	$-\sin\theta$	V_x, A_x
V'_{y_b}, A'_{y_b}	=	$-\cos\phi \sin\psi + \sin\theta \sin\phi \cos\psi$	$\sin\theta \sin\phi \sin\psi + \cos\phi \cos\psi$	$\cos\theta \sin\phi$	V_y, A_y
V'_{z_b}, A'_{z_b}		$\sin\theta \cos\phi \cos\psi + \sin\phi \sin\psi$	$\sin\theta \cos\phi \sin\psi - \sin\phi \cos\psi$	$\cos\theta \cos\phi$	V_z, A_z

Table 3 Wind axes' transformation

Wind axes					Body axes
A_{x_w}		$\cos\alpha \cos\beta$	$\sin\beta$	$\sin\alpha \cos\beta$	A_{x_b}
A_{y_w}	=	$-\cos\alpha \sin\beta$	$\cos\beta$	$-\sin\alpha \sin\beta$	A_{y_b}
A_{z_w}		$-\sin\alpha$	0	$\cos\alpha$	A_{z_b}

Table 4 IIRS performance usage

Flight path acceleration	Turn rate
Normal acceleration	Body axes' velocities and accelerations
Rate of climb	C_L [a]
Angle of attack	C_D [a]
Angle of sideslip	C_Y [a]
Flight path angle	C_N [a]
Specific energy E_S	C_A [a]
Specific energy rate P_S	$C_{Y\text{body}}$ [a]
Angular rates and accelerations about body axes	Takeoff and landing distances and velocities

[a] Gross weight, gross thrust, and ram drag from other sources.

flight than they are in stabilized flight, since they are dependent only on the accuracy of the three axes' inertially derived velocity components

$$\alpha = \tan^{-1}(V_{zb}/V_{xb}) \tag{28}$$

$$\beta = \tan^{-1}[V_{yb}/(V_{xb}^{\,2} + V_{zb}^2)^{1/2}] \tag{29}$$

$$\gamma = \tan^{-1}[-V_z/(V_x^2 + V_y^2)^{1/2}] \tag{30}$$

A schematic of the determination of the preceding angles is shown in Fig. 4.

Transformation to Wind Axes

Using the angles just derived, the body axes' data now can be transformed to wind axes' information. From these data, the accelerations along and normal to the instantaneous flight path can be determined using the transform shown in Table 3.

Calculation of Performance Parameters

The following performance parameters can be calculated using the data derived in the previous subsections. A chart showing the outputs available is presented in Table 4.

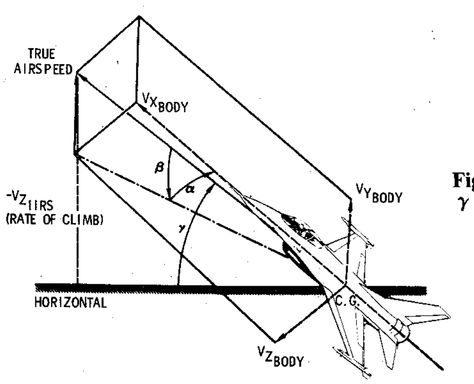

Fig. 4 α, β, and γ determination.

True Airspeed (V_T)

$$V_T = (V_{xb}^2 + V_{yb}^2 + V_{zb}^2)^{1/2} \tag{31}$$

Flight Path Acceleration (a_{FP})

$$a_{FP} = A_{xw}/g \tag{32}$$

where g is local gravitation attraction of the Earth at the test altitude.

Rate of Climb($\dot{h}$)

$$\dot{h} = -V_{Z_I} \tag{33}$$

Specific Energy (E_s)

$$E_s = h + (V_T^2/2g) \tag{34}$$

Specific Energy Rate (P_s)

$$P_s = a_{FP} V_T \tag{35}$$

In order to calculate aerodynamic parameters, the gross weight of the aircraft (W_T), gross thrust of the engine (F_g), and engine-related drag terms (F_e) must be calculated. For the YF-16, these are supplied by separate computer programs that are run upstream of the IIRS program using instrumented aircraft parameters. The aerodynamic coefficients derived below can be converted to body axes' coefficients for direct comparisons with wind-tunnel data using the inverse of the transform shown in Table 3:

Drag Coefficient (C_D)

$$C_D = (1/qS)(F_g \cos\alpha - F_e - a_{FP} W_T) \tag{36}$$

where q is dynamic pressure, and S is reference wing area.

Lift Coefficient (C_L)

$$C_L = (1/qS)(A_{z_w} W_T/g - F_g \sin\alpha) \tag{37}$$

Takeoff and landing distances are calculated using IIRS inertial velocities and altitude. The horizontal velocities are added together vectorially and integrated with respect to time to obtain distance traveled from brake release or until the aircraft is stopped. Since the IIRS can build up slight velocity errors over a period of time, the velocities measured when the aircraft is stopped are subtracted out of the data throughout the run before velocity integration. Acceleration, rate of climb, α, and β are determined exactly as they are in the equations just presented.

V. Flight Test Results

The YF-16 11-month flight test program has been very successful. A large measure of this success can be attributed to the IIRS and its availability to supply all necessary performance data in a minimum of flight test time. The author feels that no other instrumentation system available could have produced a comparable quantity and quality of data in such a short time span with as high a day-to-day reliability. The following subsections discuss in detail various aspects of the IIRS flight test methods and results and the advantages and problems experienced with the instrument during the course of the program.

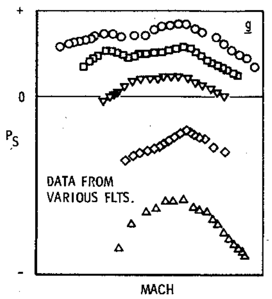

Fig. 5 Maneuver performance.

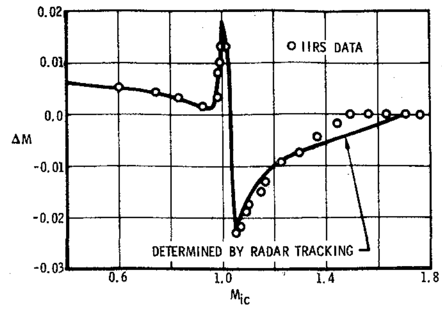

Fig. 8 Position error data.

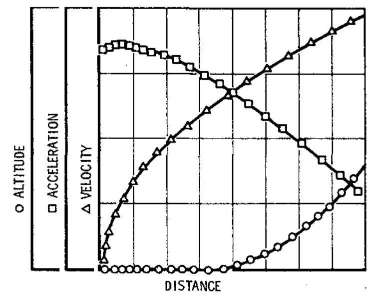

Fig. 6 Takeoff data. Lines are photo data, symbols are IIRS data.

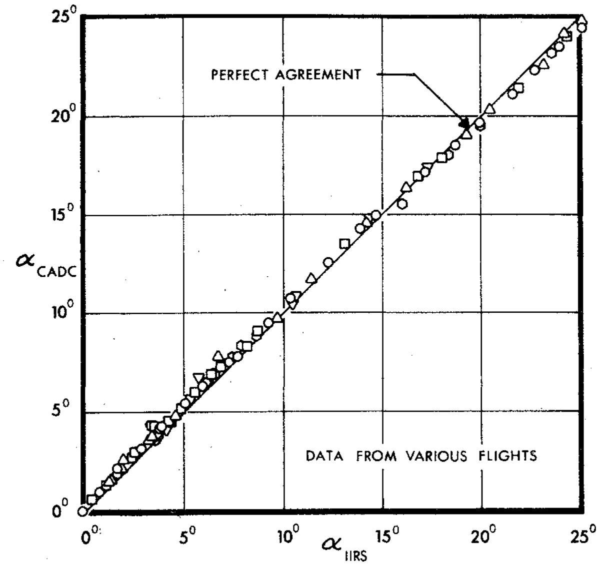

Fig. 9 α calibation.

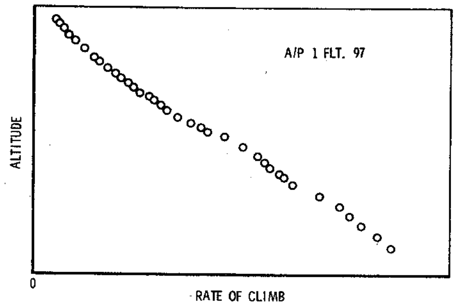

Fig. 7 Climb performance.

Test Methods and Results

The test methods used on the YF-16 program were developed to make maximum use of flight time, since the test program encompassed only 11 months, and all aircraft performance data, as well as many other YF-16 characteristics, had to be evaluated in that time. The philosophy adopted was to combine testing, on the same flight, required by the various disciplines and eliminate reliance on ground-based data gathering instrumentation whenever possible. The IIRS lended itself well to this concept. The following paragraphs address each phase of the YF-16 performance analysis and how the IIRS was used to obtain data.

The primary performance task was to evaluate the capability of the YF-16 to climb, turn, and accelerate in intermediate power and maximum afterburner. These data were used to determine the YF-16 combat potential and were called energy-maneuverability (EM) tests. Since the YF-16 is a high performance combat vehicle, all of these tests involved highly dynamic maneuvers. The ability of the IIRS to determine performance under these conditions accurately was proved out in the flight test program and, indeed, was the primary reason why it was selected for use on the YF-16 program. A representative EM plot is shown in Fig. 5.

During these EM tests, accurate wind information was needed to convert inertially sensed ground speed to airspeed information, as explained in Sec. IV. This requirement meant that a quasistabilized wind calibration had to be done before most dynamic maneuvers in order to assess accurately local wind speed and direction from a comparison of IIRS inertial velocity and pitot-static airspeed. This "wind cal" required that the pilot hold a wings-level, low rate of climb point for approximately 10 sec, which was done while the pilot was setting up on initial test Mach and altitude.

Takeoff and landing data were evaluated with several aircraft configurations during the course of the program. Initially, data reduction was done using the conventional phototheodolite ground camera method. Parallel data analysis also was made using IIRS outputs. Comparisons between the two techniques showed no appreciable differences in velocities or distances measured. Thereafter, almost all of the takeoffs and landings were reduced using IIRS data, and phototheodolite support no longer was necessary. A typical takeoff plot comparing IIRS and phototheodolite data is presented in Fig. 6.

Climbs and descents were evaluated using fixed power setting runs following a constant Mach and /or constant calibrated airspeed path. Rate of climb, pitch angle, flight path acceleration, etc., data were obtained from the IIRS. The data all were correlatable flight-to-flight, and initial radar tracking confirmed IIRS instantaneous rates of climb measured. Unlike some other possible sources of data, there was no tendency for the sensed climb rate to toggle, wander, or lag. A typical rate-of-climb plot is shown in Fig. 7.

Cruise data were evaluated using the classic speed-power approach, i.e., stabilizing on a Mach and altitude condition for 1-3 min. The IIRS was used to sense flight path acceleration.

Store drags were determined using a variety of techniques, including stabilized flight range evaluation, incremental longitudinal acceleration sensed after store separation, and fixed power windup turns. All of these data were obtained by "piggy-backing" off other types of testing. For instance, the variation in store drag as a function of lift coefficient was determined by obtaining data during stability and control windup turns.

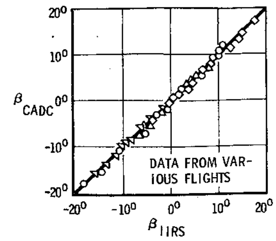

Fig. 10 β calibration.

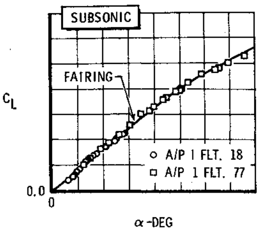

Fig. 11 Lift vs α.

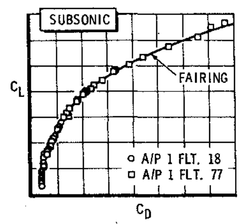

Fig. 12 Drag polar.

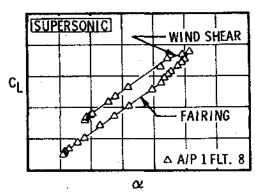

Fig. 13 Wind shear.

Air data system position error calibration was obtained using radar tracking, pacer aircraft, and tower flybys. However, it was found that good position error data through the Mach jump region could be obtained during level flight accelerations and decelerations by comparing IIRS inertial altitude with pitot-static pressure altitude as a function of time. This is again an instance of the IIRS allowing a single test run to serve several purposes simultaneously and requiring less ground support equipment. Mach jump position error data as determined by radar tracking and IIRS outputs are shown in Fig. 8.

Angle-of-attack and sideslip calibration was done during speed-power points, level flight accelerations, and windup turns using the IIRS α and β as the references. This allowed the static and dynamic characteristics of the aircraft α and β probes to be established throughout the YF-16 maneuvering envelope. Flight test experience has shown that the IIRS supplies accurate data well about 40° α in very dynamic maneuvers. Since it does not rely on dynamic pressure to drive it, the IIRS can supply good α and β calibration results even at low airspeeds. Typical calibration curves are presented in Figs. 9 and 10.

Aerodynamic lift and drag data also were evaluated in conjunction with other testing. No specific-purpose evaluation maneuvers, such as roller coasters, were found to be necessary. Most data were obtained during fixed-power EM testing, stability and control windup turns, climbs, and takeoffs and landings. Lift vs angle-of-attack data at a typical flight condition is presented in Fig. 11. Figure 12 illustrates the quality of drag polar data obtainable.

IIRS Flight Test Experience

The IIRS lends itself well to real-time ground monitoring and to quick-turnaround postflight data reduction, as well as to highly automated conventional postflight data reduction and standardization because it outputs nearly all data needed for performance work in a convenient serial-digital word format at 5 times/sec. With the aid of a small ground-based online computer, IIRS telemetered outputs could be used to display to the engineer real time altitude, instantaneous rate of climb, flight path acceleration, specific energy and energy rate, turn rate, normal acceleration, and range traveled along the flight path. These data were very useful in determining quickly whether a data run was satisfactory or needed to be repeated.

Quick-turnaround data processing of all of the parameters developed in Sec. IV was done using a Hewlett Packard 9820A desk-top computer with a paper tape reader, two cassette drives, and an $X-Y$ plotter. The IIRS data were fed in via paper tape, and finalized test day performance and aerodynamic data automatically were plotted out a short time later. Total quick-look-turnaround time to obtain these data was as little as 4 hr after flight.

IIRS reliability and usability throughout the course of the flight test program have been exceptional. The system averaged 18.4 flight hours between IIRS unscheduled maintenance actions and approximately 35 flights between removals of the instrument for repairs or recalibrations. No flight ever has had to be aborted due to IIRS failure, and less than 1% of all of the performance data gathered on the program was lost due to IIRS degradation or failure. The IIRS was active on all but four of over 300 flights.

The few problems encountered with the IIRS have been mainly mechanization and programming changes, which were easy to identify and correct. Most of these occurred during the initial shakedown phase of the flight test program and thus did not affect performance data gathering. Data-reduction problems related to IIRS use have been encountered during the program. The first of these was erratic calculation of angular rates in the data-reduction program and was caused by a data-smoothing problem under certain high rate conditions. More careful choice of sample times and scrutiny of the program outputs reduced this problem to an occasional nuisance.

Another problem was wind fluctuation during the course of a run. This normally took the form of a wind shear front and could be recognized easily by analyzing the computer output plots. A typical wind shear is shown in Fig. 13. The data recovered after the shear was encountered generally were not usable unless the new wind velocity and direction could be determined by doing a "wind cal" after the maneuver. Wind shear conditions were encountered mostly while flying over the mountains surrounding Edwards AFB and invalidated approximately 2% or 3% of the total IIRS data obtained during the course of the program.

VI. Future Use

The IIRS system of instrumentation has a great deal of potential for further development and flight test use. Experience with the YF-16 program has provided many guidelines for future use, especially in the areas of changes and refinements to the present system. Specific modifications that are planned for the Delco Carousel V IIRS include the incorporation of an onboard capability to decouple the baroinertial altitude loop for takeoff and landing and for certain high-rate-of-climb tests. This will allow more accurate measurement of inertial short-term changes in altitude. Another change will be the expansion of the onboard wind calculation function to allow accurate determination regardless of aircraft roll angle or rate of climb. Any future IIRS-type system should be selected with the following criteria in mind:

1) Accuracy: the accuracy of any current gimbaled navigation platform should be sufficient for performance work. However, in many of these systems, the internal determination of acceleration is not available for output without an extensive rework of the platform electronics. This type of

rework is costly and can have an adverse effect on overall performance and reliability.

2) Reliability: since flight test time is very expensive, demonstrated reliability should be weighed heavily in evaluating an IIRS candidate. A high mean time between failures and an extensive self-test capability are very desirable features.

3) Data output rate: an output rate of 5 times/sec is adequate for almost any type of performance work. However, if stability and control or handling qualities work is planned using the IIRS, an output rate of 30 to 50 times/sec is advisable.

4) Independence: the IIRS must be able to function from takeoff to landing on each flight with no Doppler, TACAN, Omega, or other type of in-flight updata that can produce discontinuities in the IIRS output data.

5) Data synchronization: the IIRS contractor must be able to supply a time line analysis of all output parameters so that the time relationships between outputs can be determined. A good deal of data-reduction complexity can be eliminated if internal IIRS data synchronization can be mechanized.

6) Computer mechanization: a general-purpose digital computer incorporated into the IIRS is highly desirable. It allows outputs in a digital format which are interfaced more easily with ground-based data-reduction equipment. Also, reprogramming and expansion of internal computing capabilities, if needed, is facilitated.

7) Shock mounting: most platforms have shock mounts installed in them to attenuate high-frequency vibration. The charactetics and play in these mounts should be investigated to determine at what frequency they begin to smooth out sensed accelerations and what, if any, error they produce in body axes' angular position during dynamic flight conditions.

8) Location: the location of the IIRS unit within the aircraft should be given careful consideration, since it, more than any other single factor, dictates the complexity of the data-reduction procedures. The IIRS should be placed at or near the aircraft nominal c.g. on a rigid structural support.

9) Alignment:alignment of the IIRS baseplate with respect to the aircraft body axes is critical. An angular alignment of no more than 3 arc min in each axis should be specified. The IIRS installation should be designed so that the platform can be removed and replaced without the need for a new boresight alignment.

10) Cost: the initial cost of an IIRS system is high relative to other types of performance instrumentation. However, over the course of a flight test program, the total cost of an IIRS could be much lower when such factors as reliability, data-reduction time, engineering support, maintenance, ground instrumentation required, and flight test time are taken into consideration. In addition, lease arrangements, rather than outright purchase, may be arranged with some inertial platform manufacturers.

VII. Summary

The IIRS concept has made significant contributions to the YF-16 flight test program and has a tremendous potential for future application, particularly when accurate data in a dynamic flight environment are desired. To make the most of this potential, care should be taken in the selection of the platform and computer, the location of the IIRS in the aircraft, the interfacing between it and other onboard and ground equipment, and the structuring of the data-reduction procedures needed to analyze the IIRS outputs and convert them to good performance data.

The information from this type of flight test instrumentation far exceeds the capabilities of past performance data sources, and the trend toward more efficient use of flight test time indicates that this concept will find many applications in the future. If the engineer has a solid understanding of the capabilities and limitations of the IIRS and takes a good deal of care in its implementation for a particular flight test application, the IIRS concept can be a significant advance in the state-of-the-art of performance flight testing.

References

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[2] "Carousel V Inertial Navigation System-System Technical Description," EP 1433, Delco Electronics, General Motors, Corp., Milwaukee, Wis.