A Method for Flight-Test Determination of Propulsive Efficiency and Drag

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A flight-test method is described from which propulsive efficiency as well as parasite and induced drag coefficients can be directly determined using relatively simple instrumentation and analysis techniques. The method uses information contained in the transient response in airspeed for a small power change in level flight in addition to the usual measurement of power required for level flight. Measurements of pitch angle and longitudinal and normal acceleration are eliminated. The theoretical basis for the method, the analytical techniques used, and the results of application of the method to flight-test data are presented. Flight-test data showed performance parameters measured with a standard deviation of about 0.8% for propulsive efficiency, 0.3% for parasite drag coefficient, and 8% for the airplane efficiency factor, *e*.

Nomenclature

$\mathcal{R}$	= aspect ratio
BHP	= input power to propeller
C_{DO}	= parasite drag coefficient
$\underline{e}$	= efficiency factor
er	= nondimensional error
g	= local acceleration of gravity
$\boldsymbol{h}$	= vector relating z and $\boldsymbol{x}$
m	= aircraft mass
$\boldsymbol{n}$	= zero-mean, Gaussian noise vector
S	= aircraft wing surface area
t	= time
V	= true airspeed
W	= aircraft weight
$\boldsymbol{x}$	= vector of unknowns
z	= measurement vector
η_p	= propulsive efficiency
ρ	= atmospheric density
σ_x	= standard deviation of x

Subscript

0	= value prior to power change

Introduction

OPERATIONAL performance information needed by the pilot, such as cruising speed or range, can be determined directly from flight tests but the factors that influence the performance are not readily accounted for. The engineer needs to know such factors as drag and propulsive efficiency to decide where efforts to improve the performance will be most productive. He also needs to be able to measure the results of these efforts. However, the airspeed in steady flight which results from a given power is affected not only by the drag but also by the propulsive efficiency. The term propulsive efficiency is used to indicate the efficiency of the propeller as installed on the airplane as opposed to the efficiency of the isolated propeller. The usual flight-test methods do not provide enough information to separate the factors. The engineer cannot tell, for example, whether disappointing performance is caused by too much drag or an inefficient propeller. A common practice is to assume a propulsive efficiency and then use speed-power data from flight tests to determine drag; this is useful, but still leaves doubts as to whether the assumed propulsive efficiency was correct.

Design parameters such as drag, propulsive efficiency, and airplane efficiency factor are related to speed and power by the equations describing the motion of the airplane. If the motion is measured accurately enough under circumstances that provide at least as many independent equations as the number of unknowns, then presumably the unknowns can be determined. Even with sophisticated statistical smoothing of the data, the character of the equations is such that measurements must be made very accurately. Instrumentation with the required accuracy and the necessary analytical techniques are available and used successfully in flight testing of military and large transport airplanes. A comprehensive investigation[1,2] has been made into the application of these modern methods to determine the performance and stability characteristics of smaller general aviation airplanes. However, the instrumentation and analytical methods required by these techniques have been beyond the reach of much of the general aviation industry. A need exists, therefore, for flight-test methods which are relatively simple and use affordable instrumentation and analytical procedures.

A method has been developed that makes use of the information contained in the transient response of the speed of the airplane following a change in power in level flight. This information, combined with the information available from the power required to maintain speed in steady level flight, is sufficient to determine the propulsive efficiency and the drag terms from flight test with relatively simple instrumentation. If the power is suddenly increased in an airplane flying in steady flight while the altitude is held constant, the airspeed will increase to a new steady-state value. The time history of the speed will be in the form of an exponential, as represented by the response of a first-order system to a step input. The time constant and the magnitude of the velocity change will be affected by both the propulsive efficiency and the drag of the airplane.

The time history of speed in this level flight transient maneuver is easy to measure. Keeping the altitude constant reduces the performance problem to a single degree of freedom and simplifies the problem of making the necessary

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measurements. Notice that measurements of pitch angle, longitudinal and vertical acceleration, etc., which are required in some parameter identification flight tests, are not required here. Keeping the altitude constant reduces requirements on the instrumentation, but imposes a requirement for accurate flying by the pilot. Given a sufficiently good reference and smooth air, a pilot can readily maintain altitude to within a few inches, as shown by flying in close formation or very near the top of an agricultural crop. At altitude the pilot does not normally have such a good reference. For these tests, the altitude information provided by the test instrumentation was used to drive meters in the cockpit which showed rate of climb and incremental altitude with an expanded scale. With this information the pilot could usually maintain altitude to within 1 ft. The drag polar was assumed to be parabolic and the propulsive efficiency and the drag coefficients were assumed to be constant over the speed range covered in the transient maneuver. Thus, the power change was required to be relatively small to produce a relatively small change in speed. A power change that was too small would be hard to measure, and one that was too large would produce a speed change large enough to violate some of the assumptions.

The transient response in airspeed in level flight has been investigated before,[3,4] but the emphasis has been on stability and other considerations rather than on development of a method to measure performance. Acceleration in level flight has also been used widely as a means of measuring excess thrust or power for climb performance; these methods are summarized in Ref. 5. The transient response in speed is one element of aircraft response exploited in methods known as equations of motion parameter identification. To the authors' knowledge, the transient response in speed previously has not been separated out and used in a relatively simple manner to determine drag and propulsive efficiency.

The flight-test data from the transient maneuvers were handled as a set, and a maximum likelihood technique was used to extract propulsive efficiency and the drag coefficients from the set of several transients. It will be seen that this analysis technique produced values for these performance parameters which were internally consistent and in accord with values determined from steady flight tests.

The instrumentation used to obtain the data from the transient maneuvers offered attractive accuracy for conventional performance data measured in steady flight. Accordingly, level speed-power, sawtooth climb, and feathered propeller glide tests were made.[6,7] Summarized results of these tests are shown here to compare with results obtained by the transient analysis method.

Theory

The airplane was assumed to be flying straight and level with the force resolved into the conventional thrust, drag, lift, and weight. Thrust was assumed coincident with the velocity vector and lift equal to weight. The drag polar was assumed to be parabolic, representing most general aviation airplanes with reasonable aspect ratios flying over a small speed range at modest Mach numbers. The basic differential equation can be written as follows:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{\eta_p \mathrm{BHP}}{mV} - \frac{C_{DO}\rho V^2 S}{2m} - \frac{2mg^2}{\rho S \pi Æ e V^2}$$

where η_p, C_{DO}, and e are unknown.

Since the acceleration was not measured, it was necessary to use a nonlinear parameter estimation method to solve for the unknowns. The method chosen was a modified maximum likelihood estimation (MMLE) technique similar to that of Grove et al.[8] In this, the measurement vector is expressed as

$$z(t) = \boldsymbol{h}(\boldsymbol{x},t) + \boldsymbol{n}(t)$$

where z is the measured variable, $\boldsymbol{x}$ the vector of unknowns, $\boldsymbol{h}$ the functional relationship between z and $\boldsymbol{x}$, and $\boldsymbol{n}$ the measurement noise vector. For this application, the vector $\boldsymbol{x}$ was

$$\boldsymbol{x} = \begin{bmatrix} \eta_p \\ C_{DO} \\ e \end{bmatrix}$$

and the measurement vector $z(t)$ consisted of the velocity change at each time step, or

$$z(t) = \begin{bmatrix} 0 \\ \Delta V_1 \\ \Delta V_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta V_{N-1} \end{bmatrix}$$

where N is the number of data points. For the first point, the function $\boldsymbol{h}$ was the steady-state equation relating thrust and drag, or

$$h(x,o) = \frac{\eta_p \mathrm{BHP}_0}{V_0} - \frac{C_{DO}\rho V_0^2 S}{2} - \frac{2m^2 g^2}{\rho S \pi Æ e V_0^2}$$

For all other points, the function $\boldsymbol{h}$ is defined as

$$h(x,t_i) = \int_0^{t_i} \left(\frac{\eta_p \mathrm{BHP}}{mV} - \frac{C_{DO}\rho V^2 S}{2m} - \frac{2mg^2}{\rho S \pi Æ e V^2} \right) \mathrm{d}t$$

and was the integral of excess thrust/mass through time.

Given the measurement vector z and an initial guess of $\boldsymbol{x}$, the maximum likelihood technique then used an iterative process to solve for the unknowns. This technique could also combine several runs to produce better estimates of the unknowns.

Error Analysis

Before the flight tests began, a computer simulation was used to examine the acceleration maneuver and show that the maximum likelihood technique could extract the flight unknowns when given perfect data. The simulation data was then corrupted with noise and bias to determine the effects on the results and show the sensitivity of the results to errors in measurement.

The NASA Langley General Aviation Simulation program was used with T-34B characteristics inserted into this six-degree-of-freedom generalized program. A parabolic drag polar was assumed and propulsive efficiency, zero lift drag, and wing efficiency were held constant. The simulation began with the airplane in straight and level flight. After 3 s the power was increased 10% over the cruise setting and the airplane accelerated to a new flight condition. The simulation autopilot held heading and altitude constant during the maneuver. A plot of the simulation of change in velocity vs time is shown in Fig. 1. Time started when the power was increased to initiate the transient.

The curve fitted through the points represents a first-order exponential, confirming that in this maneuver the airplane could be represented by a first-order system. Furthermore, flight-test results, Figs. 2 and 3, showed that a first-order

Table 1 Performance parameters

	Assumed in simulation	Extracted from simulation
η_p	0.750	0.751
C_{DO}	0.0260	0.0260
e	0.650	0.650

exponential was a good representation of the flight data. The assumed and extracted performance parameters were as listed in Table 1.

Clearly, the estimation technique worked well on the perfect simulation data. Noise and bias were then applied to the simulation data to determine the effect of measurement errors on the results obtained by the maximum likelihood estimation technique. The errors most likely to occur in the flight tests would be in measurements of power, airplane weight, and velocity. The power and weight were varied 1%, while the velocity measurements were corrupted with a pseudorandom number generator that provided various levels of zero-mean noise. The velocity supplied to the estimation program was thus the true velocity plus the generated error. In addition, a bias of 1 ft/s was added to determine the effect of bias. The results, Table 2, demonstrated that the procedure was relatively insensitive to weight errors and velocity bias, but that errors in power caused errors in the estimated wing efficiency e, while noise in velocity measurements caused errors in all three unknowns.

The combined effects of the measurement errors were then investigated. An analysis of the flight-test measurement system indicated that engine power could be measured to within ± 50 ft-lb/s and velocity to within ± 0.25 ft/s. Errors in weight would be very small, probably within ± 10 lb.

Nine sets of runs were initially done, with each set consisting of 20 accelerations using the baseline simulation run corrupted by noisy data. The nine sets were combinations of errors in velocity, initial power, and change in power with standard deviations in velocity of $\sigma_v = 0.1$, 0.25, and 0.5 ft/s and power of $\sigma_p = 25$, 50, and 100 ft-lb/s. Each run in each set was then processed individually to see how the noisy data in velocity and power affected the estimation.

An example of processed data from one set of individual runs is shown in Table 3. The true values of the flight unknowns were $\eta_p = 0.750$, $C_{DO} = 0.0260$, and $e = 0.650$. Velocity, initial power, and change in power were corrupted by noise having a mean value of 0.0 and standard deviations of $\sigma_v = 0.25$ ft/s for the velocity and $\sigma_p = 50$ ft-lb/s for the power. Even small errors in velocity and power produced considerable variation in the estimates. The estimated values of η_p varied from 0.685 to 0.820, C_{DO} from 0.0241 to 0.0280, and e from 0.557 to 0.765. As an aid in selecting the best estimate of the 20 runs, the standard deviations estimated by the MMLE program were employed. It was assumed that the estimates closest to the flight unknowns would have the lowest deviations. That, however, was not always the case.

Although the standard deviations were measures of the goodness of the estimates, they did not identify the best estimate of the values of η_p, C_{DO}, and e. These same results of scatter were seen in all nine sets of runs, with the largest scatter in the set of runs having the noisiest data.

To solve these problems, runs from a set were combined. Multiple runs with small state changes preserve the linear assumptions made during engineering analysis and offer the opportunity for averaging out errors in measurement of system parameters such as mass and engine power. Iliff and Maine[9] state that "no single maneuver···can provide a definitive description of an aircraft····There is no substitute for making several maneuvers at a single flight condition."

The question then arose as to which runs should be combined. An approach that proved successful was that of using

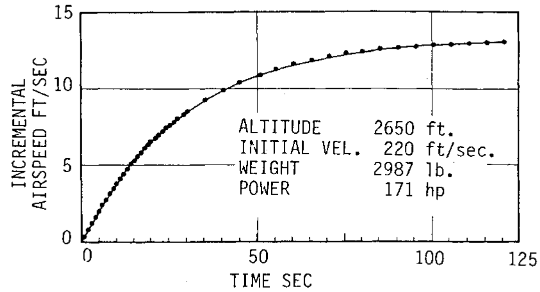

Fig. 1 Simulation of transient response.

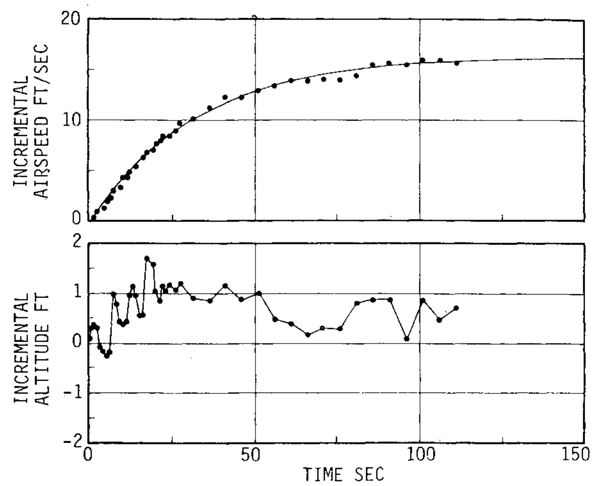

Fig. 2 Flight-test transient—power increase.

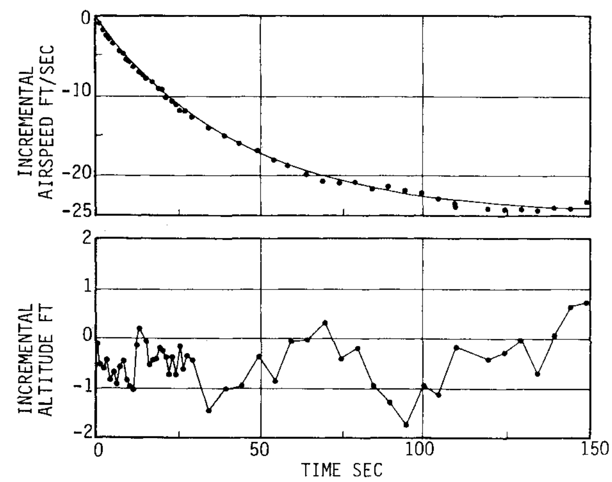

Fig. 3 Flight-test transient—power decrease.

an average nondimensional error. The MMLE program provided a value for the sum of the squares of the residuals of each processed run, where the residual was the difference between the actual and estimated velocity change at each data point. The square root of this value was taken and then divided by the number of data points to produce an average velocity error at each point. This average was then nondimensionalized by dividing it by the magnitude of the total velocity change during the transient. This produced the nondimensional error term

$$\overline{\text{er}} = \sum_{i=1}^{N} \sqrt{(\text{residual})_i^2} \Big/ (N\,|\,\Delta V\,|\,)$$

Table 2 Effect of errors on simulation results

Run No.	Description	Calculated value of unknowns η_p	C_{DO}	e
1	Perfect data	0.751	0.0260	0.650
2	Initial power, 1% high	0.751	0.0261	0.630
3	Initial power, 1% low	0.751	0.0260	0.673
4	Power change, 1% high	0.744	0.0260	0.673
5	Power change, 1% low	0.759	0.0261	0.629
6	Airplane mass, 1% high	0.759	0.0258	0.657
7	Airplane mass, 1% low	0.744	0.0258	0.657
8	Velocity bias, +1 ft/s	0.755	0.0259	0.652
9	Velocity bias, −1 ft/s	0.748	0.0262	0.649
10	Velocity noise $\sigma = 0.1$ ft/s	0.747	0.0259	0.656
11	Velocity noise $\sigma = 0.5$ ft/s	0.732	0.0254	0.677
12	Velocity noise $\sigma = 1.0$ ft/s	0.712	0.0248	0.705

Table 3 Simulation runs processed separately

Run No.	η_p	σ_{η_p}	C_{DO}	$\sigma_{C_{DO}}$	e	σ_e	$\bar{e}r \times 10^3$
1	0.792	0.012	0.0271	0.00048	0.591	0.016	3.07
2	.718	.011	.0249	.00045	.690	.021	2.93
3	.778	.009	.0264	.00036	.580	.012	2.35
4	.685	.011	.0241	.00049	.765	.028	3.18
5	.764	.009	.0263	.00036	.620	.014	2.38
6	.725	.009	.0253	.00039	.695	.019	2.52
7	.813	.012	.0276	.00049	.557	.015	3.16
8	.714	.010	.0249	.00042	.705	.021	2.74
9	.820	.011	.0280	.00046	.561	.014	2.93
10	.734	.009	.0253	.00039	.658	.017	2.52
11	.778	.010	.0268	.00040	.615	.015	2.52
12	.709	.008	.0249	.00033	.729	.017	2.14
13	.751	.012	.0260	.00050	.645	.020	3.21
14	.752	.010	.0261	.00041	.658	.018	2.66
15	.761	.010	.0265	.00039	.652	.016	2.50
16	.738	.013	.0259	.00054	.696	.025	3.43
17	.753	.011	.0261	.00048	.649	.020	3.10
18	.720	.010	.0252	.00041	.709	.020	2.64
19	.763	.009	.0264	.00039	.628	.015	2.49
20	.703	.011	.0240	.00044	.675	.021	2.98

The best five runs from each set were then processed to estimate the flight unknowns. For each set of five, it was assumed that there was one unknown C_{DO}, one unknown e, but five unknown values of n_p because of the possible effect on propulsive efficiency of the small differences in initial conditions of power and velocity for the different runs. This was consistent with the flight-test program, where propulsive efficiencies might differ between runs, but the drag coefficient and wing efficiency would be expected to remain the same. It would also check to see if the program would identify the same propulsive efficiencies in each of the five runs.

The results of combining the best five from each set are shown in Table 4. The ranges of the five propulsive efficiencies were all very close to one another in each run, and all were close to the actual value of 0.75. The scatter in C_{DO} and e were also markedly reduced by combining the runs.

Weight errors ($\sigma_w = 30$ lb) and velocity bias (3.37 ft/s) were then combined with the noisy velocity and power measurements. The addition of these errors showed little effect on the results of the MMLE estimation technique.

A series of runs was made with different propulsive efficiencies to determine if the MMLE program could sort out the different values. Five runs were made and processed using perfect data. These five were then corrupted with errors in velocity, power, and weight, and the data reprocessed to determine the flight unknowns. The results in Table 5 show that the program could identify the different values of η_p along with C_{DO} and e, although the error in e for the noisy data was larger than those with the same value of η_p.

The results of all the runs indicated that the test technique could work if given reasonable flight-test data. It was clear that the MMLE procedure worked well, but good results could not be obtained from a single acceleration or deceleration. These runs would have to be combined to produce good estimates of η_p, C_{DO}, and e.

Flight Tests

Equipment

The test airplane was a Beech T-34B Navy trainer used in previous work at Mississippi State University.[6,10-12] It was a two-place tandem, low-wing airplane powered by a Continental 0-470-4 engine driving a Hartzell two-blade, metal, full-feathering propeller. The airplane characteristics are listed in Table 6. The airplane configuration was standard except for the installation of the torquemeter and an airspeed boom on the left wing. The airplane was equipped with instrumentation to measure and record quantities sufficient to define the performance of the airplane. Special instruments were installed to assist the pilot to maintain constant altitude during the test runs. The quantities measured were engine speed and torque to define power, flight conditions including fuel quantity to determine weight, and performance parameters including altitude, rate of climb, airspeed, and time. Engine speed was recorded by a system that counted pulses as the magneto armature turned. Engine speed could be resolved to within 0.8 rpm and the governor would regulate engine speed to within 2-3 rpm. Torque was measured by a Lebow torquemeter. Calibrations showed that the instrument was accurate to about 1 lb-ft. In flight the measured torque varied 2 lb-ft about a well-defined mean. The variations were believed to be actual variations in torque produced by individual power pulses recorded at the instant the data was scanned by the recording system. The only variation in weight between runs was caused by consumption of fuel. Fuel flow was measured by a Silver Fueltron I Fuel Computer which measured fuel flow to 0.1 gal/h, and integrated it to display quantity of fuel used to within 1%.

Altitude was measured by a Rosemount Engineering Company Barometric Altitude Transducer, Model 1241. Laboratory tests showed that the altitude signal was linear and the instrument could resolve a change in altitude of 4 in., and that the hysteresis at 5000 ft was not over 2-3 in. Laboratory tests showed that the instrument output was not affected by temperatures between 6 and 38°C. The quality of the altitude data provided by this instrument should be emphasized. It was possible to fly at a test altitude and detect a change in altitude of 4 in.

Table 4 Simulation runs combined

σ_v	σ_p	η_p	C_{DO}	e
0.1	25.0	0.7476-0.7481	0.02589	0.6513
0.1	50.0	0.7428-0.7432	0.02567	0.6522
0.1	100.0	0.7330-0.7347	0.02529	0.6537
0.25	25.0	0.7473-0.7979	0.02588	0.6515
0.25	50.0	0.7419-0.7426	0.02566	0.6526
0.25	100.0	0.7326-0.7345	0.02528	0.6540
0.50	25.0	0.7471-0.7479	0.02588	0.6511
0.50	50.0	0.7411-0.7423	0.02564	0.6532
0.50	100.0	0.7317-0.7321	0.02526	0.6548

Table 5 MMLE estimates for different values of η_p

σ_v	σ_p	σ_w	η_1	η_2	η_3	η_4	η_5	C_{DO}	e
0	0	0	0.692	0.712	0.732	0.752	0.772	0.02604	0.6490
0.25	50	10	0.689	0.708	0.737	0.757	0.767	0.02567	0.6375
True values			0.690	0.710	0.730	0.750	0.770	0.0260	0.650

Table 6 Characteristics of T-34B test airplane

Standard gross weight	3000 lb
Wing span	32.82 ft
Wing area	177.6 ft^2
Wing aspect ratio	6.066
Engine	Continental 0-470-4, 225 hp at 2600 rpm unsupercharged
Propeller	Hartzell HC-C2YF-2F FC 8468R
No. of blades	2
Propeller diameter	7.0 ft
Blade chord	0.667 ft
Blade activity factor	90.0

The Rosemount altitude transducer incorporated circuitry to differentiate the altitude signal to provide a rate of climb signal. This signal was used to check the quality of the level flight runs and was also used in the pilot guidance meters.

Airspeed was measured with a Rosemount Airspeed Transducer, Model 1221D, which incorporated a network to linearize the output and produce a signal proportional to indicated airspeed. The departure from a linear signal was measured and handled as a correction term in the calculation of indicated airspeed from the output of the transducer. Hysteresis and repeatability totaled about 0.1 knot and was independent of temperature over a range of 6 to 38° C. Calibrations showed no change after a lapse of two months. Total pressure and static pressure were obtained from a NASA-type swiveling pitot-static head mounted on a boom one chord length ahead of the left wingtip. The position error was calculated from NASA data[13] and correlated with experimental speed course data.[11,14] The airspeed and altitude transducers were mounted at the base of the boom, resulting in short lines to the transducers. Lag in the airspeed system approximated a first-order time constant of 0.01 s, negligible for any maneuver used in these flight tests.

Flight data was recorded by a Mississippi State University digital data system. The transducer signal was passed to signal conditioning circuits and then to a Hewlett-Packard 2070A Data Logger, which performed the analog-to-digital conversion, stored the data until scanned, and then scanned the various channels at intervals set by an electronic timer. The data was then passed to a SYM-1 microprocessor in digital form which identified each run and stored the data collected during a run. At the completion of a run the data stored in the microprocessor was transferred to a tape in a cassette

Table 7 Summary of flight conditions for transient tests

Run No.	Initial airspeed, ft/s	Initial altitude, ft	Initial power, hp	Power change, hp	Airspeed change, ft/s
1	222.0	1017	149.0	24.3	17.3
2	230.3	1017	173.8	−39.1	−20.9
3	212.0	1017	134.8	37.2	26.6
4	237.9	1018	172.3	−24.8	−17.2
5	221.6	1018	147.7	25.7	16.7
6	239.0	1017	173.4	−16.2	−9.4
7	223.7	1017	147.1	24.8	16.2
8	239.4	1018	171.8	−31.5	−24.8
9	221.8	1017	145.4	26.0	19.9
10	240.7	1018	171.6	−29.6	−23.4
11	221.8	1017	141.4	30.3	18.6
13	209.2	8275	117.6	22.1	27.1
14	235.0	8277	139.6	−19.1	−15.7
15	223.9	8277	120.6	19.3	14.7
16	233.8	8278	139.9	−16.3	−11.0
17	219.1	8278	123.6	16.3	17.0
18	231.4	8279	139.6	−11.9	−4.6
19	228.0	8278	127.7	11.9	7.5
20	214.1	8278	119.0	20.7	20.5
21	233.7	8278	139.7	−26.9	−30.7

Table 8 Flight-test runs processed separately

Run No.	η_p	C_{DO}	e	$\ddot{e}r \times 10^3$
21	0.78	0.020	0.57	1.31
13	0.71	0.018	0.65	1.33
3	0.87	0.025	0.65	1.80
8	0.77	0.020	0.50	2.15
1	0.79	0.022	0.61	2.56
14	0.50	0.015	1.47	2.69
20	0.93	0.026	0.61	2.71
7	0.76	0.022	0.79	2.89
5	0.91	0.027	0.66	3.00
9	0.76	0.020	0.75	3.20
4	0.57	0.016	0.83	3.60
11	0.65	0.020	1.18	4.19
15	0.74	0.023	1.39	4.22
10	0.76	0.019	0.50	4.30
6	0.83	0.026	0.94	4.55
17	0.82	0.022	0.61	6.31
19	0.87	0.031	2.86	6.37
16	0.56	0.020	2.66	8.43
18	0.29	0.015	−1.59	8.76
2	0.56	0.017	3.22	19.80

recorder. After the flight, these data were transferred to a ground-based computer for processing.

The approach used in this project was to simplify the instrumentation and data analysis requirements by restricting the degrees of freedom of the airplane. Calculations and experience in related flight tests[10,15] showed that use of conventional flight instruments as flight references for the pilot would induce unacceptable errors in the data. Therefore, the resolution of the altitude transducer was exploited to provide the pilot with guidance to fly at a constant altitude by displaying incremental altitude data using an electrical version of a statoscope. The altitude signal from the Rosemount transducer was balanced against a suitable voltage source and the difference was displayed on a needle-type display directly in the line of vision of the pilot. The reference voltage was adjusted to center the needle of the pilot's indicator and then left alone for the duration of the run. The pilot then flew to keep the needle centered. The rate of change of altitude signal was used to drive a second meter adjacent to the incremental altitude meter to provide rate information. A similar arrangement could provide the pilot with an expanded scale indication of incremental airspeed or vertical speed for other tests. A single flight-director-type indication combining the rate and error information into a single "follow the needle" command presentation would have been desirable.

Test Technique

Except for changing the power to produce the transient in airspeed while maintaining level flight, the test technique was standard. Only the technique associated with the transient will be described. Tests described herein were made only to provide data to establish the validity of the transient method and all data was taken at one airspeed and two altitudes. No attempt was made here to cover a wide range of flight conditions.

Data flights were made only in smooth air, with winds light or calm. In general, this meant flights in the stable air of an inversion in the early morning.

At the test altitude the observer adjusted the voltage reference source for the incremental altitude indicator to center the needle on the pilot's indicator. The airplane was controlled in pitch to maintain the desired altitude as shown on the incremental altitude indicator. Power and mean pitch were adjusted to produce the desired starting airspeed. Steady conditions were more important than attaining exactly a specified speed. One of the products of this project was a clear understanding of the time required to reach a steady speed, so ample time was allowed to reach a steady speed. At the start of recording the airplane was held undisturbed for about 1 min to define a convincing initial condition, then the throttle was moved quickly to a new position to provide a step input in power. Typical inputs were 2 in. Hg manifold pressure, or 20-30 hp change from a 150-170 hp base. The size of the input was a compromise between conflicting requirements—small inputs would keep the aerodynamics linear to make the analysis applicable but large inputs would increase the accuracy with which they could be measured. Transients were recorded with both increases and decreases in power. As the speed changed in response to the power change, the pilot adjusted the pitch angle to maintain constant altitude. Data runs typically lasted about 2 min, with altitude excursions of 1-1½ ft.

The improvement in the control of flight path using the special pilot guidance instruments was significant. Rate information as well as incremental altitude information was important. When using a meter to close a control loop, a pilot will normally use not only the indication of the meter but also the first derivative (rate of motion of the meter needle) and second derivative (how fast the rate of motion is changing). These instruments thus provided the pilot with altitude error and its first, second, and third derivatives. He adjusted the elevator to control pitch angle using rate of climb as an inner loop and altitude error as an outer loop, and used the first and second derivatives of rate of climb to tell what rate of change of elevator was needed. Placement of instruments in the pilot's line of vision was important so that he could scan them while visually flying the pitch angle. An analog presentation (needles) was used rather than a digital display because the pilot needed the derivative information that he readily obtained from observation of the moving analog presentation. It was possible to maintain altitude during a level flight transient in speed to within about 1 ft for runs of 2-3 min, Figs. 2 and 3, in spite of the disturbance in trim caused by the transient. Complete concentration was required to fly these two instruments but it could be done for several minutes at a time for flights lasting 2 h. A vernier throttle adjustment would simplify adjustment of power for level flight, and a fixture allowing selectable and repeatable step inputs of power would aid initiation of the transient. The flight records showed an oscillation of a small but noticeable amplitude at a period that varied but which was commonly around 15 s. This was neither the short period nor the phugoid mode of the airplane, but instead was a combined pilot-airplane mode characteristic of an airplane being controlled precisely by the pilot, and has been seen and reported in flight-test programs in other airplanes[16] where it showed plainly in power spectral density analyses.

Small variations in velocity caused by momentary deviations in altitude were smoothed by assuming changes in altitude and velocity were exchanges between kinetic and

Table 9 Flight-test results; combined runs

Run No.	η_p	C_{DO}	e
Best 5 runs:			
1	0.758		
3	0.769		
8	0.754	0.0207	0.591
13	0.798		
21	0.789		
Accelerated runs:			
1	0.767		
5	0.768		
7	0.778	0.0216	0.646
9	0.780		
11	0.779		
Decelerated runs:			
4	0.765		
6	0.757	0.0204	0.554
8	0.760		
10	0.766		

Table 10 Comparison of results from transient and steady flight

Tests transient maneuver	η_p	C_{DO}	e
Accelerate	0.774	0.0216	0.646
Decelerate	0.762	0.0204	0.554
Feathered glide[7]			
Generalized plot of power required		0.0209	0.858
Plot of C_D vs C_L^2		0.0201	0.870
Numerical estimate		0.0208	0.905
Level flight[6]	η_p^{max}		
Constant speed Propeller	0.708		
Fixed pitch,			
$\beta = 17.45$ deg	0.756		
$\beta = 15.7$ deg	0.750		
$\beta = 13.45$ deg	0.712		

potential energy, expressed as

$$V_l^2 = V_2^2 + 2g\Delta h$$

where V_l is the speed the airplane would have if there had been no change in altitude, V_2 the measured true airspeed, and Δh the change in altitude. Thus,

$$V_l = (V_2^2 + 2g\Delta h)^{1/2}$$

The velocity V_l can be found from the measured velocity and the change in altitude from the initial height since the pilot was trying to maintain this altitude. Simulator studies showed that this correction improved the results provided the altitude deviations were on the order of 4-5 ft. When the errors were smaller the improvement was negligible, and when they were larger the concept of a simple energy exchange became invalid as the thrust of the airplane had time to influence the velocity and the altitude variations.

Results

Twenty flight-test runs are listed in Table 7. The processed results of each of the runs are shown in Table 8, arranged in order of the error term $\overline{er}$. As can be seen, there was considerable variation in the flight unknowns determined from the different runs. Considering the fairly limited range of power and velocity during the tests, the values of C_{DO} and e should be constant for all of the runs. The propulsive efficiency would be expected to vary, but not much over $\pm 5\%$, based on wind tunnel tests of a similar propeller.[17] Instead, the propulsive efficiency varied between 0.29 and 0.92, the drag coefficient between 0.015 and 0.031, and the wing efficiency between -1.59 and 3.51. It was interesting that the wing efficiency seemed to be well behaved in the sense that, for low values of $\overline{er}$, the value of e stayed around 0.58-0.60 and then diverged from that as $\overline{er}$ increased. The propulsive efficiency and drag coefficient, however, seemed to vary considerably from run to run as $\overline{er}$ increased, sometimes being higher than expected and other times much lower. As in the simulation data, it was obvious that the runs would have to be combined to yield valid results.

The runs were combined using two different criteria. First, the five runs with the lowest error term were combined and processed for seven unknowns, specifically one drag coefficient, one wing efficiency, and five propulsive efficiencies, to see if they varied from run to run. The results, Table 9, were much improved compared to analysis of each run individually. The propulsive efficiencies varied only a few percent and the uncertainties for the propulsive efficiency and the drag terms were lower. Second, runs with similar flight conditions were combined. Runs 1, 5, 7, 9, and 11 were all accelerations with similar initial power and speed, while runs 4, 6, 8, and 9 were decelerations with similar initial conditions. Propulsive efficiency is a function of speed and power so grouping the runs in this way could be expected to minimize the variation in propulsive efficiencies determined for the runs in the group. Table 10 shows that the accelerations and decelerations had similar propulsive efficiencies within their group. The acceleration data showed an average propulsive efficiency of 0.774 with a standard deviation of 0.006, while the deceleration, taken with a slightly lower power and speed, showed an efficiency of 0.762 and a standard deviation of 0.004. All three combinations of runs produced similar values for C_{DO} and e. The average C_{DO} was 0.0209 with a standard deviation of 0.0006 and the average e was 0.597 with a standard deviation of 0.046. Combining several runs gave better results with lower values of uncertainty than processing each run individually. The flight-test results were consistent and confirmed the validity of the transient method of obtaining performance parameters.

Comparison of Results from Transient and Steady Tests

Steady level speed-power tests, climb tests, and glide tests with the propeller feathered were made[6,7] to exploit the accuracy of the data system. The level flight tests were made with the propeller governed to run at a constant speed, and also with the propeller blade angle fixed at three different blade angles. With the propeller feathered, the power was known to be zero and the drag terms were determined by conventional means. The propulsive efficiency was determined by comparing the power required in the feathered glide with power required in level flight. In the glide tests with the propeller feathered there were obviously no effects of power on C_{DO} and e as would occur in powered flight. Thus there was no effect of slipstream on the fuselage drag or the flow at the juncture of the wing and fuselage, no engine exhaust, and no effect of the hot engine on the cooling air flow. In contrast, the powered tests included these effects, which were lumped into propulsive efficiency by the method used to determine the efficiency. Parameters obtained from steady power-required tests used data from a range of speeds compared to the point data obtained from the transient method. This resulted in ambiguity if the parameters did not remain constant with speed and power as assumed. The transient method required the parameters to remain constant only over the small speed and power range covered in the transient. In the transient method the performance parameters were determined at essentially a single speed, with the engine running at the power corresponding to that speed, so power effects were accounted for directly.

The propulsive efficiency and drag terms obtained from the transient method and from steady flight tests are compared in Table 10. The results are consistent and show the effect on the parameters of the different ways in which the power effects are included.

Conclusions

1) The performance parameters (propulsive efficiency, parasite drag coefficient, and airplane efficiency factor) could be determined from flight tests with relatively simple instrumentation by analysis of the transient in airspeed in level flight.

2) The accuracy of the determination of the performance parameters was good, with a standard deviation of about 1%. The estimates of the unknowns were consistent with those obtained by steady-state methods.

3) The flight tests required to determine the performance parameters were relatively simple.

4) Pilot guidance instruments using signals available in the measuring instrumentation permitted significant improvement in the quality of the flight-test data. Altitude was maintained to within ½ ft in steady flight and to within 1 ft during the transient.

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