FIGHTER AIRCRAFT DYNAMIC PERFORMANCE

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Abstract

Flight testing in the area of performance has been considered for years to be straightforward. However, with the advent of ultra-performance fighter aircraft, performance flight test has had to deal with dynamic and diverse environments. In addition to the usual how far and how fast, there are questions to be answered in the areas of high response turning performance and expanded lift and drag regions. The advent of sophisticated high resolution, high response INS systems, has brought into its own the area of dynamic performance testing. Dynamic performance incorporates new maneuvers which not only give excellent results, but also can cut the number of performance test points required. Wind-up turns (WUTs), roller-coasters (RCMs) and split-s' (SS) are maneuvers considered as dynamic performance. These dynamic maneuvers were used to compute lift and drag with very good results. The quality of the data and the correlation with the conventional maneuvers (cruise, accelerations, climbs, and turns) was excellent. Obtaining this data from the sophisticated INS system required innovative analysis methods. Alone, the INS will provide excellent three-dimensional velocities, accelerations and rates. However, it will not provide the required wind axis flight path accelerations and angle of attack for dynamic performance testing. This paper addresses the methods used to obtain performance parameters from the INS as well as a break down of how dynamic performance testing can greatly reduce flight test time and effort.

Introduction

This paper describes dynamic performance data acquired during an AFFTC flight test program. These data were obtained from RCM, SS, and WUT maneuvers. For simplicity and brevity, only data at one Mach number are presented. Specific details on aircraft type and flight conditions are deleted in order to avoid classification problems. The data presented in this paper does not by any means represent the first application of INS data to performance testing. An early limited application at the AFFTC was in the late 60s on the SR-71 project. On that project the INS accelerations were used only during cruise testing. The general concept of using an INS was studied at the AFFTC in the late 60s and early 70s, but no funds were available for any testing. The first major application of an INS was on the YF-16 project in 1974. Mr. James Olhausen of General Dynamics, Fort Worth was primarily responsible for the success of that effort. The INS data was used also on the STOL transport projects in 1975. What the authors feel the data in this paper represents is the highest quality dynamic performance data obtained to date. Also, this paper represents the first unclassified documentation of the wind calculation algorithms.

Flight Maneuvers

The first maneuver presented is the RCM. The objective was to have a sinusoidal variation of load factor at a rate of 0.5 gs per second. Figure 1 is a time history of a RCM. The RCM maneuver extends over a g range of zero to two gs but other g ranges are possible. The problem with larger load factor ranges is the Mach number excursions accompanying the large g changes. These excursions can be very large. This is especially true in a pull-up maneuver. At high g levels in a pull-up the aircraft will decelerate substantially. However, this is not the case for the split-s maneuver. Therefore, the SS maneuver was devised to obtain aerodynamic data at high g levels while minimizing the Mach excursions. A time history of the SS is given in Figure 2. The SS is performed by rolling inverted then increasing the load factor at about one g per second until either the limit g or limit angle-of-attack is reached. As can be seen, there is very little Mach number loss. This is due to a combination of two factors. First, the maneuver is highly dynamic (one g per second) and the entire maneuver takes approximately 5 seconds, which typically is not enough time for large Mach excursions. Secondly, the maneuver is inverted and a trade-off is made between airspeed and altitude. The third dynamic maneuver is the WUT. This is a turn maneuver where g is increased at a rate of one g per second until limit g or limit angle-of-attack is reached. The WUT is primarily a flying qualities maneuver. However, the superior quality of the data from the INS has allowed us to apply WUT maneuvers to performance lift and drag curves. The range of data in a WUT is identical to the SS and for the first time the results were also comparable to the SS. The WUT time history is shown in Figure 3.

INS Data Reduction

The INS used on this project was a system containing two gyroscopes and three accelerometers connected to the aircraft by a gimballed platform. The three accelerometers are located at 90 degrees to each other on a platform stabilized by the two gyroscopes. These accelerometers sense the aircraft's velocity changes in the north, east, and down (or x, y and z) directions. The two gyro spin axes are also perpendicular to each other and free-floating. The vertical gyro's spin axis is in the vertical position sensing roll and pitch motion. The azimuth gyro's spin axis is in the horizontal position and senses yaw motion. These accelerometers and gyros allow the INS to measure any accelerations or angular rate changes and output these parameters at 50 samples per second. Data analysis for performance parameters utilizing this INS involved only nine parameters. The first three are the x, y, z components of inertial velocity. The second three are the x, y, z components of inertial acceleration. The inertial acceleration components were computed by differentiating the inertial velocities. The last three parameters are the Euler angles (roll, pitch and heading). These nine parameters from the INS are combined with true airspeed to compute angle of attack and flight path accelerations. In order to make the required axis transformation it is necessary to compute winds. During wings level constant altitude flight the INS computer will produce the horizontal components of winds. But these winds are computed using true airspeed which has not been corrected for pitot static position errors determined during the flight test program. Also, the winds are only valid for zero bank and zero vertical speed. It was necessary to develop computer algorithms to compute winds for any maneuver. The details of these equations are contained in the Appendix.

There are three basic transformation equations from the earth axis system to the flight path or wind axis system. Unfortunately, there are five unknowns for these three equations. The five unknowns are three components of wind, angle-of-attack and sideslip. To solve these equations it was assumed that the vertical component of wind and sideslip were zero. This algorithm worked quite well for maneuvers where bank angle was small. This includes climbs, accelerations, cruise, RCM and SS. But for turns and WUT maneuvers, the terms in the equation (equation three in the Appendix) which were set to zero in order to solve the equation became significant for high bank angles. The data became unusable and in many cases the equations were unsolvable.

A new algorithm was developed to reduce turn and WUT data. The assumption was made that the horizontal components of wind remained constant during the maneuver. This is a good assumption for constant altitude turns. For WUT data where altitude is lost in order to minimize Mach number variations, the winds can vary somewhat but if then altitude loss is small (less than 1,000 feet) then the constant wind assumption is approximately correct. The vertical component of wind was again assumed to be zero. A least squares solution for winds was found using the basic equation for true airspeed (equation 12 of the Appendix). This method worked quite well for the turning data but could not be applied to data at zero bank angle. The reason for this is that to acquire a statistically valid set of wind components requires that the x and y components of velocity have some significant relative variation. During maneuvers such as accels and cruise the x and y velocities are nearly linearly dependent. That is, the x velocity is approximately a linear function of the y velocity. In order to solve for x and y wind components it is required that the x and y velocities be linearly independent. This is not true for non-turning maneuvers. Therefore, we used two methods for determining winds. The first method incorporated the zero bank analysis for cruise, climb, accelerations, RCM, and split-s maneuvers. The second method used the least squares method discussed above.

Aerodynamic Data

Lift and drag coefficients were computed and standardized to a common set of reference conditions. The reference conditions were a standard altitude and center of gravity. The equations used will not be represented here since they are standard aerodynamic equations and details of the corrections to reference conditions have no relationship to the purpose of this paper. The corrections were very small since most of the data presented herein was flown near the reference conditions. All of the data presented were flown at or near the same Mach number. This Mach number was well below the transonic drag rise so no Mach corrections were made. Only one Mach number is shown since this is all that is necessary to illustrate the data quality and data correlation.

A substantial amount of conventional maneuver data was collected during the tests. Figures 4 and 5 present the drag polar data for accelerations, climbs, cruise and turns. Figures 6, 7 and 8 present the drag polar data for single RCM, SS and WUT maneuvers, respectively. In order to facilitate comparison of the various maneuvers the same fairing is shown on each plot. The data is also presented with the same scales. As can be seen there is excellent agreement between all the maneuvers. A similar set of plots for angle of attack is presented in Figures 9 through 13.

Conclusion

Every paper on dynamic performance testing usually comes to the same conclusion. That is, that the data contained in the paper demonstrates conclusively that dynamic performance techniques can save tremendous amounts of flight test time. We could easily reach the same conclusion. However, there is more to a performance evaluation than obtaining the lift and drag data. It is still necessary to evaluate the thrust and fuel flow characteristics of the engine. For this it is necessary to do climbs, accelerations and cruise testing. Still, by incorporating dynamic performance techniques into a performance evaluation we can vastly improve the ability to define the drag polar and lift curves. We can cover the entire lift coefficient range of the aircraft at one Mach number with just two maneuvers (RCM and SS). Dynamic performance techniques can reduce flight time significantly, but the main advantage of the method is the improvement in the overall performance definition which it affords.

It is now up to a very conservative flight test community to reconsider the methods of obtaining lift and drag. This not only means a re-evaluation of the maneuvers involved, but also the type of instrumentation used. The INS system we were involved with has proven to be an excellent navigation device and an invaluable tool for determining basic performance parameters with a high level of accuracy.

Appendix

Flight Path Calculations From Inertial Platform Measurements and True Airspeed

A calculation of wind velocities was necessary in order to translate inertial accelerations in the earth-axis-system (north-east-down) to accelerations in the wind-axis-system. Two different wind calculation routines were used, depending upon the type of maneuver.

The first wind method was designed for maneuvers where bank angle was near either 0 degrees or 180 degrees. The assumptions made were that sideslip (β) and vertical wind (V_{W_Z}) were zero. The exact equations for airspeed components in the earth axis system are as follows:

$$V_{A_X} = (\cos\psi \cos\theta \cos\alpha \cos\beta + \cos\psi \sin\theta \sin\phi \sin\beta + \cos\psi \sin\theta \cos\phi \sin\alpha \cos\beta - \sin\psi \cos\phi \sin\beta + \sin\psi \sin\phi \sin\alpha \cos\beta)\, V_T \quad (1)$$

$$V_{A_Y} = (\sin\psi \cos\theta \cos\alpha \cos\beta + \sin\psi \sin\theta \sin\phi \sin\beta + \sin\psi \sin\theta \cos\phi \sin\alpha \cos\beta + \cos\psi \cos\phi \sin\beta - \cos\psi \sin\phi \sin\alpha \cos\beta)\, V_T \quad (2)$$

$$V_{A_Z} = (-\sin\theta \cos\alpha \cos\beta + \cos\theta \sin\phi \sin\beta + \cos\theta \cos\phi \sin\alpha \cos\beta)\, V_T \quad (3)$$

where

$$V_{A_X} = V_{I_X} + V_{W_X} \quad (4)$$

$$V_{A_Y} = V_{I_Y} + V_{W_Y} \quad (5)$$

$$V_{A_Z} = V_{I_Z} + V_{W_Z} \quad (6)$$

V_{A_X} = X component of earth axis airspeed

V_{A_Y} = Y component of earth axis airspeed

V_{A_Z} = Z component of earth axis airspeed

V_{I_X} = X component of earth axis inertial speed

V_{I_Y} = Y component of earth axis inertial speed

V_{I_Z} = Z component of earth axis inertial speed

V_{W_X} = X component of windspeed

V_{W_Y} = Y component of windspeed

V_{W_Z} = Z component of windspeed

V_T = true airspeed

ϕ = bank angle

θ = pitch angle

ψ = heading angle

α = angle of attack

β = sideslip angle

By incorporating the assumption of $\beta = V_{W_Z} = 0$ and combining equations (3) and (6) yield the following:

$$V_{A_Z} = V_{I_Z} = (-\sin\theta \cos\alpha + \cos\theta \cos\phi \sin\alpha)\, V_T \quad (7)$$

Equation (7) is readily solved for α using a one dimensional Newton-Raphson iteration scheme. Once α was calculated the wind components were computed using equations (4), (5) and (6) by substituting into (1), (2) and (3). The set of equations (1) through (6) reduced to three equations with five unknowns. The unknowns were the three components of wind and α and β. In order to solve these equations it was necessary to make the zero β and zero V_{W_Z} assumptions. Then, once the winds were computed, the accelerations could be transformed into the wind axis using the following equations which are simply the inverse of equations (1) through (3).

$$A_X = (\cos\beta \cos\alpha \cos\theta \cos\psi + \cos\beta \sin\alpha \sin\phi \sin\psi + \cos\beta \sin\alpha \cos\phi \sin\theta \cos\psi - \sin\beta \sin\psi \cos\phi + \sin\beta \sin\phi \sin\theta \cos\psi) \cdot A_N$$
$$+ (\cos\beta \cos\alpha \cos\theta \sin\psi - \cos\beta \sin\alpha \sin\phi \cos\psi + \cos\beta \sin\alpha \cos\phi \sin\theta \sin\psi + \sin\beta \cos\phi \cos\psi + \sin\beta \sin\phi \sin\theta \sin\psi) \cdot A_E$$
$$+ (-\cos\beta \cos\alpha \sin\theta + \cos\beta \sin\alpha \cos\phi \cos\theta + \sin\beta \sin\phi \cos\theta) \cdot A_D \quad (8)$$

$$A_Y = (-\sin\beta \cos\alpha \cos\theta \cos\psi - \sin\beta \sin\alpha \sin\phi \sin\psi - \sin\beta \sin\alpha \cos\phi \sin\theta \cos\psi - \cos\beta \sin\psi \cos\phi + \cos\beta \sin\phi \sin\theta \cos\psi) \cdot A_N$$
$$+ (-\sin\beta \cos\alpha \cos\theta \sin\psi + \sin\beta \sin\alpha \sin\phi \cos\psi - \sin\beta \sin\alpha \cos\phi \sin\theta \sin\psi + \cos\beta \cos\phi \cos\psi + \cos\beta \sin\phi \sin\theta \sin\psi) \cdot A_E$$
$$+ (\sin\beta \cos\alpha \sin\theta - \sin\beta \sin\alpha \cos\phi \cos\theta + \cos\beta \sin\phi \cos\theta) \cdot A_D \quad (9)$$

$$A_Z = (-\sin\alpha \cos\theta \cos\psi + \cos\alpha \sin\phi \sin\psi + \cos\alpha \cos\phi \sin\theta \cos\psi) \cdot A_N$$
$$+ (-\sin\alpha \cos\theta \sin\psi - \cos\alpha \sin\phi \cos\psi + \cos\alpha \cos\phi \sin\theta \sin\psi) \cdot A_E$$
$$+ (\sin\alpha \sin\theta + \cos\alpha \cos\phi \cos\theta) \cdot A_D \quad (10)$$

where

A_N = acceleration in the north direction

A_E = acceleration in the east direction

A_D = acceleration in the down direction

A_X = X flight path acceleration (longitudinal)

A_Y = Y flight path acceleration (lateral)

A_Z = Z flight path acceleration (normal)

The wind calculation method as described above seemed to degenerate during turning maneuvers. The reason for the problem can be seen by examining the term which was deleted in equation (3). The term is $\cos\theta \sin\phi \sin\beta$. For small bank angles and small sideslip the term vanishes, but as bank angle gets large (60 degrees or more) and sideslip becomes nonnegligible (on order of 1 degree) the term becomes significant in comparison with other terms in the equation. In many cases, the errors were so large that equation (7) became unsolvable. An alternative wind calculation method was required. The method developed was simply a solution of the basic velocity equation as follows:

$$V_T^2 = (V_{I_X} + V_{W_X})^2 + (V_{I_Y} + V_{W_Y})^2 + (V_{I_Z} + V_{W_Z})^2 \quad (11)$$

The basic problem with equation (11) is that it is one equation with three unknowns. Theoretically any three unique data points could be used to produce three equations in three unknowns. Practical data considerations required that the equation be reduced to two dimensions by assuming $V_{W_Z} = 0$.

There is simply not enough information in the Z direction during a constant altitude turn to determine the Z wind component. Equation (11) reduces to the following:

$$V_T^2 = (V_{I_X} + V_{W_X})^2 + (V_{I_Y} + V_{W_Y})^2 + V_{I_Z}^2 \quad (12)$$

The above one equation and two unknowns were expanded to N equations where N is the number of data points in the data run. The solution was obtained by minimizing the sum of the squared residual error of equation (12) with respect to each of the unknowns. The resulting two equations in the unknowns are as follows:

$$\sum_{i=1}^{N} \left[V_T^2 - (V_{I_X} + V_{W_X})^2 - (V_{I_Y} + V_{W_Y})^2 - V_{I_Z}^2 \right] \cdot (V_{I_X} + V_{W_X}) = 0 \quad (13)$$

$$\sum_{i=1}^{N} \left[V_T^2 - (V_{I_X}^2 + V_{W_X})^2 - (V_{I_Y} + V_{W_Y})^2 - V_{I_Z}^2 \right] \cdot (V_{I_Y} + V_{W_Y}) = 0 \quad (14)$$

Equations (13) and (14) are solved by a two dimensional Newton-Raphson iteration scheme. In order to utilize the winds computed above, it was first necessary to compute airspeed velocities in the body axis as follows:

$$V_{B_X} = (\cos\theta \cos\psi)(V_{I_X} + V_{W_X}) + (\cos\theta \sin\psi)(V_{I_Y} + V_{W_Y}) - \sin\theta \, V_{T_Z} \quad (15)$$

$$V_{B_Y} = (-\cos\phi \sin\psi + \sin\phi \sin\theta \cos\psi)(V_{I_X} + V_{W_X}) + (\cos\phi \cos\psi + \sin\phi \sin\theta \sin\psi)(V_{I_Y} + V_{W_Y}) + \sin\phi \cos\theta \, V_{I_Z} \quad (16)$$

$$V_{B_Z} = (\sin\phi \sin\psi + \cos\phi \sin\theta \cos\psi)(V_{I_X} + V_{W_X}) + (-\sin\phi \cos\psi + \cos\phi \sin\theta \sin\psi)(V_{I_Y} + V_{W_Y}) + \cos\phi \cos\theta \, V_{I_Z} \quad (17)$$

To compute α and β the following equations were used.

$$\alpha = \tan^{-1} (V_{B_Z}/V_{B_X}) \quad (18)$$

$$\beta = \sin^{-1} (V_{B_Y}/V_T) \quad (19)$$

The problem was completed using equations (8) through (10) to transform accelerations from the earth axis system to the flight path axis system.

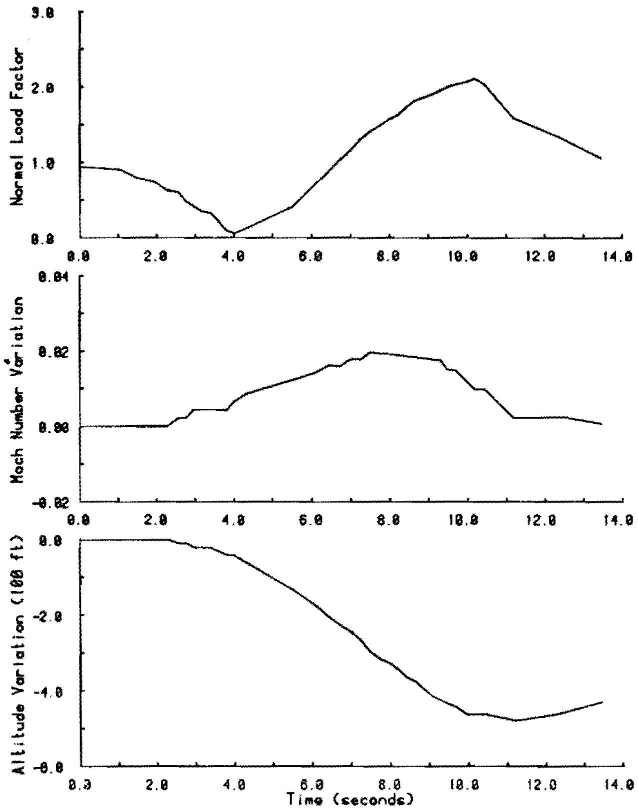


Figure 1 Roller Coaster Time History

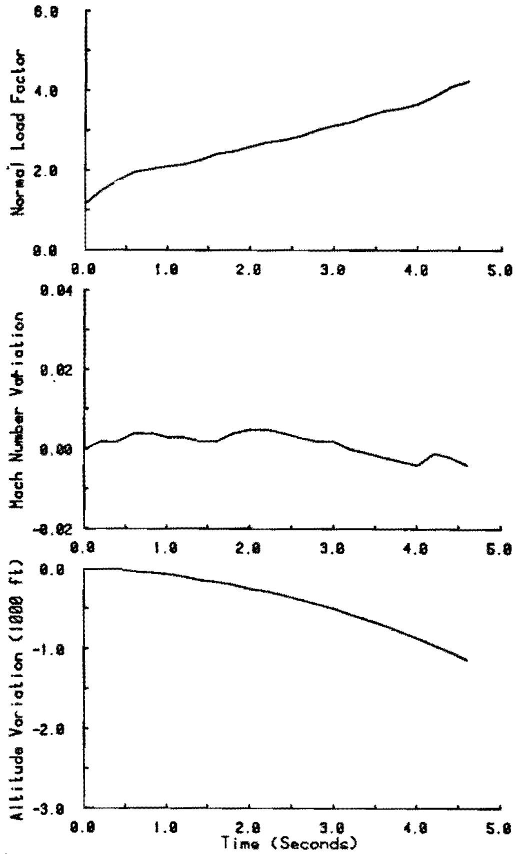


Figure 3 Split S Time History

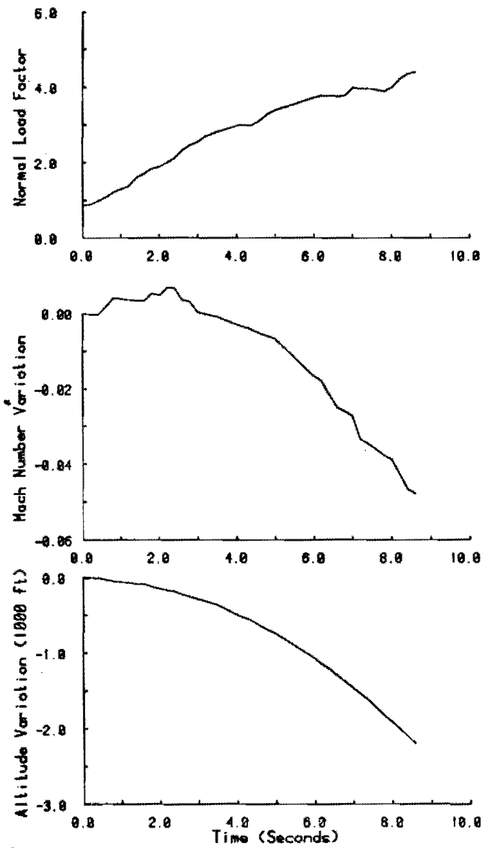


Figure 2 Wind Up Turn Time History

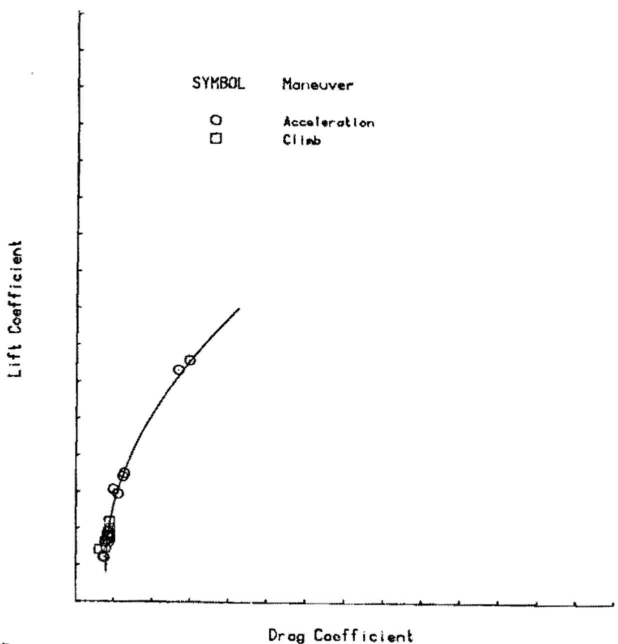


Figure 4 Acceleration and Climb Drag Polar

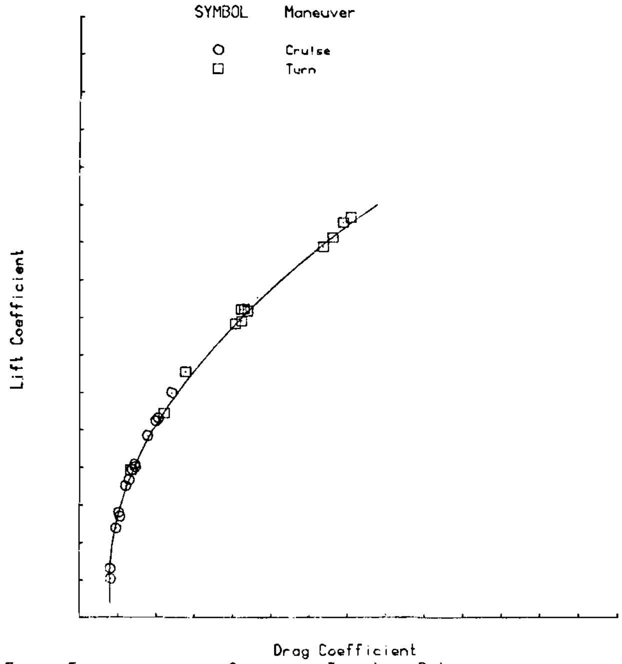


Figure 5 Cruise and Turn Drag Polar

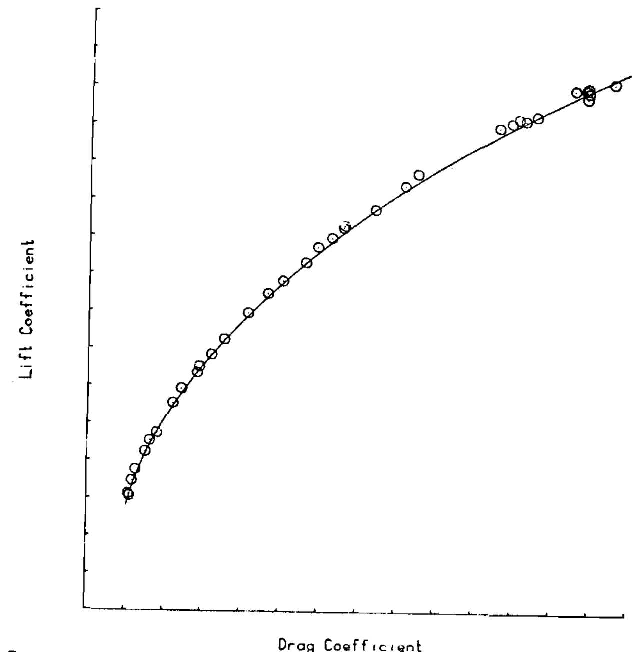


Figure 7 Wind Up Turn Drag Polar

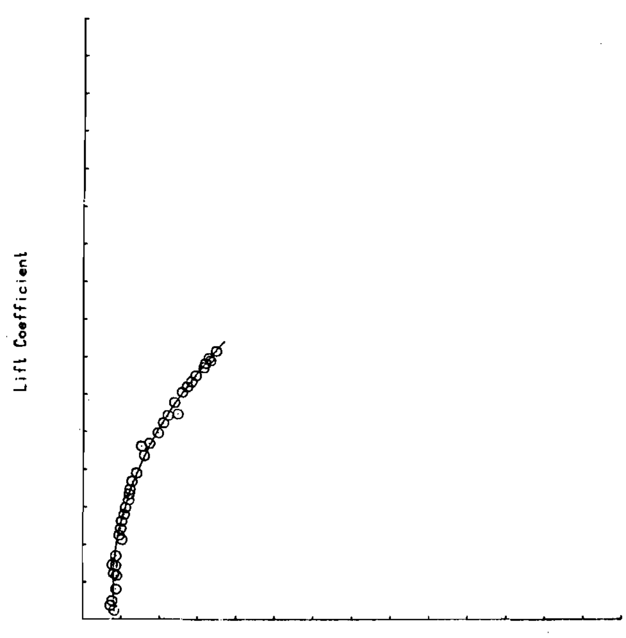


Figure 5 Roller Coaster Maneuver Drag Polar

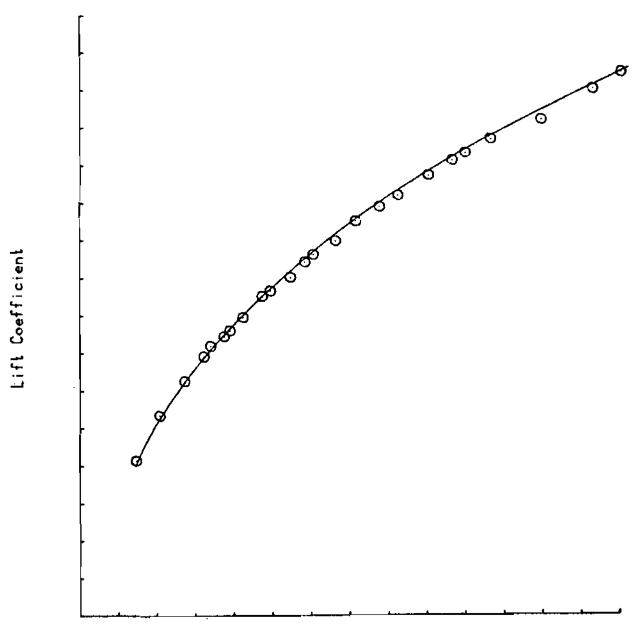
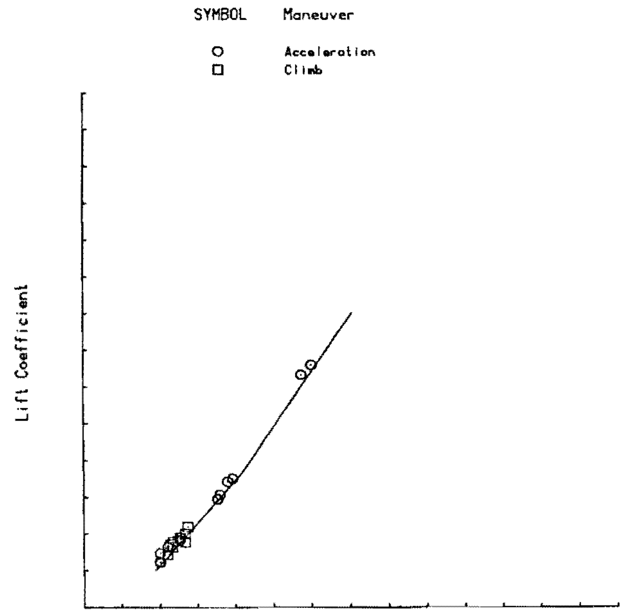
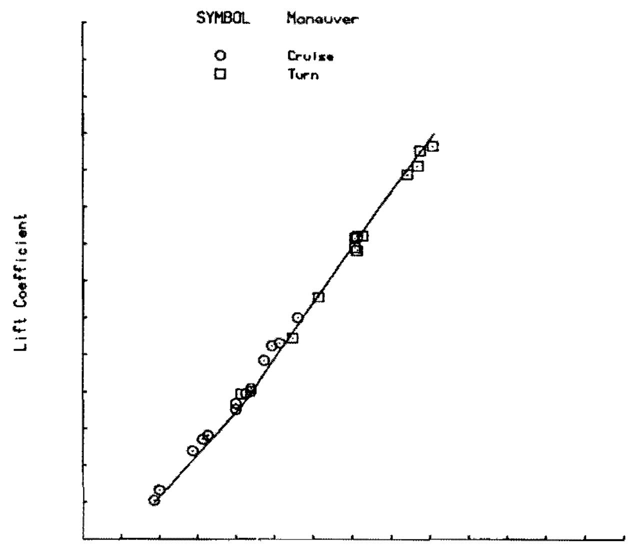


Figure 8 Split S Drag Polar



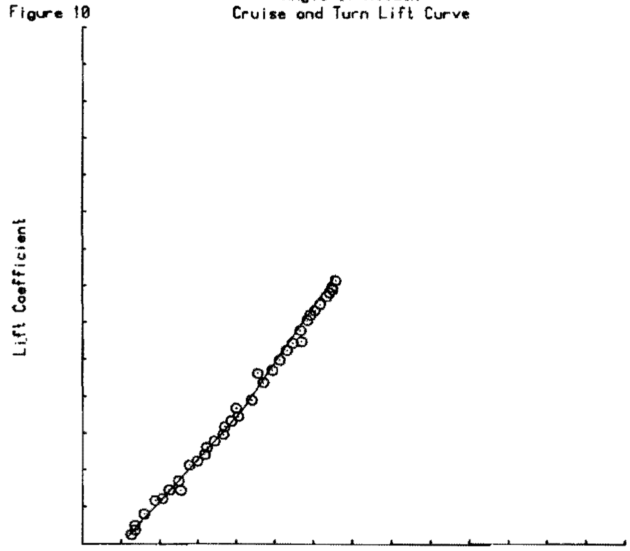
Angle of Attack

Figure 9 Acceleration and Climb Lift Curve



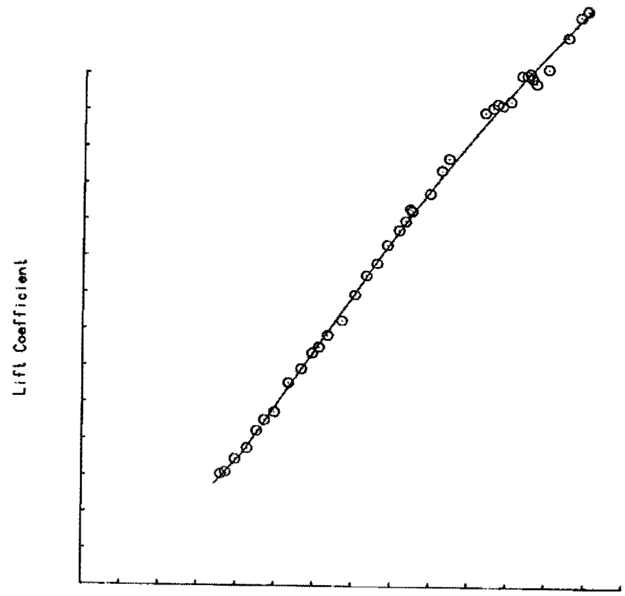
Angle of Attack

Figure 10 Cruise and Turn Lift Curve



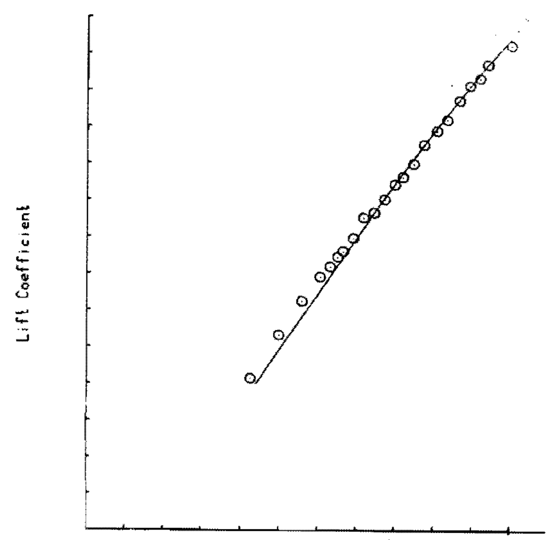
Angle of Attack

Figure 11 Roller Coaster Maneuver Lift Curve



Angle of Attack

Figure 12 Wind Up Turn Lift Curve



Angle of Attack

Figure 13 Split S Lift Curve