

5-13-13

INTRODUCING HANDLING AND AGILITY
INTO ENERGY MANEUVERABILITY

August 30, 1970

INTRODUCTION

The advent of Energy Maneuverability Theory has revolutionized the description of fighter performance. The introduction of the Advanced Energy Maneuverability Theory, which has added the kinematic aspects of maneuvering to the previously established energy concepts through the use of turn rate and turn radius, has placed an even greater premium on obtaining the most realistic possible estimates of thrust, drag and useable lift under maneuvering conditions. Some of the earliest energy maneuverability comparisons of aircraft were made by assuming that aircraft could use all values of lift up to the aerodynamic limit, $C_{L_{\max}}$. It was quickly recognized that, in fact, very few air-

craft can be flown to this limit due to stability and control restrictions encountered at lift values that may fall considerably short of the aerodynamic limit. An attempt was made to compare aircraft only up to maximum useable lift values by using published flight test and flight handbook restrictions. Unfortunately, this approach still proved unsatisfactory since there existed no consistent, objective and quantitative methodology for describing the handling limitations of a fighter aircraft. Thus, truly fair comparisons of existing U.S. and foreign fighters could not be achieved. Perhaps even more serious was the fact that this lack of methodology made it impossible to arrive at realistic comparisons of fighters still in the design stage.

Recent theoretical advances including the correlation of a dynamic directional stability parameter with flight test experience by Chambers and Anglin (NASA TND5361) plus the parametric exploration of a six degree of freedom spin dynamics simulation by Weyl and Casteel (AIAA 70-928) make it possible to correct the above deficiencies in the realistic description of fighter maneuvering performance. The following paper summarizes a quantitative approach to establishing handling qualities limitations on the following aspects of fighter maneuverability, in order:

- a. Maximum lift available without rolling, e.g., symmetrical, turning maneuvers such as the hard break.
- b. Maximum lift available while rolling at constant rate, e.g., three dimensional tactical maneuvers such as high g rolls, "pirouettes", etc.
- c. Average turn rate available including the effects of roll transients necessary to establish the turn, e.g., turn reversals, scissors, high g jinking.

It should be understood that the limits defined in this approach are not absolute restrictions on the feasible flight regime of an aircraft;

Exceptional pilots have and will continue to fly beyond the limits defined. However, flying beyond these limits is difficult and dangerous and will occur only rarely in air combat with average pilots. Current military practice is to establish restrictions in flight handbooks to assure that the average pilot will not encounter dangerous flight conditions.

II. CONCEPT

A. TURNING WITHOUT ROLLING

There are basically five phenomena that can potentially inhibit a pilot from pulling g in a non-rolling maneuver right up to the maximum aerodynamic or stall limit of an aircraft:

1. Directional instability -- as angle of attack increases, the ability of the vertical tail to keep the aircraft stable in yaw decreases, due to wing wake blanking the tail. If a point is reached where the tail provides no net restoring moment toward neutral yaw, as measured by the usual parameter $C_{n\beta}$ going through zero, the aircraft will begin to diverge in yaw.
2. Pitch-up -- there exist aircraft which have a tendency, upon reaching critical angles of attack below stall, to increase pitch angle without further back stick force being required - a highly dangerous condition that almost invariably leads to loss of control. Pitch-up can be caused by three basic sources: (a) center of pressure movement forward due to tip stall on high sweep wings; (b) increasing downwash at the horizontal tail due to high tail location and (c) decreased dynamic pressure at the tail due to wing wake. This condition is easily detected using the standard stability parameter $C_{m\alpha}$.
3. Heavy buffet -- most fighter aircraft experience increasingly violent buffet as they approach maximum lift. In some aircraft the magnitude of the buffet can limit the utility of the high lift region.
4. Wing rock -- Chambers and Anglin (NASA-Langley) have recently analyzed this high angle of attack phenomenon of increasing simultaneous yaw and roll oscillations (nose slicing and wing rock) as consisting of divergent dutch roll excursions. It is associated with aircraft of combined low directional stability and roll stability (dihedral effect). It can be measured by the NASA-developed dynamic stability parameter, $C_{n\beta dyn}$.

5. Spin susceptibility -- for the case of turning maneuvers without rolling, the angle of attack region in which the aircraft is spin-prone is the same as the wing rock region identified by $C_{n\dot{\phi}_{dyn}}$.

These five restrictions on lift capability in non-rolling maneuvers are depicted in the sample lift curve of Figure 1. Having defined a useable maximum lift from this figure (over an appropriate range of Mach numbers), this same limit is applied to all Advanced Energy Maneuverability plots involving maximum lift turn rates, e.g., the Quickest, Tightest Turn Diagram and the Maximum Maneuver Diagram. Figure 2 shows the substantial impact of non-rolling maneuver restrictions on a typical Maximum Maneuver Diagram. This difference becomes particularly important for differential diagrams comparing two aircraft.

B. TURNING WHILE ROLLING

The menu of useful air combat maneuvers includes not only simple turns without rolling, but many additional two and three dimensional maneuvers covering the spectrum of feasible roll and turn rates. Figure 3 shows this clearly. The introduction of rolling at high angle of attack brings with it two new handling limitations, in addition to the five discussed in the preceding section:

1. Loss of adequate roll control--as g or angle of attack increases, ailerons lose effectiveness due to flow separation until roll control becomes unsatisfactory for maneuvering flight. The normal parameter for measuring this effect is the rolling moment due to aileron deflection $C_{L\delta_a}$. However, stick force requirements must also be checked to ensure effective roll control.
2. Roll reversal--Some aircraft experience a relatively dangerous condition wherein, beyond a certain angle of attack, right stick commands produce left roll or vice versa. This can occur as a result of one of two causes: (a) the down aileron stalling its wing panel, or (b) the adverse yaw (nose away from direction of turn) due to aileron deflection causes increased lift on the wing to the inside of the turn. The reversal condition can be detected very easily using a simple function of standard static parameters, as discussed in Appendix A. Taylor and Ifliff (NASA Miscellaneous paper for Agard in 1966) clearly related adverse tendencies to degradation of handling qualities.

INFLUENCE OF HANDLING QUALITIES ON USEABLE LIFT CAPABILITY

TURNING WITHOUT ROLLING MANEUVERS

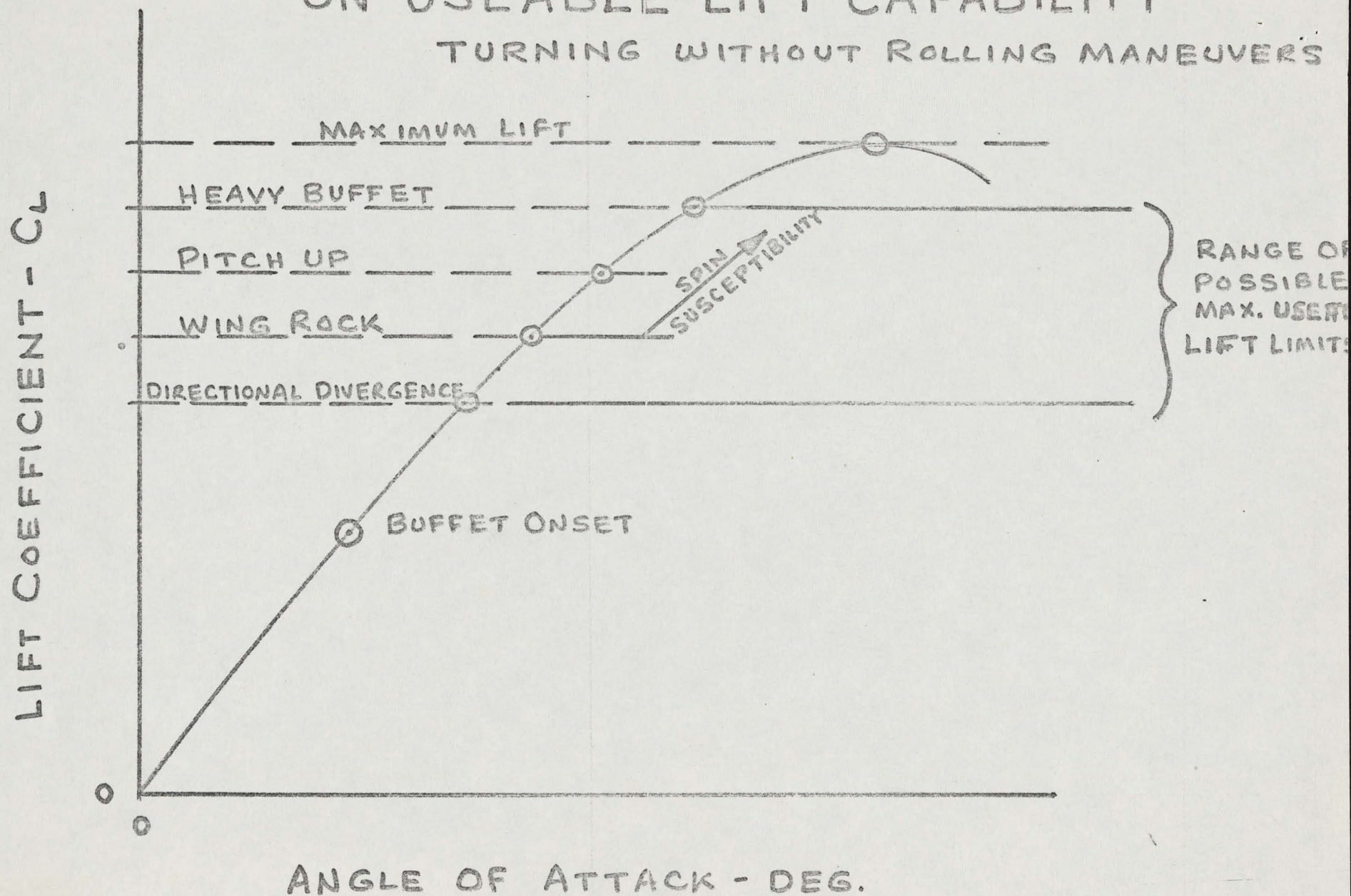


FIGURE 1

MAXIMUM MANEUVER DIAGRAM (NO ROLLING) A/C 504 - MAX. POWER

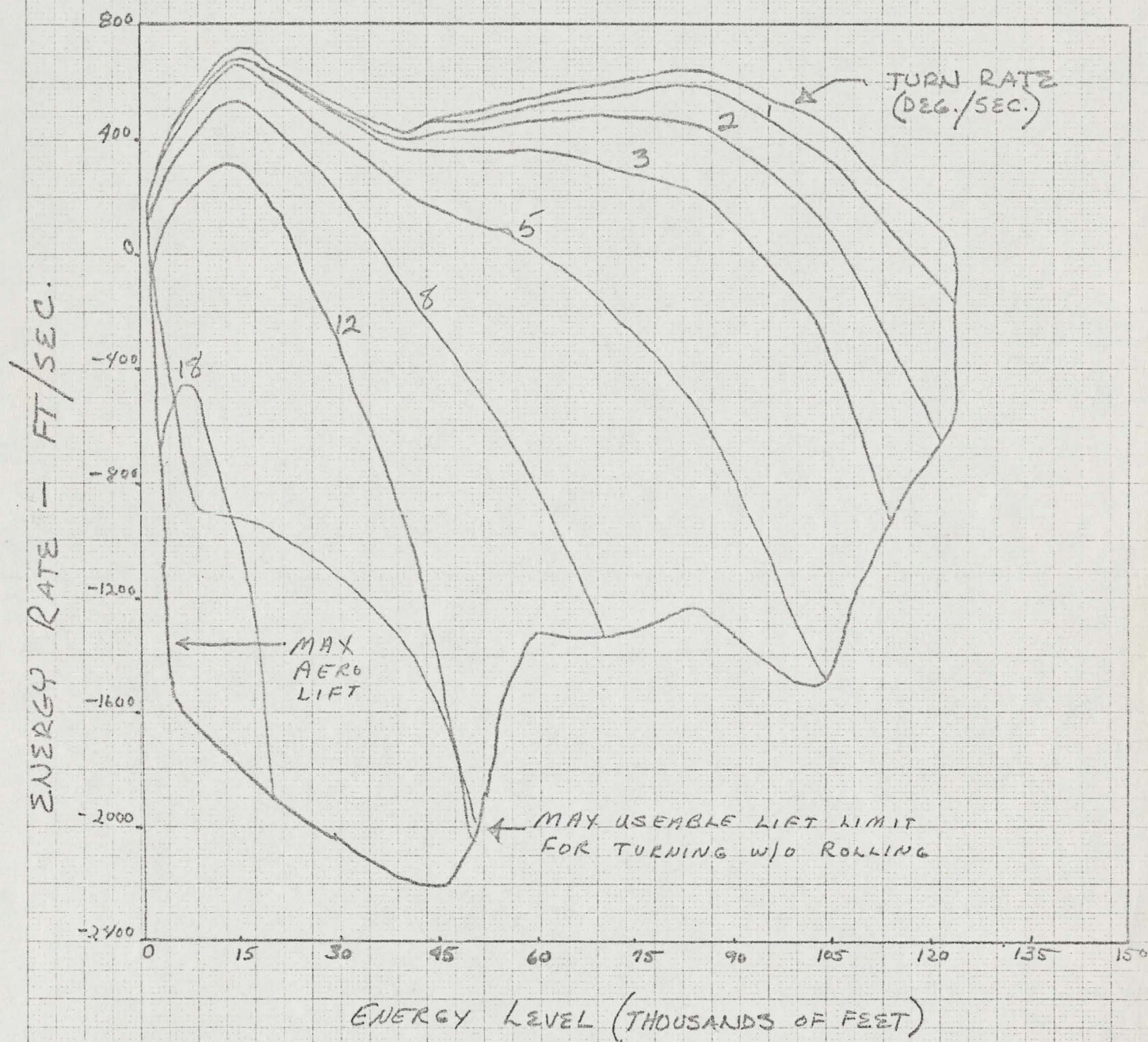


FIGURE 2

AIR COMBAT MANEUVERS

DESIRED COMBINATION OF TURNING & ROLLING

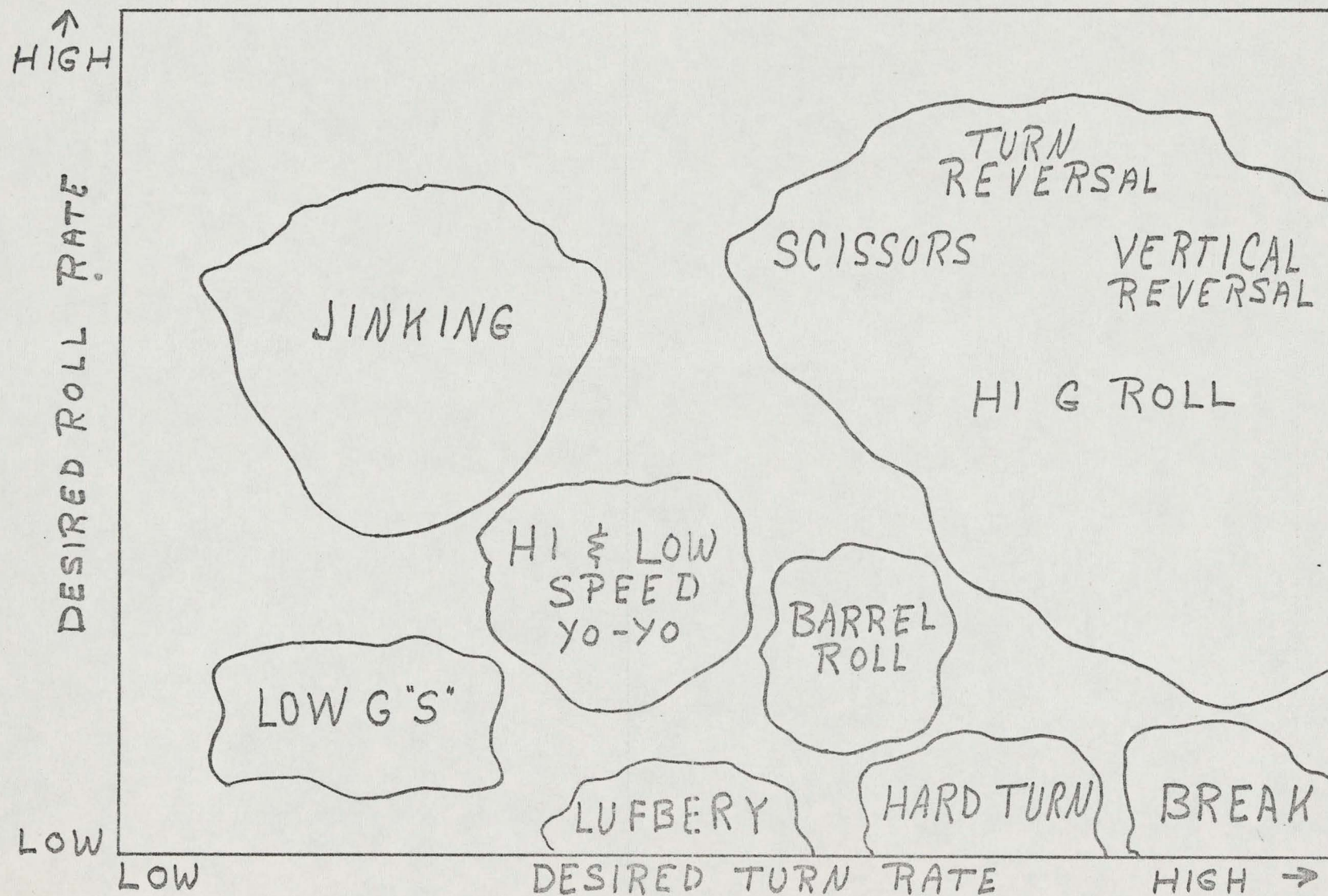


FIGURE 3

3. Spin susceptibility -- The same function that is used to identify roll reversal also identifies the spin susceptibility region in the case where maximum aileron inputs are applied.

Figure 4 shows the impact of these potentially more stringent handling limitations on maximum useable angle of attack as roll inputs are increased.

Once established, these angle of attack limits under maximum rolling conditions (or their equivalent lift limits) need to be applied to both the Quickest, Tightest Turn Diagrams and the Maximum Maneuver Diagrams. Figure 5 shows a typical example of rolling limitations superimposed on a Maximum Maneuver Diagram together with the previously established turn without roll limits. Note that in this case rolling and roll-free limits are very close. This is normal for most current aircraft though there is no inherent necessity for the two types of limits to be close.

C. AVERAGE TURN RATE DURING TRANSIENT MANEUVERS

The previous section identified as one important handling problem area the reduction in roll control effectiveness with increasing angle of attack as represented in Figure 6. This reduction is serious enough to have a significant impact on the actual "agility" of the fighter aircraft. This can be seen in Figure 7 which repeats the desired roll and turn rate combinations of Figure 3 overlaid with a sample plot of the reduction in available roll rates.

To usefully quantify this effect in terms comparable to the previously used turn rates, the concept of average turn rate through a transient maneuver is established. As a realistic desired maneuver, the following case is used:

Starting from an established level turn, maximum available reverse roll is initiated until an equal rate level turn in the opposite direction is established and held in order to obtain a total heading change of 45° ¹.

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45° is roughly equivalent to a minimum of 5-8 seconds, a reasonable upper bound for scissors or jinking turns.

MAXIMUM USEABLE LIFT FOR TURNING WHILE ROLLING

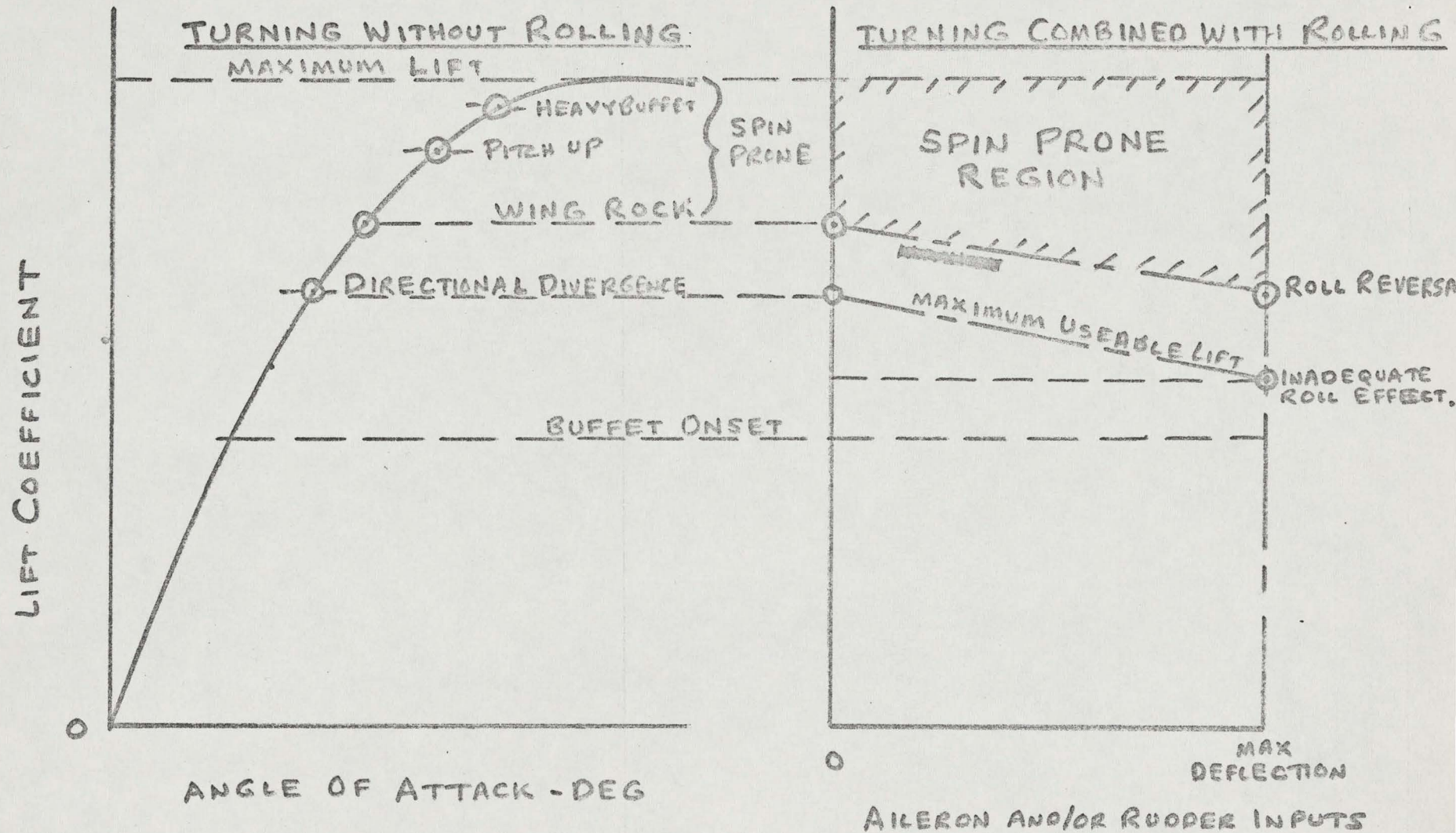


FIGURE 4

MAXIMUM MANEUVER DIAGRAMS (ROLL)

A/C 504 - MAX POWER

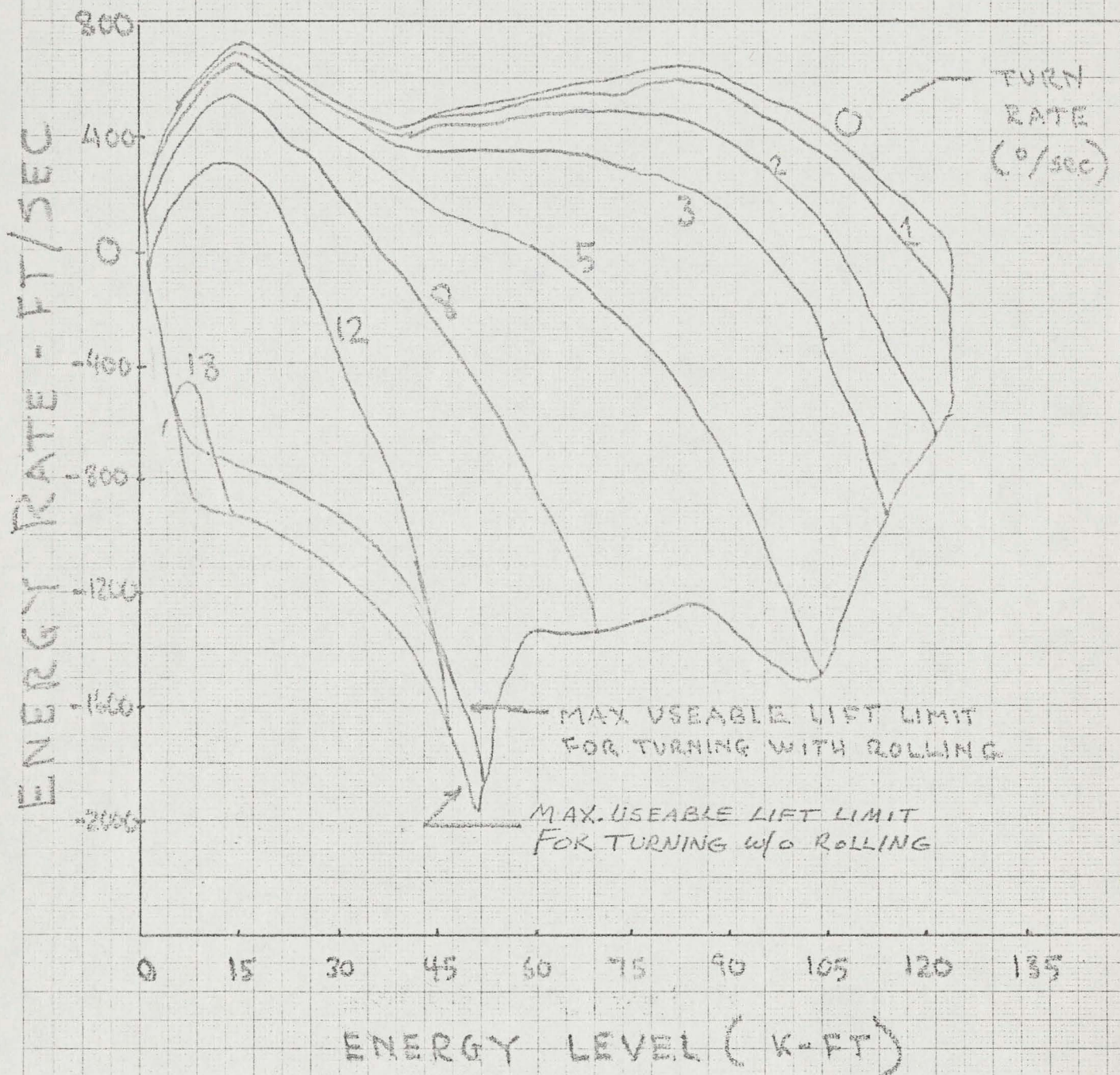


FIGURE 5

REDUCTION IN ROLL RATE WITH
INCREASING ANGLE OF ATTACK

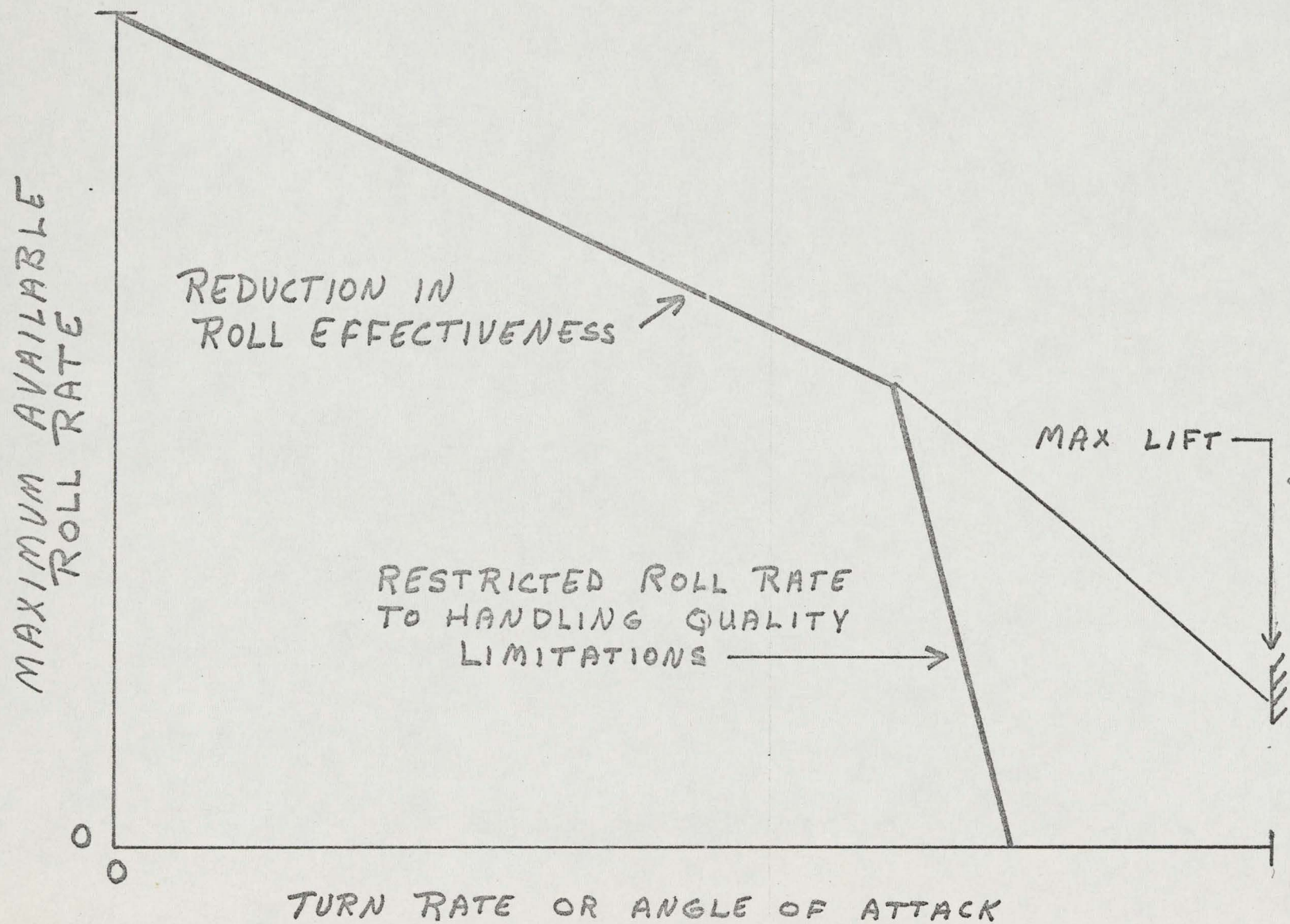


FIGURE 6

THE IMPACT OF ROLL RESTRICTIONS ON AIR COMBAT MANEUVERS

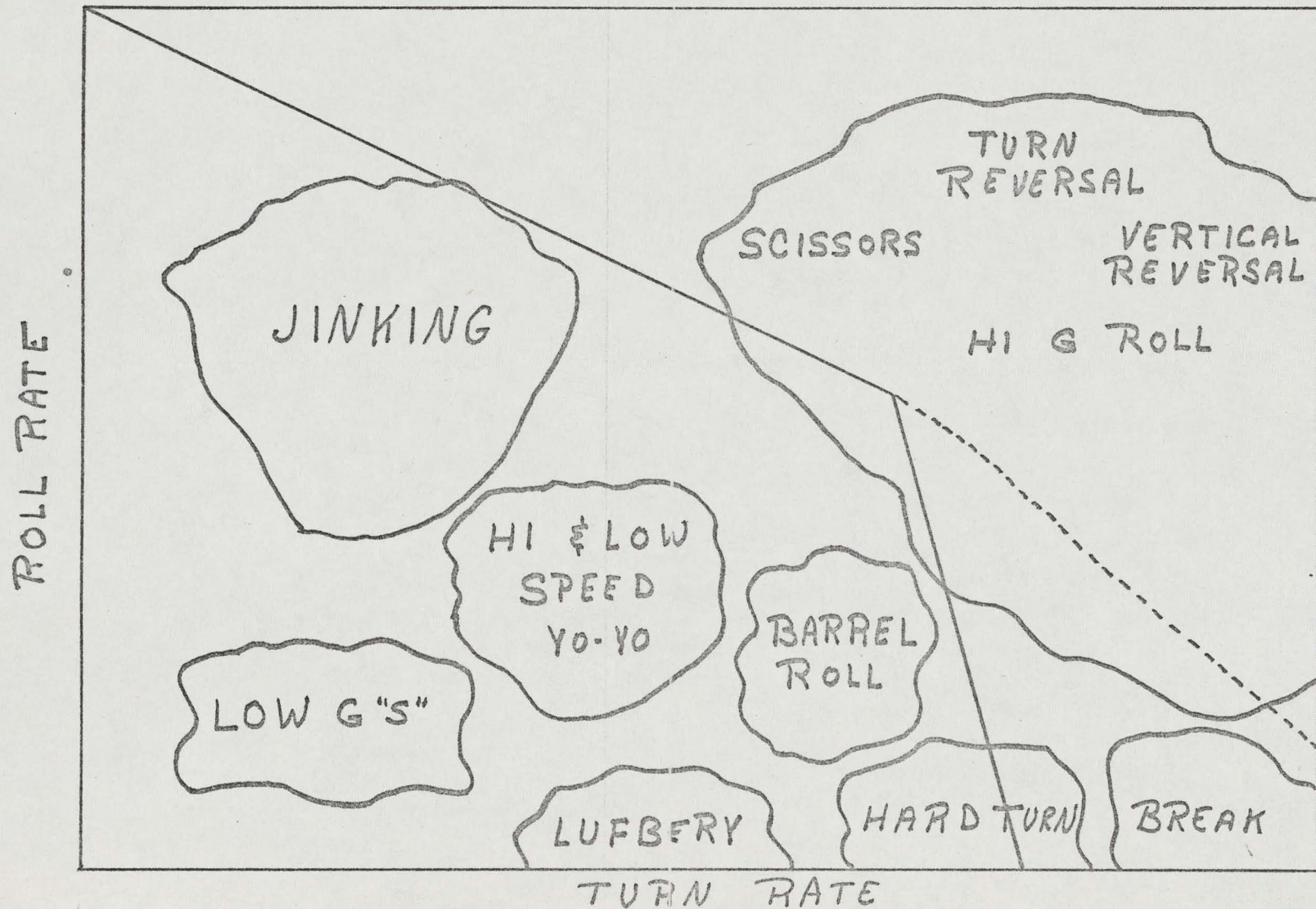


FIGURE 7

The average rate achieved through this representative maneuver (computing actual roll acceleration and time histories is discussed in Appendix B) is a useful measure of transient maneuver capability applicable to turn reversals, scissors and high g jinking. Figure 8 shows the large difference in both absolute level and trend for average turn rates through transient maneuvers versus steady turns. Note that roll rates at high turn rates can become so slow as to actually decrease achieved average rates upon increasing lift beyond the best point. Unfortunately, the Figure 8 representation only shows a single altitude and Mach number point. Therefore, a somewhat different and more comprehensive plot has been developed for addition to the standard Advanced Energy Maneuverability Theory displays. This plot is termed the Terminal Transient Maneuver Diagram and shows contours of absolute (or differential) average turn rate to achieve a 45° turn reversal on the P_s versus Mach number plane at representative altitudes of 10,000 and 35,000 feet. It indicates the ability of an aircraft to achieve quick turn reversals at all turning conditions from high energy gain to high energy loss rates. A sample is shown in Figure 9.

III. APPLICATION: F-5 vs. AIRCRAFT 504

Lift curves for the two aircraft are compared in Figure 10, showing the computed handling restrictions (both rolling and non-rolling cases). Aircraft 504 suffers a considerable penalty in useable lift due to handling restrictions. The F-5 suffers no restrictions. The practical effect of this is seen in Figure 11 which is a differential Maximum Maneuver Diagram (rolling case) for the two aircraft. The large exclusive region for the F-5 is mostly attributable to the lack of handling restrictions.

Figure 12 shows the basic input for the Terminal Transient Maneuver Diagram, a comparison of achievable roll rates for each aircraft. Figure 13 is the Terminal Transient Maneuver Diagram and shows a very large advantage in average turn rate during a transient maneuver for the F-5 at all energy rates of interest for the terminal phase of combat.

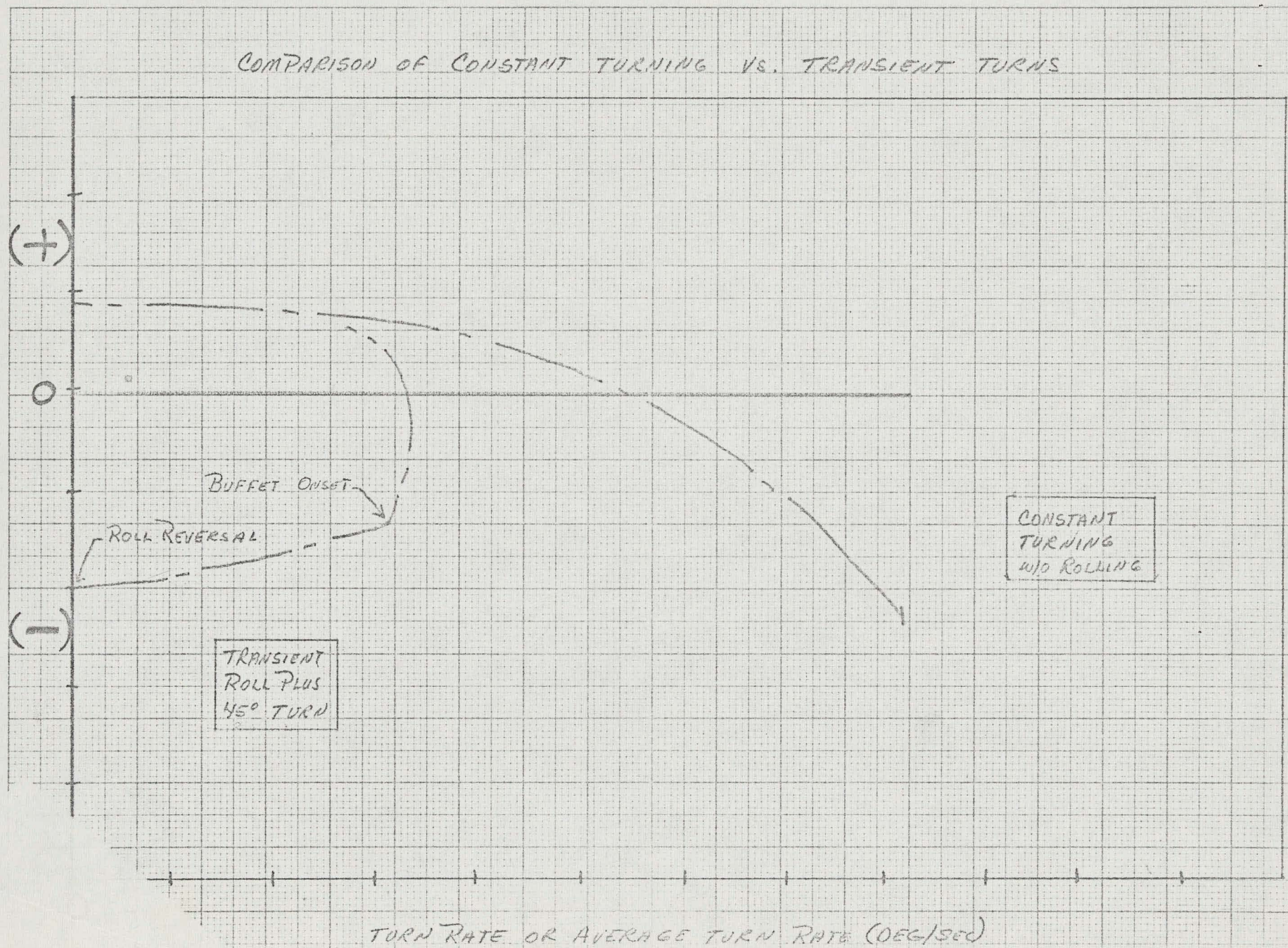
Specific Power P_s (FT/SEC)

FIGURE 3

TERMINAL TRANSIENT MANEUVER DIAGRAM

45° HEADING CHANGE - 35,000 FT

A/C 504

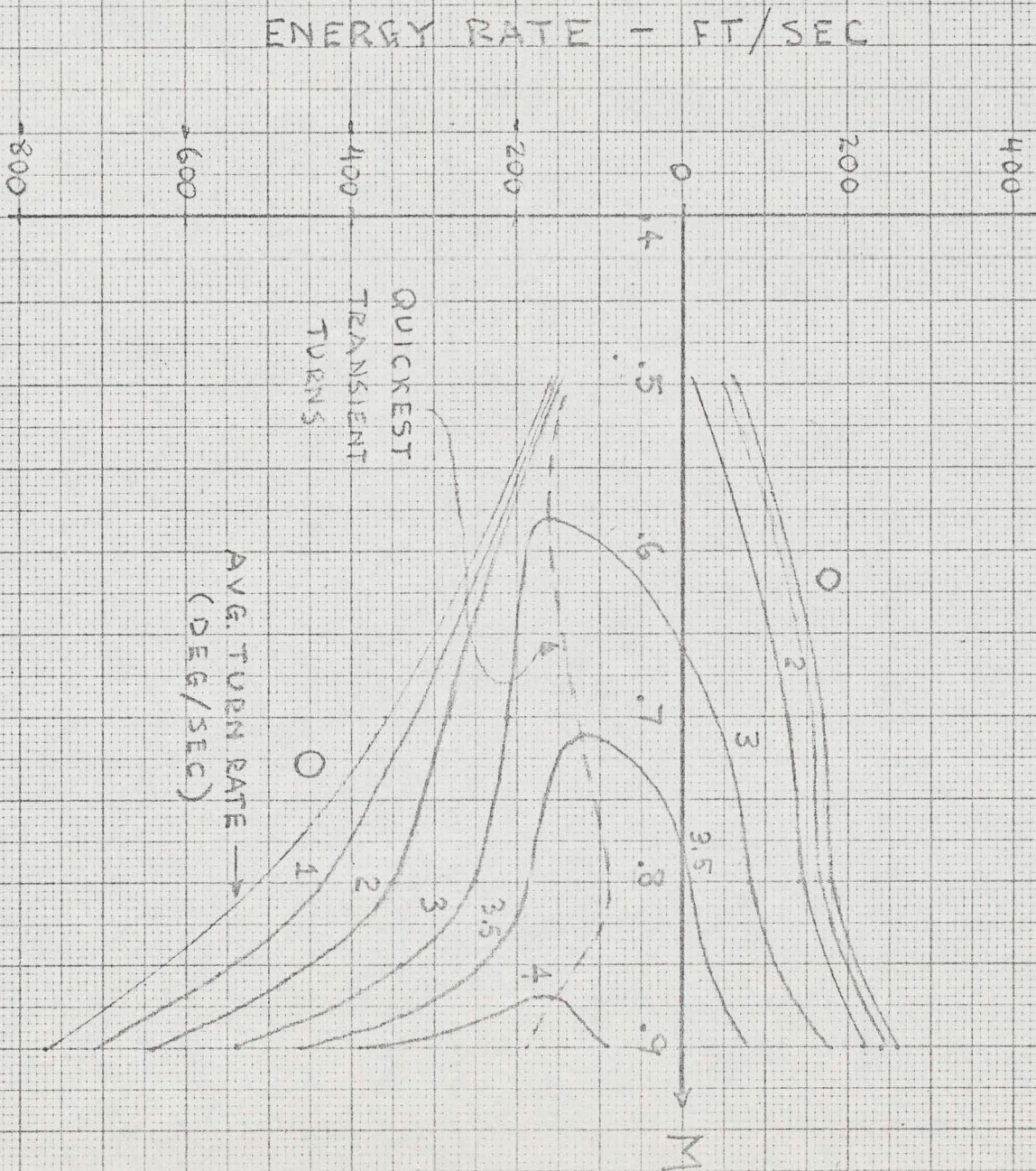


FIGURE 9

MAXIMUM USABLE LIFT COMPARISON

$M = 0.9$

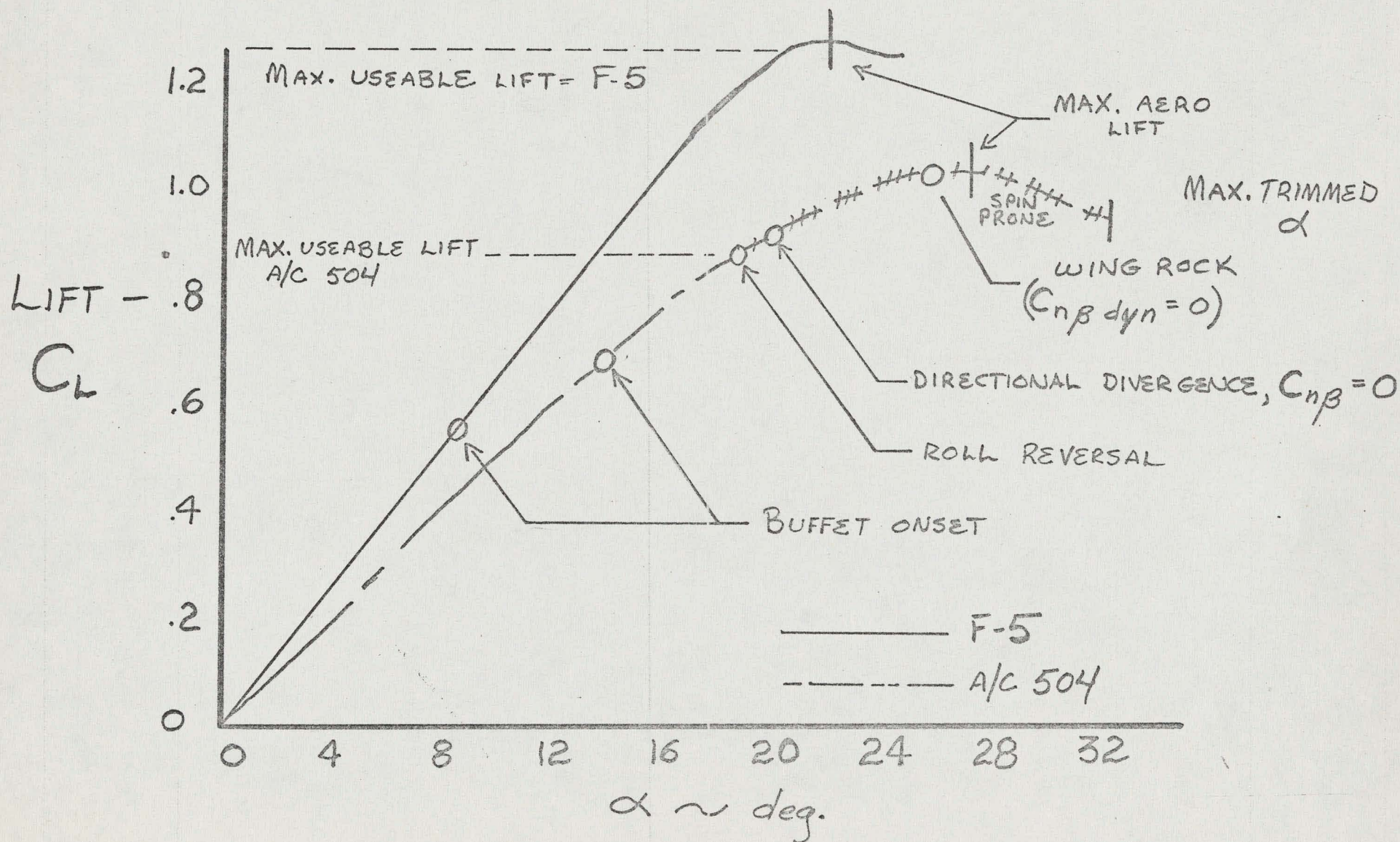
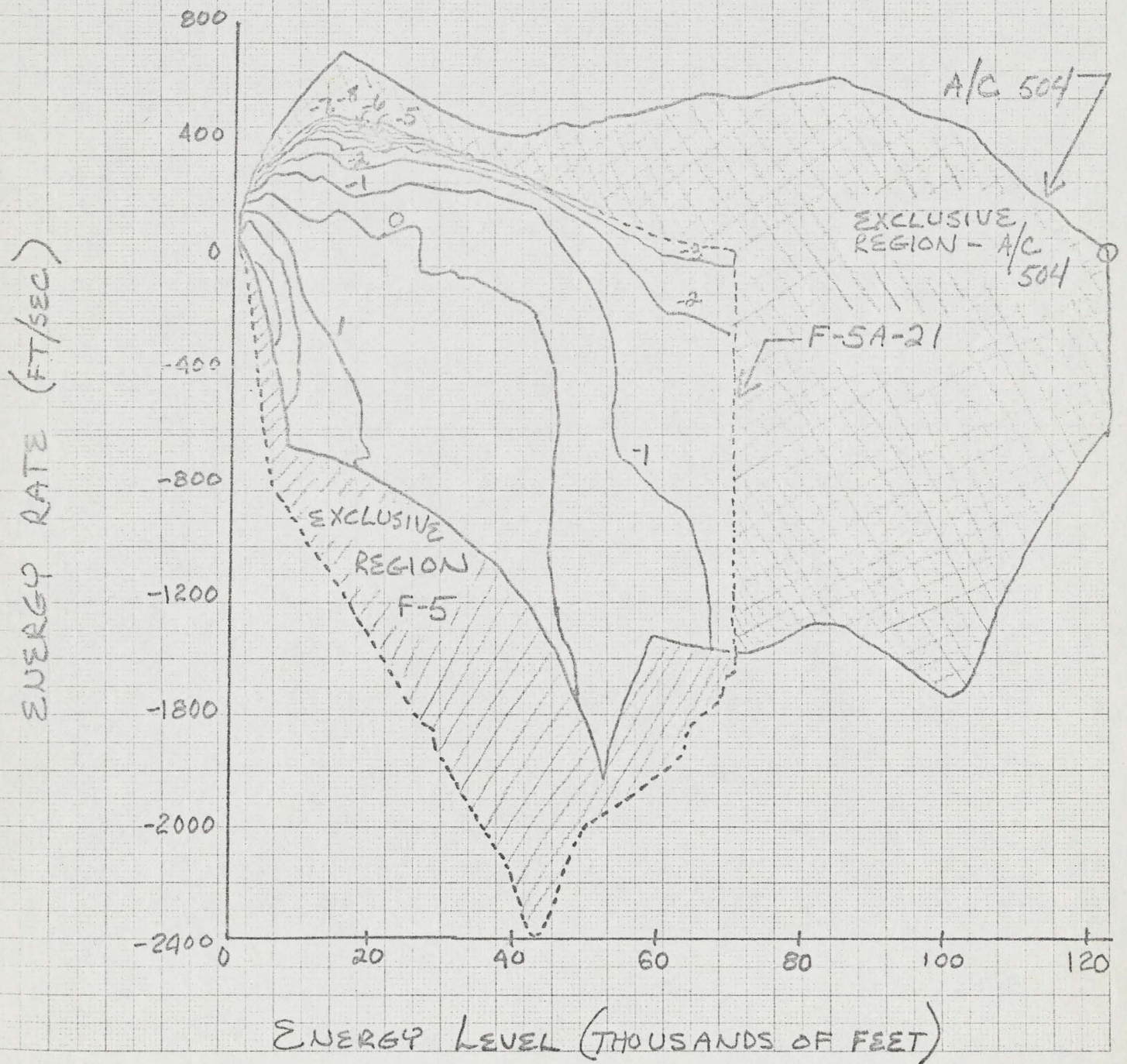


FIGURE 10

DIFFERENTIAL MAXIMUM MANEUVER DIAGRAM (ROLLING)

F-5 MINUS A/C 504



ROLL PERFORMANCE

$h = 35,000$ FT $M = 0.9$

AILERON AND RUDDER INPUTS

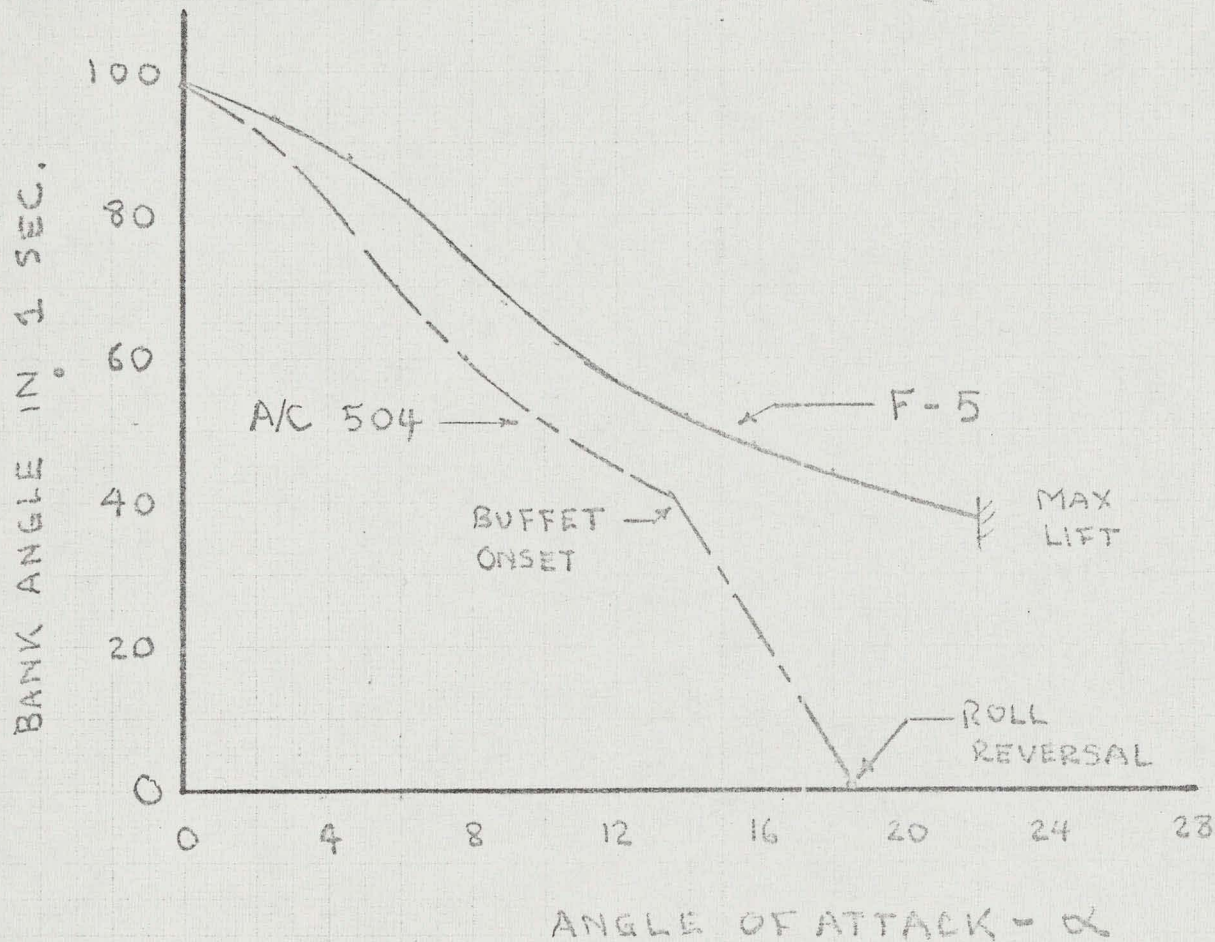


FIGURE 12

DIFFERENTIAL TERMINAL TRANSIENT MANEUVER DIAGRAM

F-5 MINUS A/C 504
35,000 FT

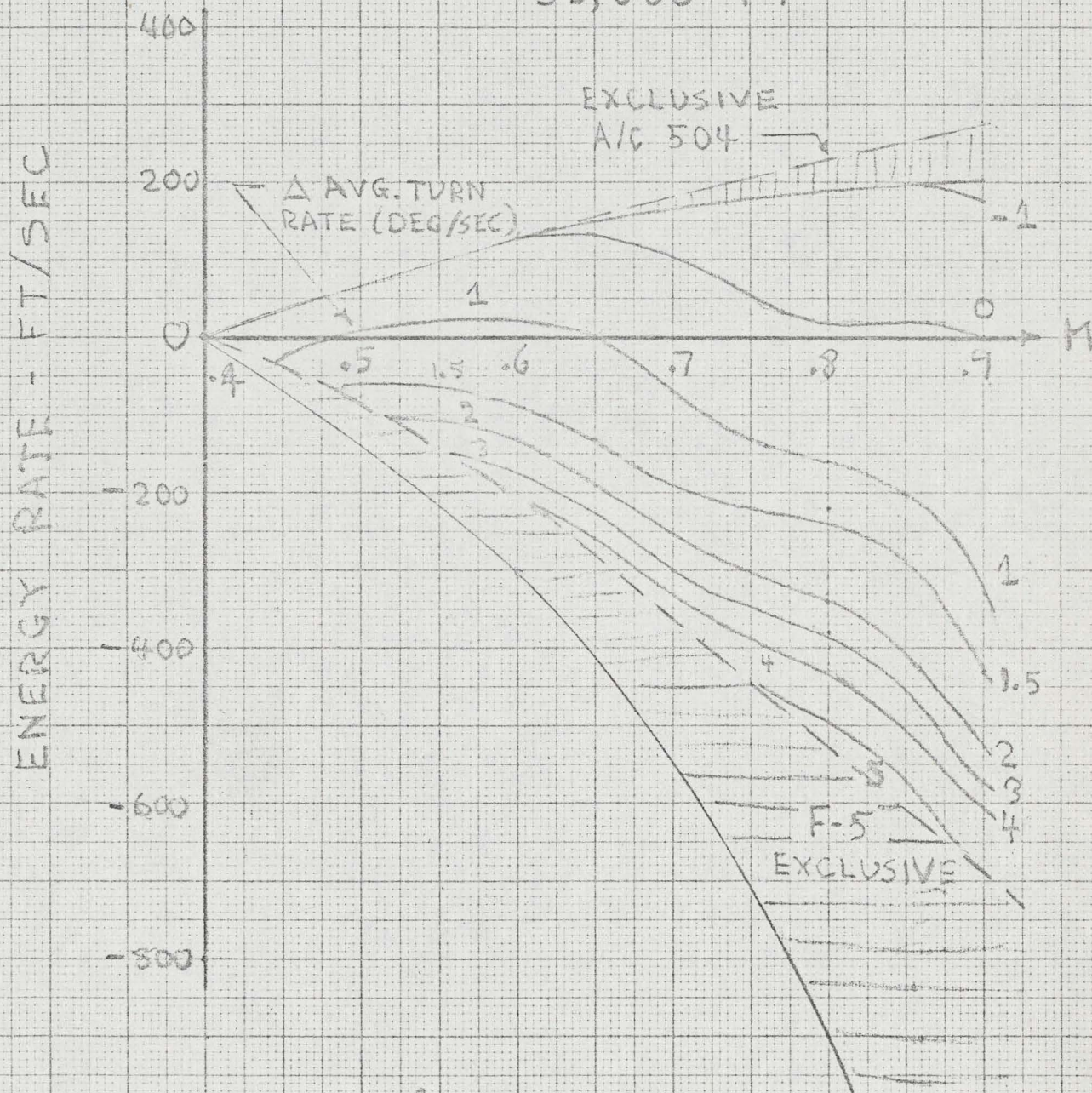


FIGURE 13

APPENDIX A

SPIN CHARACTERISTICS

The degree of susceptibility to spin during hard turns with and without rolling inputs has a significant impact on the dogfighting capability of air superiority fighter aircraft. With aircraft that are spin prone the pilot is limited to low roll and pitch rates in establishing desired maneuver attitude or transitioning from one maneuver to another. With a spin resistant aircraft the pilot is able to operate his aircraft at high angles of attack and sideslip without limitations on control deflections or rates.

The capability for analytical evaluation of spin susceptibility for preliminary design aircraft has recently been advanced through development of six degree of freedom computer simulation techniques. One such advance has been identified by Weyl and Casteel (AIAA 70-928). Spin resistance data are prepared in the format shown in Figure A-1.

As illustrated, this method consists of establishing a boundary separating regions of spin and no spin on a plot of yaw rate versus angle of attack. This boundary is established by initiating computer runs at yaw rate/angle of attack combinations, and determining those which result in return to trim angle of attack without control inputs in less than two turns and those which require more than two turns or depart to higher yaw rates and angles of attack. This approach is analogous to spin model testing where the model is thrown into the test section for various yaw rates and angles of attack and the ensuing motion observed.

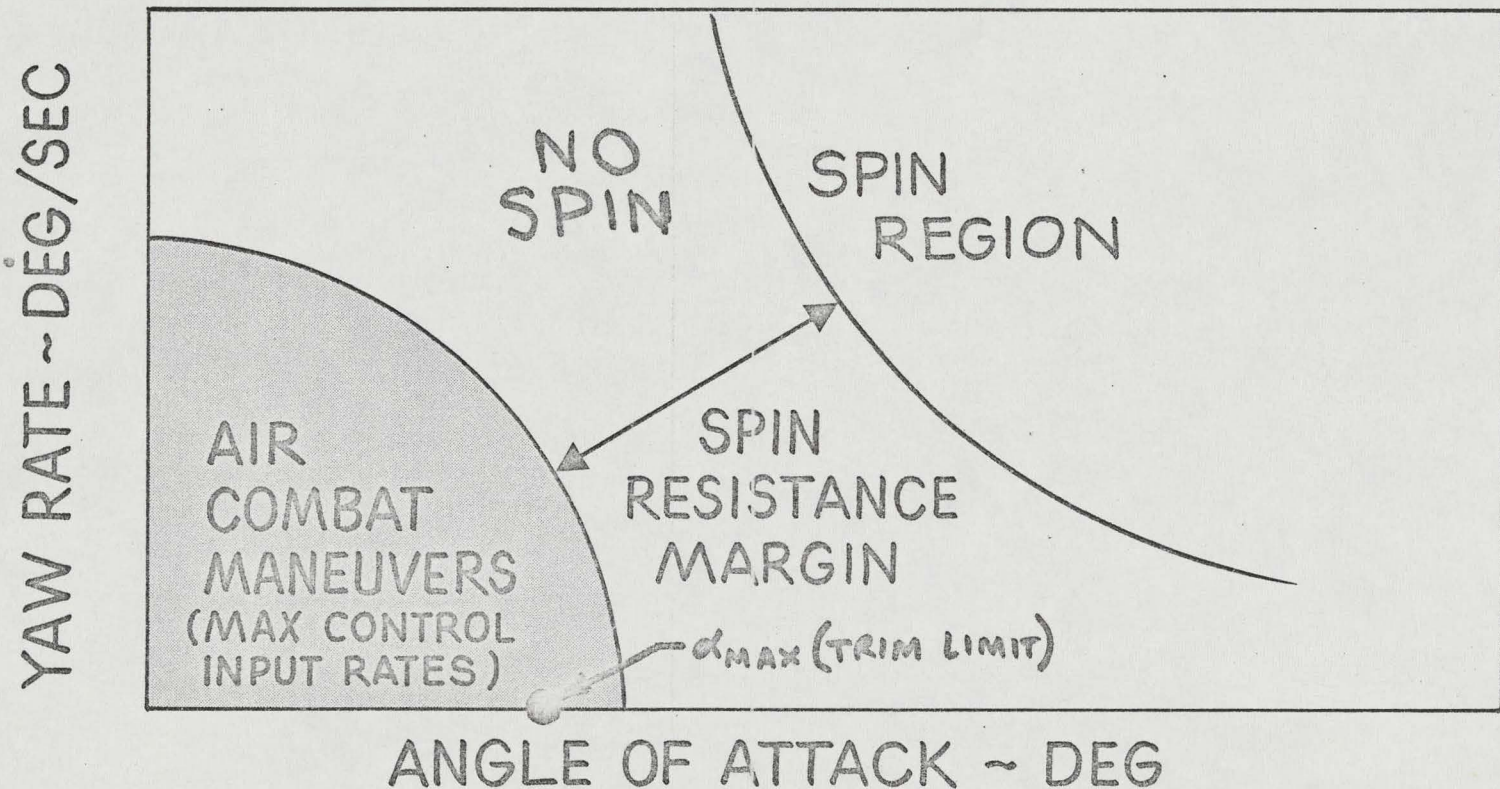
In addition, a maneuver envelope is determined by introducing control inputs from normal combat maneuvering situations. The margin between the maneuver envelope and the spin boundary is a measure of the aircraft's spin resistance. The greater the margin the more difficult it will be for the airplane to inadvertently reach the spin region. Although this approach is most desirable for a thorough analytical assessment of spin characteristics the time and effort required for a single spin plot is considerable. However, there are two simple parameters which have been related to spin resistance margin and provide a good approximation of the relative resistance of various aircraft with a consistent method.

The angle of attack region of spin susceptibility for non-rolling turning maneuvers without lateral or directional inputs has been correlated with the dynamic

directional stability parameter, $C_{n\beta_{dyn}} = C_{n\beta} - C_{\ell\beta} \frac{I_z}{I_x} \tan \alpha$,

by Chambers and Anglin (NASA-Langley). Figure A-2 presents an F-4E flight test time history for a maximum aft stick input without lateral or

SPIN RESISTANCE



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FIGURE A-1

FLIGHT TEST TIME HISTORY OF F4E LATERAL/DIRECTION EXCURSION

SOURCE - NASA TND 5361

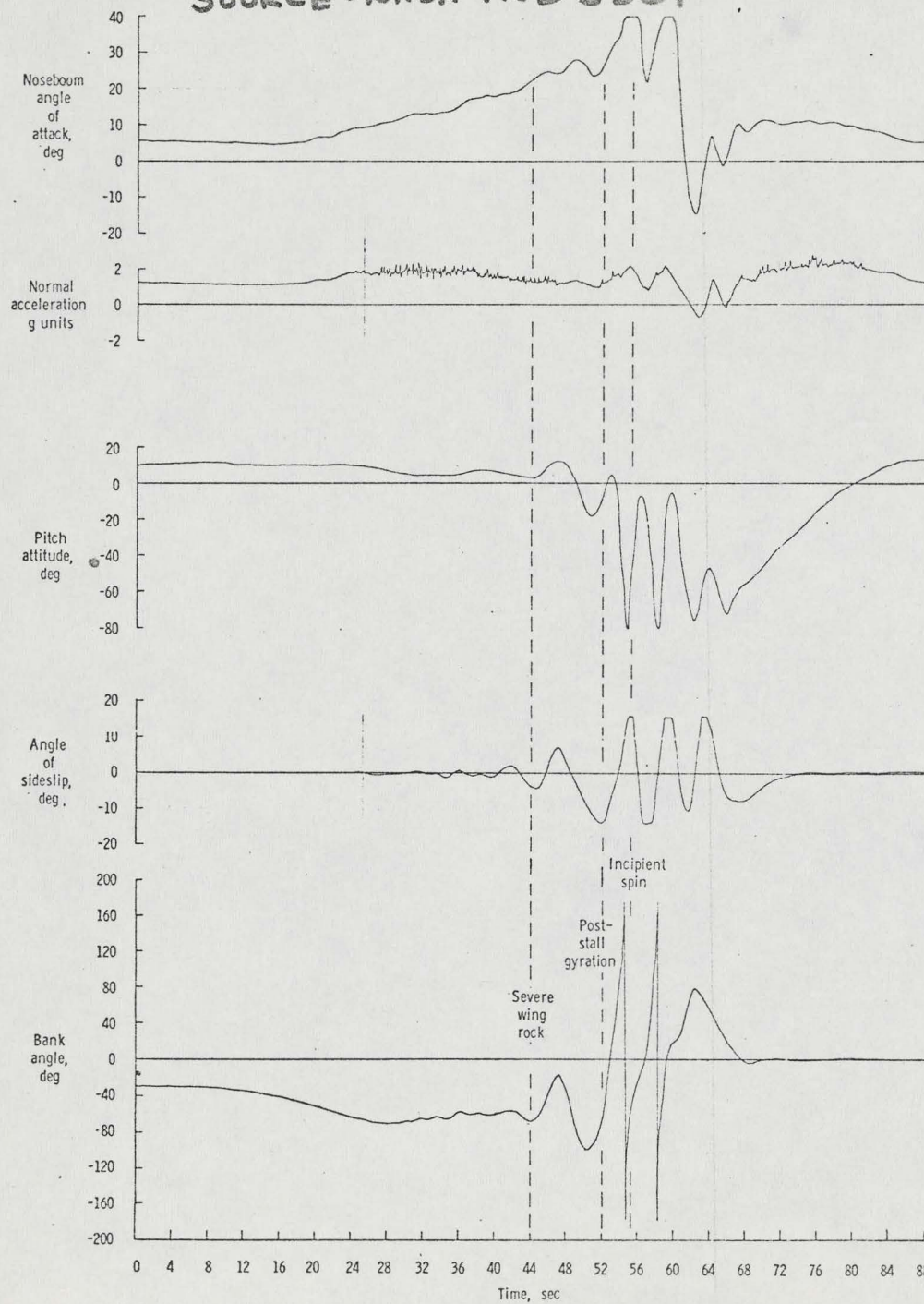


FIGURE A-2

directional inputs. The progression from severe wing, rock to post stall gyrations and incipient spin correlates with the unstable region of $C_{n\beta \text{ dyn}}$ (i.e., negative values) as illustrated in Figure A-3.

Unless the dynamic directional stability is stable throughout the possible operating angle of attack range to its trim capability, (and beyond to account for dynamic overshoot) as illustrated in Figure A-4 the aircraft will be susceptible to spin in hard non-rolling turns.

For assessing the spin susceptibility in turning maneuvers where lateral control inputs are introduced, it has been found that the angle of attack at which the roll reverses due to sideslip opposing the aileron correlates very closely with the region of spin susceptibility of a number of current fighter aircraft. Figure A-5 illustrates the typical response to a step aileron input for aircraft with and without a roll reversal problem. The dominant parameters influencing roll reversal are the yaw due to aileron $C_{n\delta_a}$ and the directional stability $C_{n\beta}$. High adverse yaw and low directional stability are detrimental. A lateral control spin parameter can be defined by the equation below:

$$\text{Lateral Control Spin Parameter} = C_{n\beta} - C_{l\beta} \frac{C_{n\delta_a}}{C_{l\delta_a}}$$

Roll reversal occurs at the point where this parameter equals zero. Figure A-6 illustrates the variation of the lateral control spin parameter versus angle of attack normalized to maximum trimmed angle. If the roll reversal point is lower than an angle of attack ratio of 1.0 the spin susceptibility is high. As the reversal point increases above 1.0 the spin resistance increases. Figure A-7 presents the lateral control spin parameter variations for the F-5A, F-100D, F-8 and F-4E aircraft for which the spin characteristics are well known. The F-100D, F-8 and F-4E roll reversal points are below their maximum trimmed angle of attack while the F-5A reversal point is 80% beyond this maximum. (The F-5A exhibits high spin resistance in flight whereas the F-100D, F-8 and F-4E are spin prone and have flight handbook control restrictions above the points indicated.)

Figure A-8 presents a comparison of the F-5A with Aircraft 504 in each of the spin susceptibility parameters. A comparison of aircraft 504 predicted lift characteristics with flight test results is presented in Figure A-9. The flight test maximum useable lift is lower than the estimated maximum lift and compares closely with the lift coefficient for roll reversal.

N0.

F4E DYNAMIC DIRECTIONAL STABILITY

SOURCE - NASA TND 5361

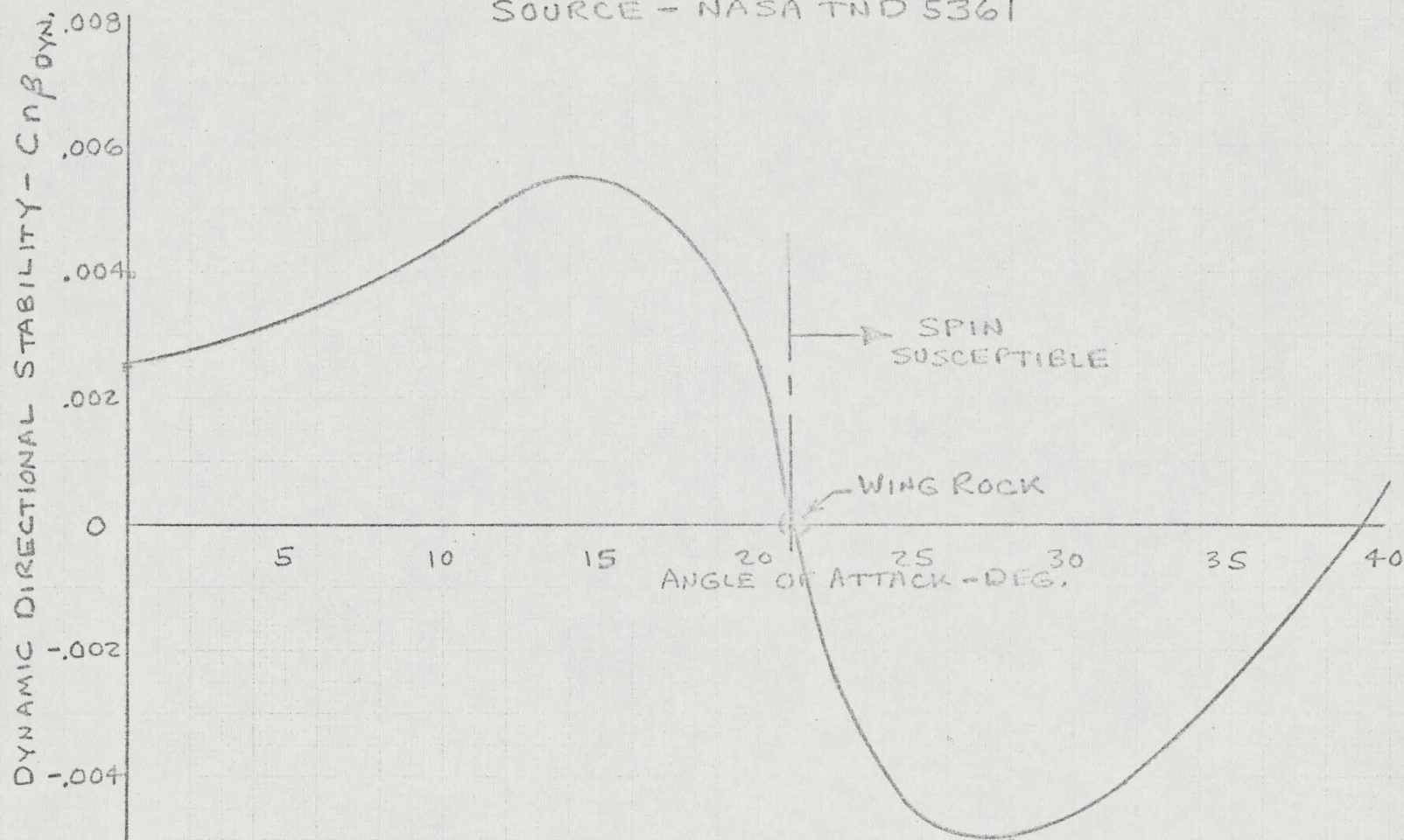


FIGURE A-3

MEASURE OF SPIN RESISTANCE - TURNING WITHOUT ROLLING

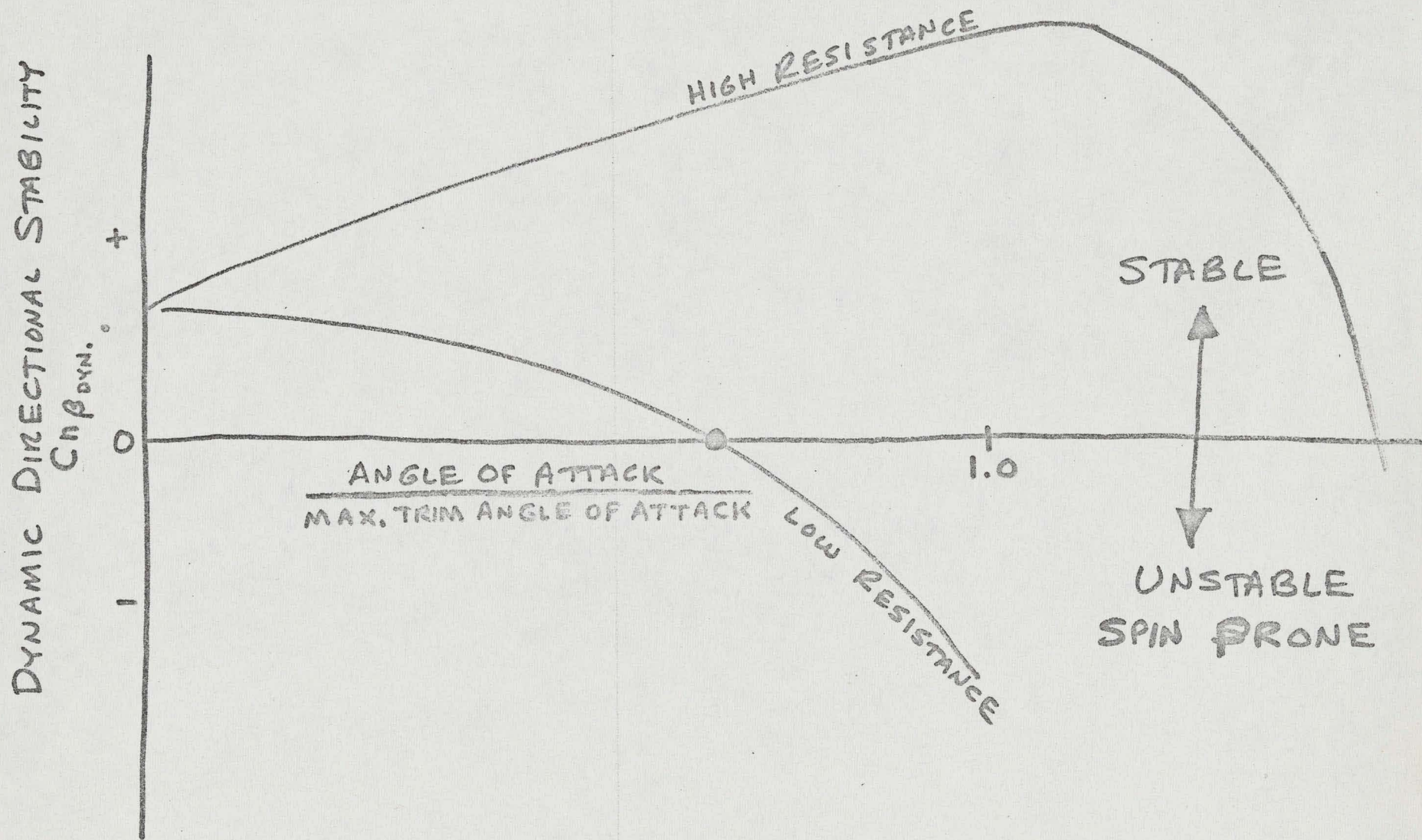


FIGURE A-4

ROLL REVERSAL

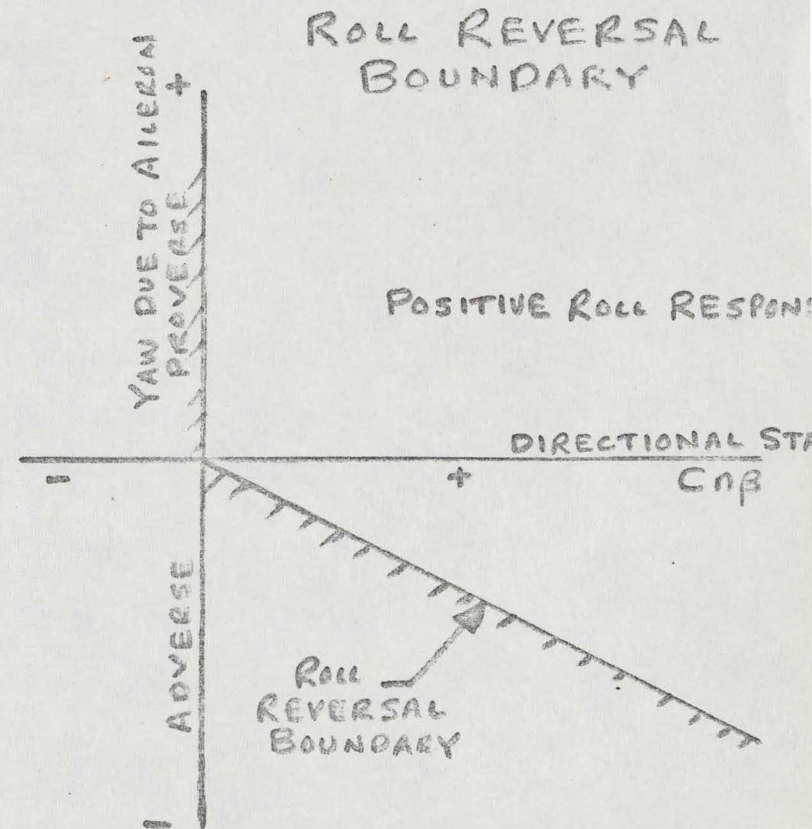
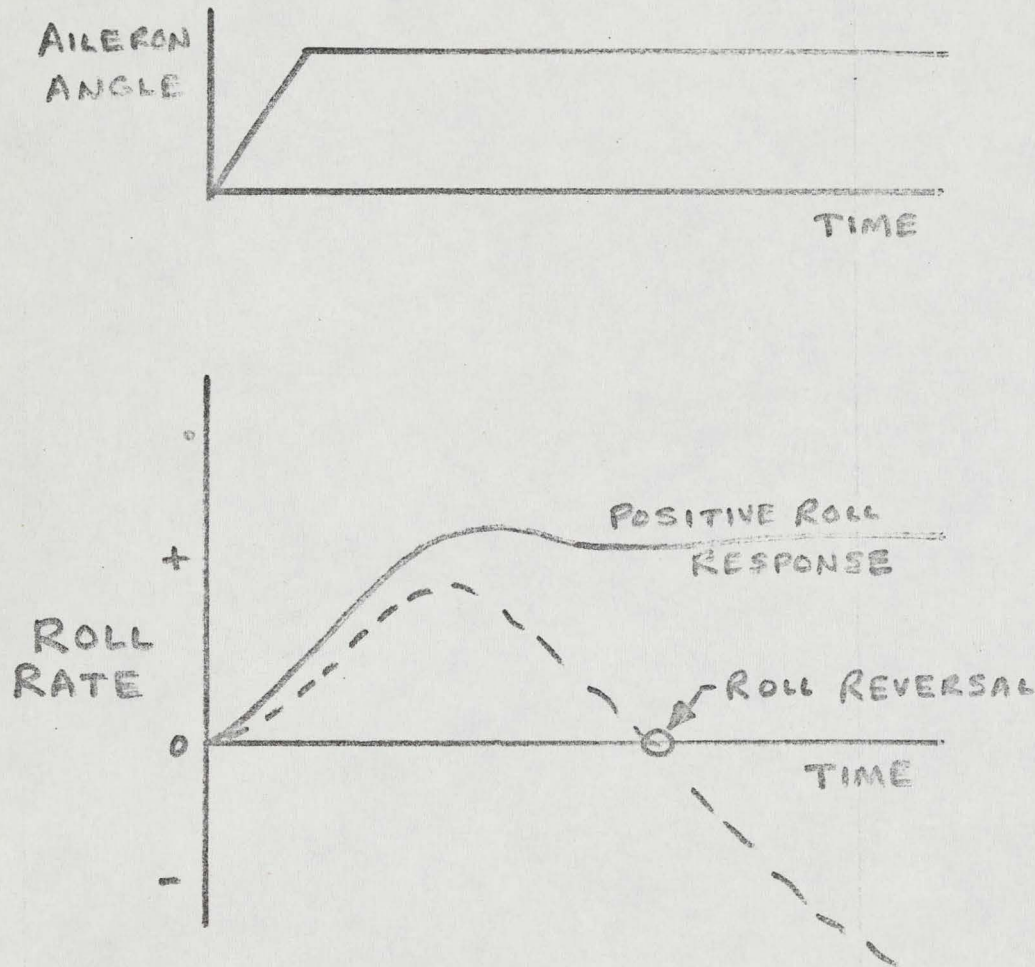


FIGURE A-5

MEASURE OF SPIN RESISTANCE - COMBINED TURNING AND ROLLING MANEUVERS

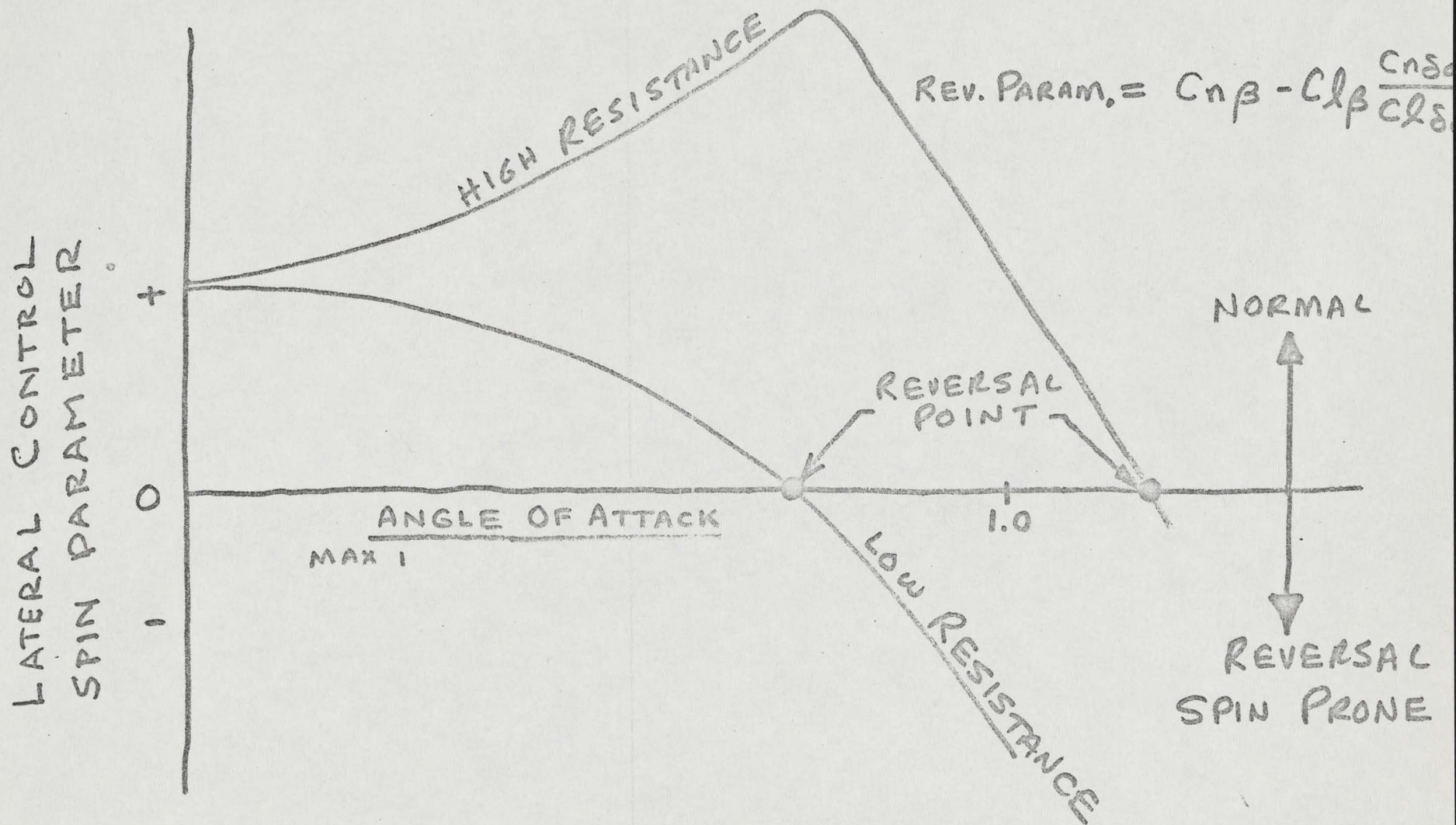


FIGURE A-6

SPIN SUSCEPTIBILITY

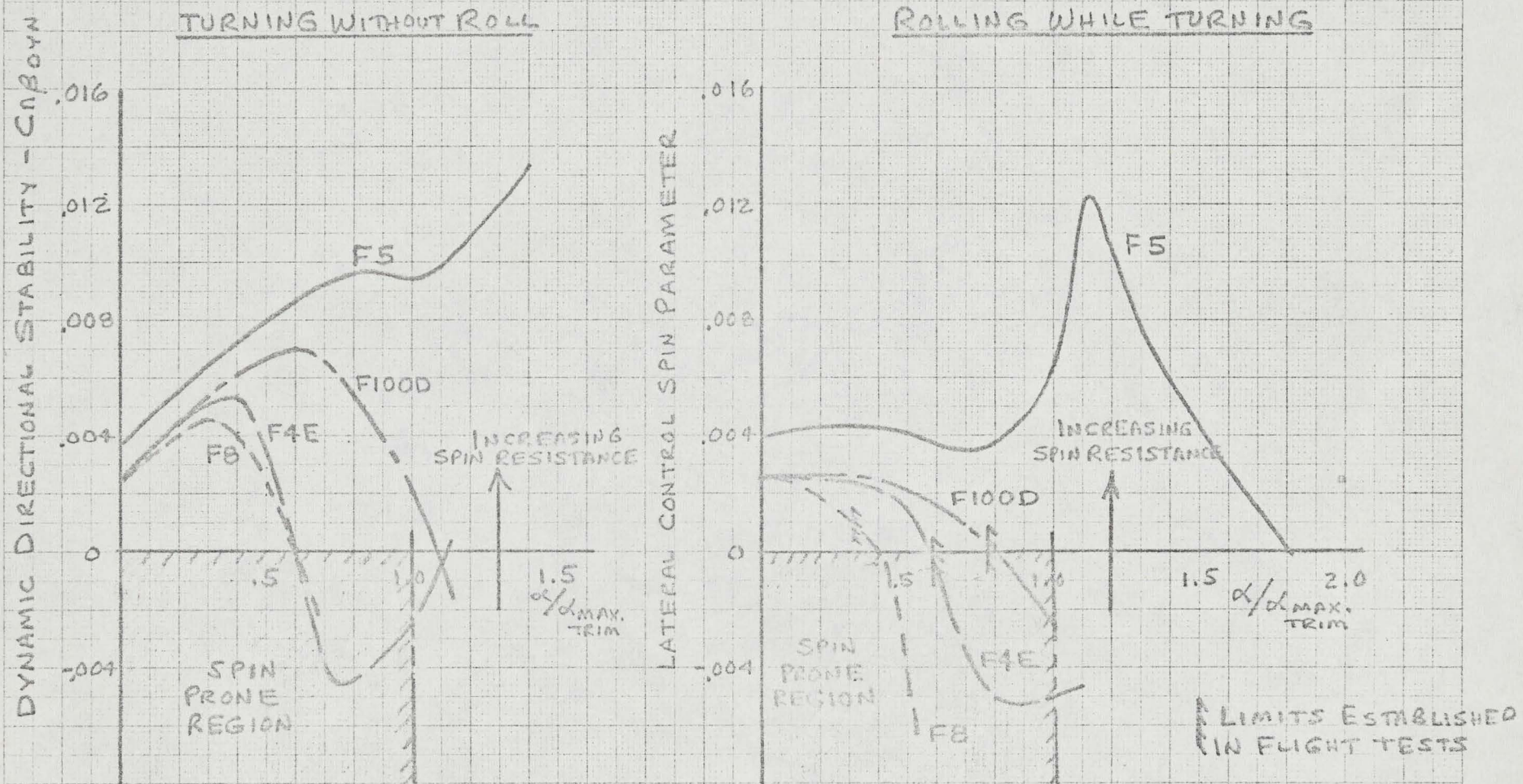
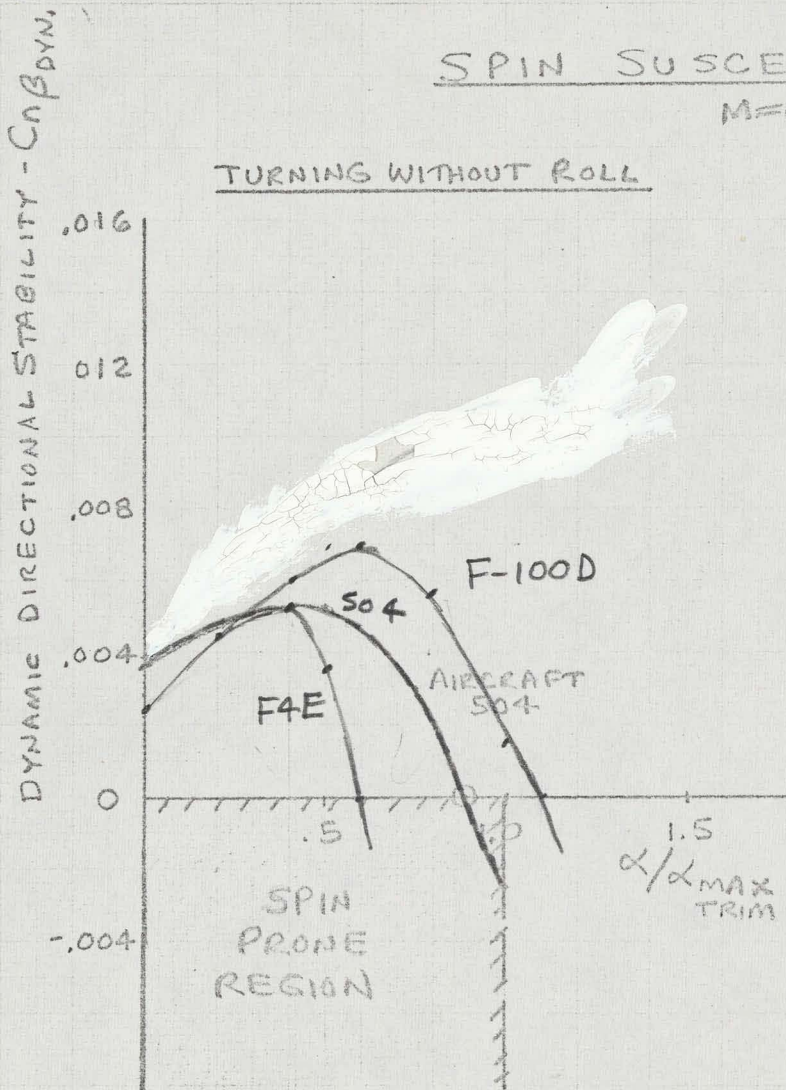


FIGURE A-7

SPIN SUSCEPTIBILITY

M=0.6

TURNING WITHOUT ROLL



ROLLING WHILE TURNING

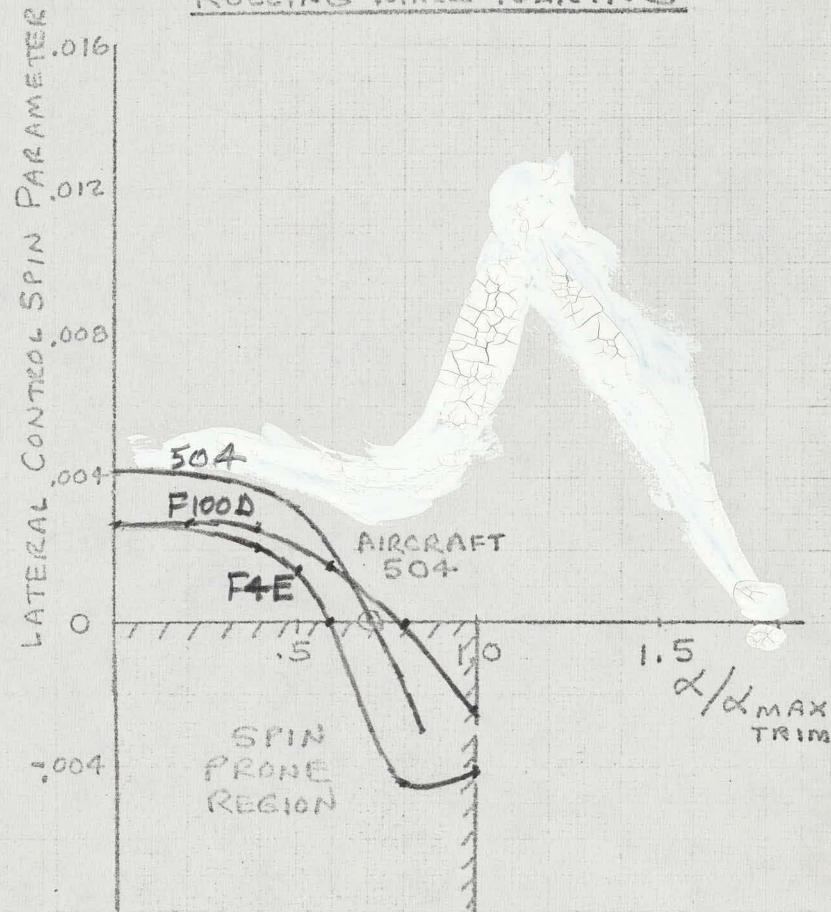


FIGURE A-8

COMPARISON OF AIRCRAFT 504 LIFT FLIGHT TEST & PREDICTED

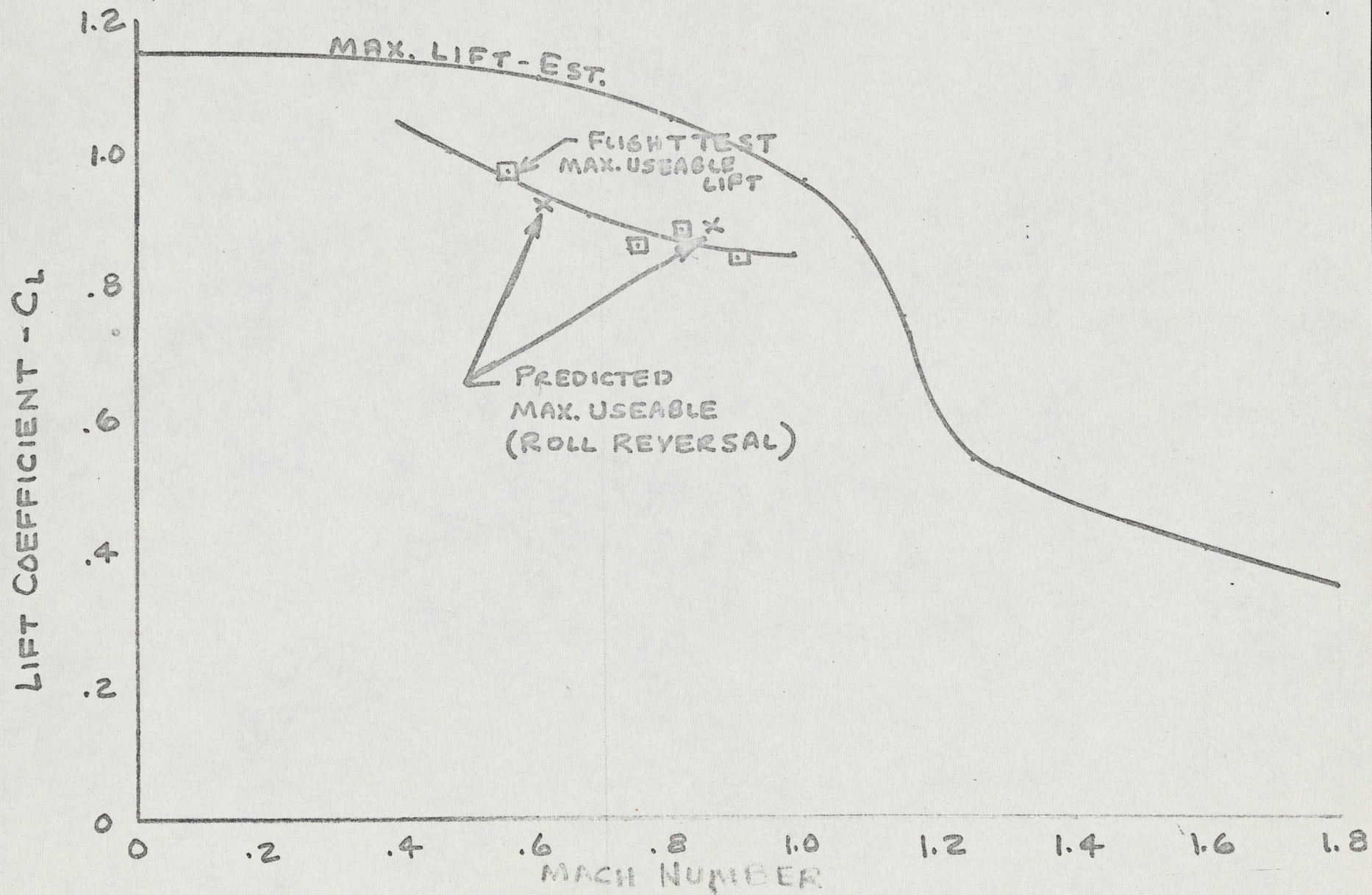


FIGURE A-9

APPENDIX B

TIME TO ROLL, ROLL RATE AND AVERAGE TURN RATE DURING TRANSIENT MANEUVERS

The first step in estimating roll characteristics is the standard measurement of rolling moment due to aileron deflection, $C_{l\delta_a}$, in Figure B-1. Neither aircraft suffers from roll reversal due to aileron-induced stall. Both have the usual decrease in rolling moment due to increasing angle of attack. However, the measurement above is not sufficient to define time to roll or maximum roll rate adequately.

The rolling moment created by aileron inputs is opposed by the following major forces:

- a. Opposite rolling moment due to sideslip - aileron inputs not only create the desired rolling moments but will also produce unfavorable sideslip in aircraft with adverse yaw (as measured by $C_{n\delta_a}$). This adverse yaw (nose to the outside of the turn) creates a sideslip that increases lift on the inside wing and decreases lift on the outside wing which represents a rolling moment opposed to the desired roll (this moment due to sideslip is represented by $C_{l\beta}$). This is the motivation for using maximum safe bottom rudder to induce favorable sideslip in order to increase rolling moments. (for positive dihedral effect)
- b. Roll damping (resistance to roll velocity) - as roll rate builds up, a resisting moment (C_{lp}) due to the rotational velocities of the aircraft also builds up.
- c. Considerably smaller opposing force contributions are attributed to such diverse influences as yaw caused by vertical tail rotation, yaw due to differential lift vector orientation on the inside and outside wings, etc.

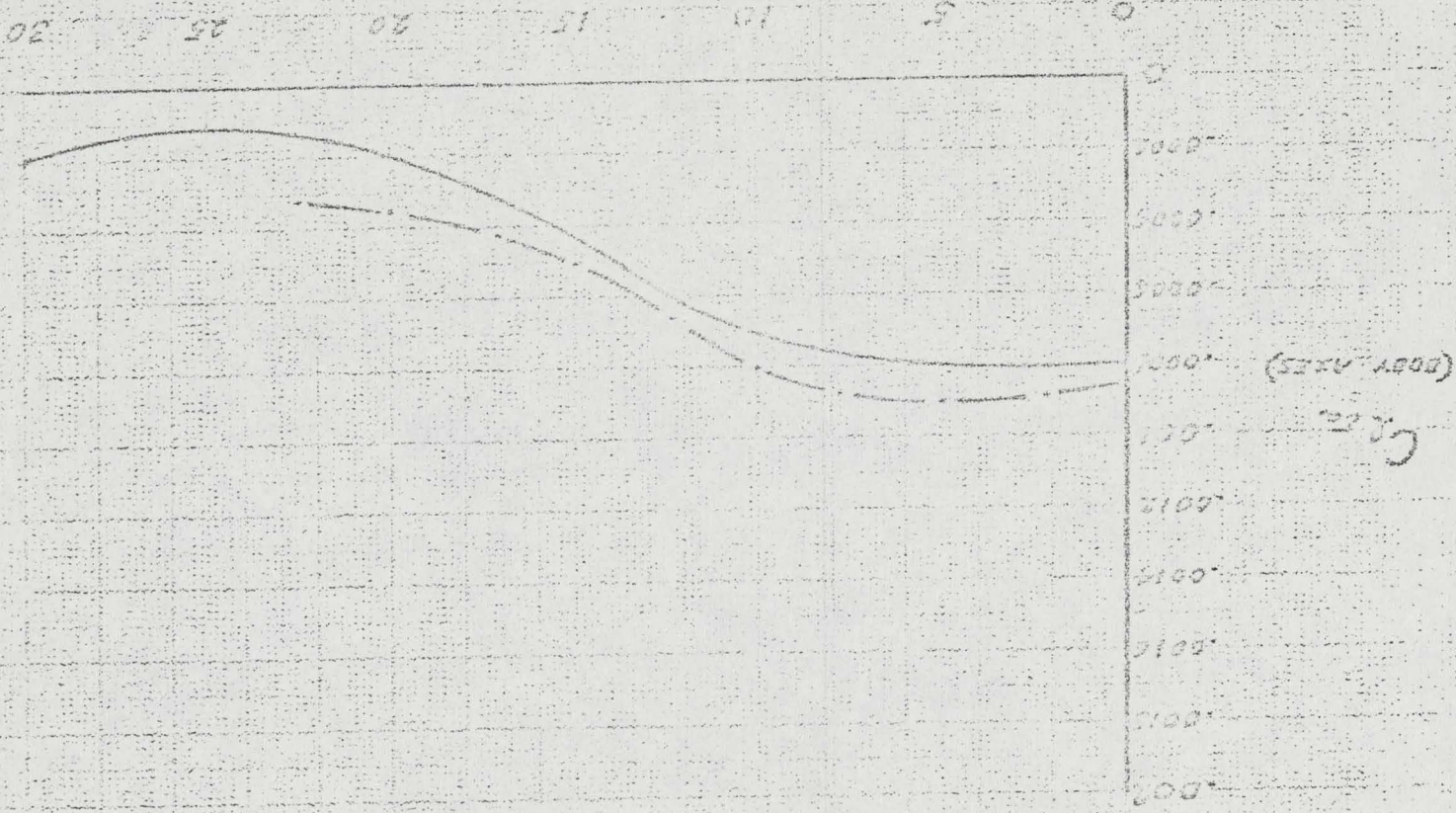
When favorable and opposing moments are in balance, the maximum steady state roll rate (without handling limitations) is achieved and can be computed with approximate closed form expressions. To obtain accurate time to roll, however, a roll time history from a 5 degree of freedom dynamic simulation should be used. In either case, the practical maximum rate is always limited by roll reversal (identical to spin susceptibility for the maximum roll input case); this limit is imposed through the use of the lateral control spin parameter (see Appendix A). 5?

Having established time to roll as limited by handling quality consideration, a generic transient maneuver case needs to be established. The most common transient maneuver, particularly in the terminal phase of combat, is the maximum roll rate reversal from a hard turn in one direction to an equal and opposite turn to be held until a desired heading change has been achieved. This encompasses such maneuvers as turn reversals, high g jinking and scissors. Any desired amount of heading change could be used: Small angles tend to over-emphasize the effect of the rolling transient; angles much beyond 45° are unrepresentative of the heading change used in scissors or jinks. Forty-five degrees has been chosen as a reasonable compromise. Average turn rate over the entire maneuver including roll transients is used as the "agility" measure; it is computed as shown in Figure B-2. Note that there is a major difference between ordinary turn rate and average turn rate through a transient maneuver: For ordinary turns, increasing lift always increases turn rate right up to maximum useable lift; for the transient case, too much lift can force the time to roll to very large values thus significantly slowing average turn rates. This is seen in Figure B-3, B-4 and B-5, which show a side-by-side comparison of energy rate versus turn rate for both constant and transient turns at fixed altitude - Mach points. These plots clearly show that quickest transient turn rates are achieved at moderately negative energy levels - not maximum lift. They further show that the impact of the roll transient is very large insofar as it can cut maximum turn rates in half. These plots are illuminating for a theoretical understanding of the transient turn measure. For tactical comparisons and training a more global presentation is preferred. This is contained in the Terminal Transient Maneuver Diagram already presented in Figure 9.

ALTRON EFFECTIVENESS

WAVE 0.8

F-5A ——— MC 574 ———



ANGLE OF ATTACK

0.0000

FIGURE B-1

Example of Lat-Dir Limitation in TURN REVERSAL

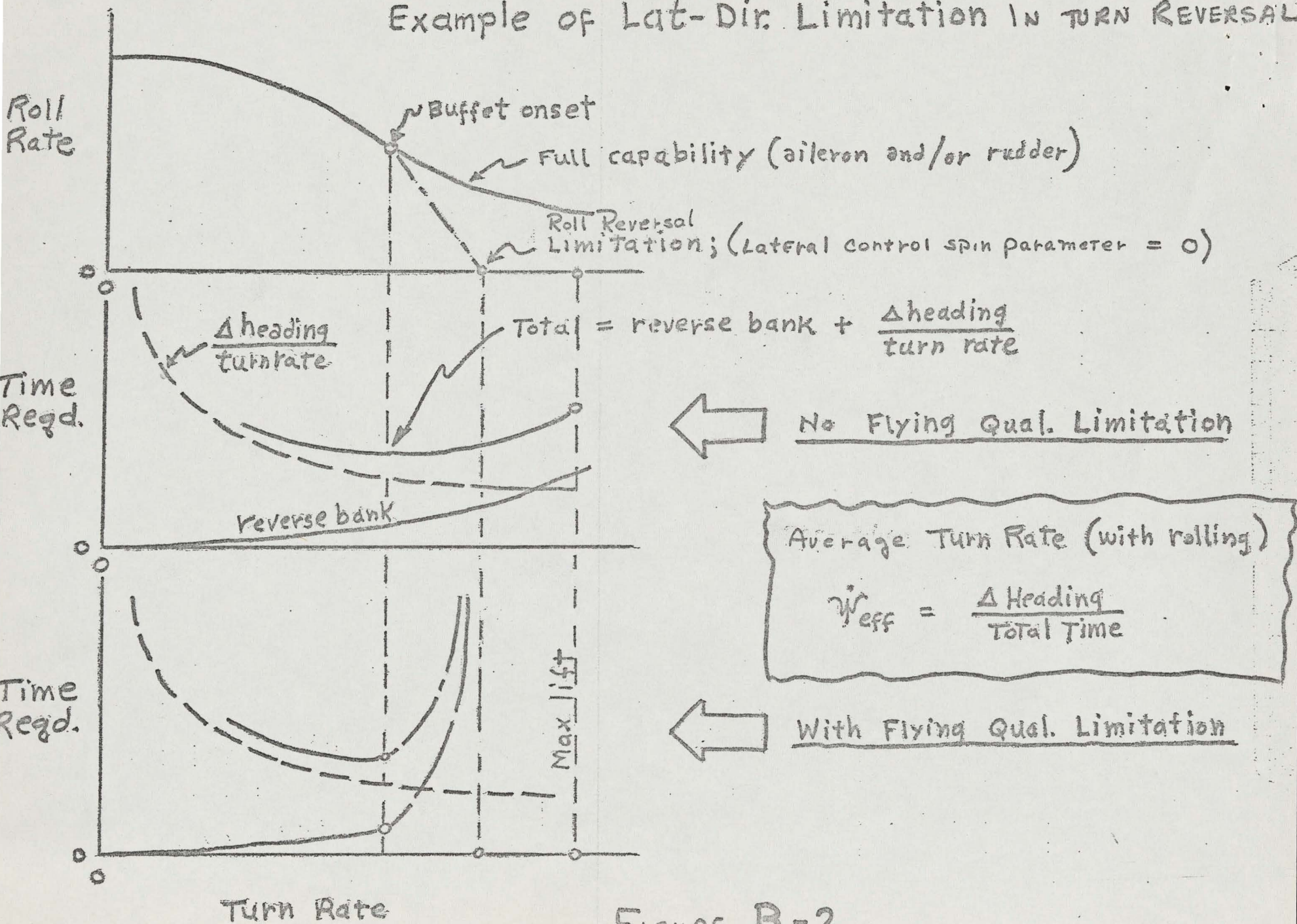


FIGURE B-2

SPECIFIC POWER P_s (FT/SEC)

COMPARISON OF CONSTANT TURNING VS. TRANSIENT TURNS

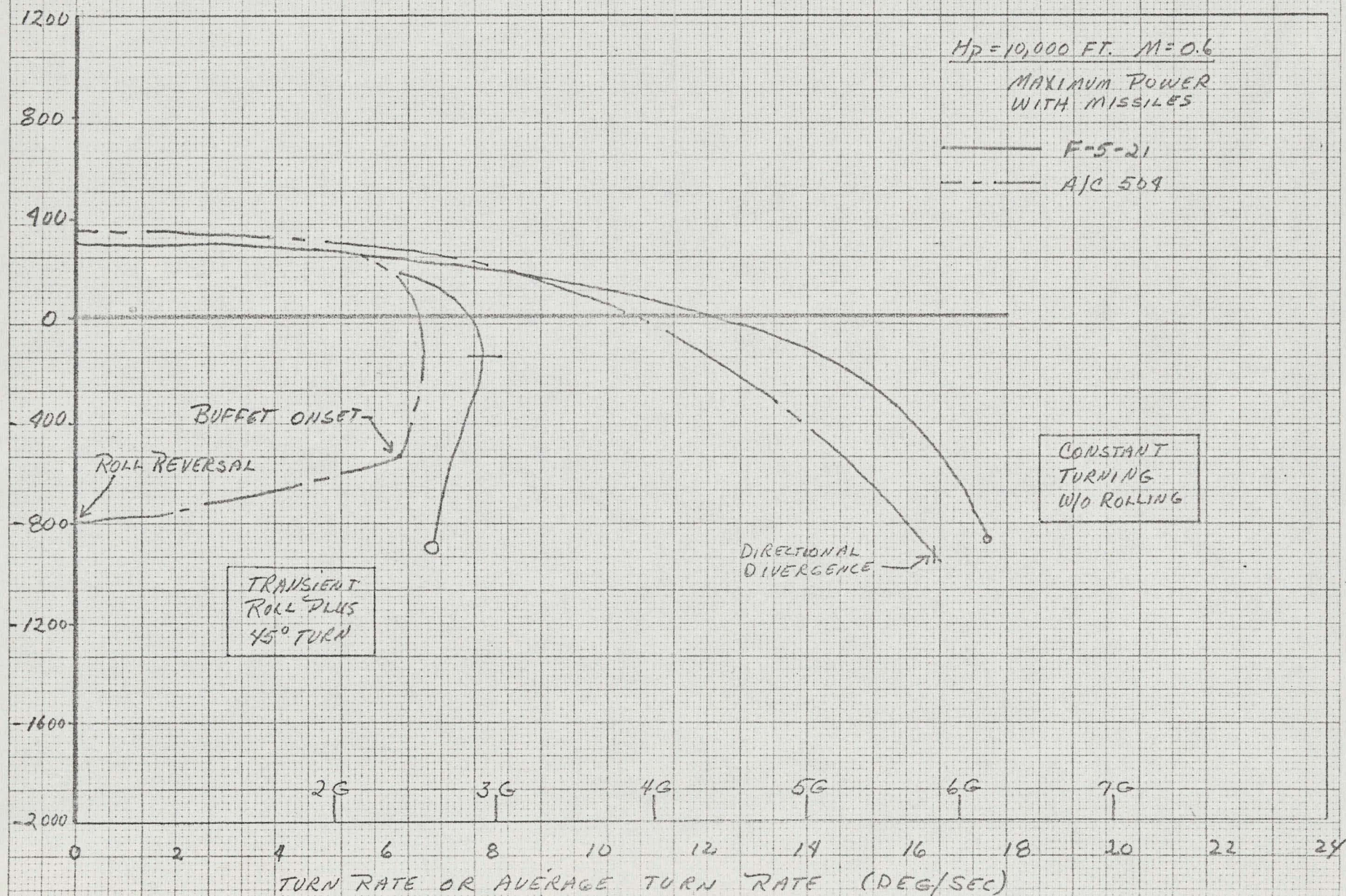


FIGURE B-3

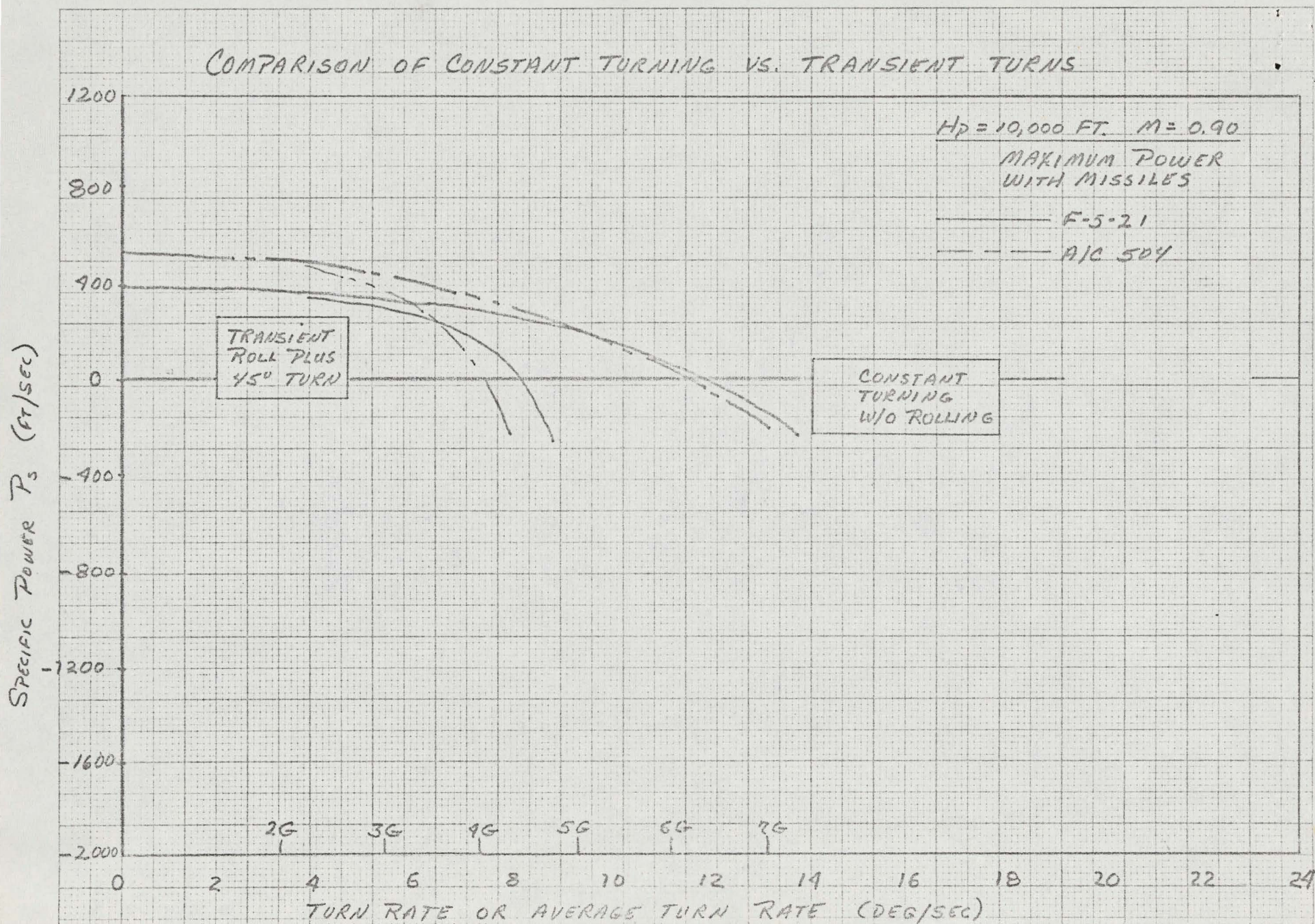


FIGURE B-4

COMPARISON OF CONSTANT TURNING VS. TRANSIENT TURNS

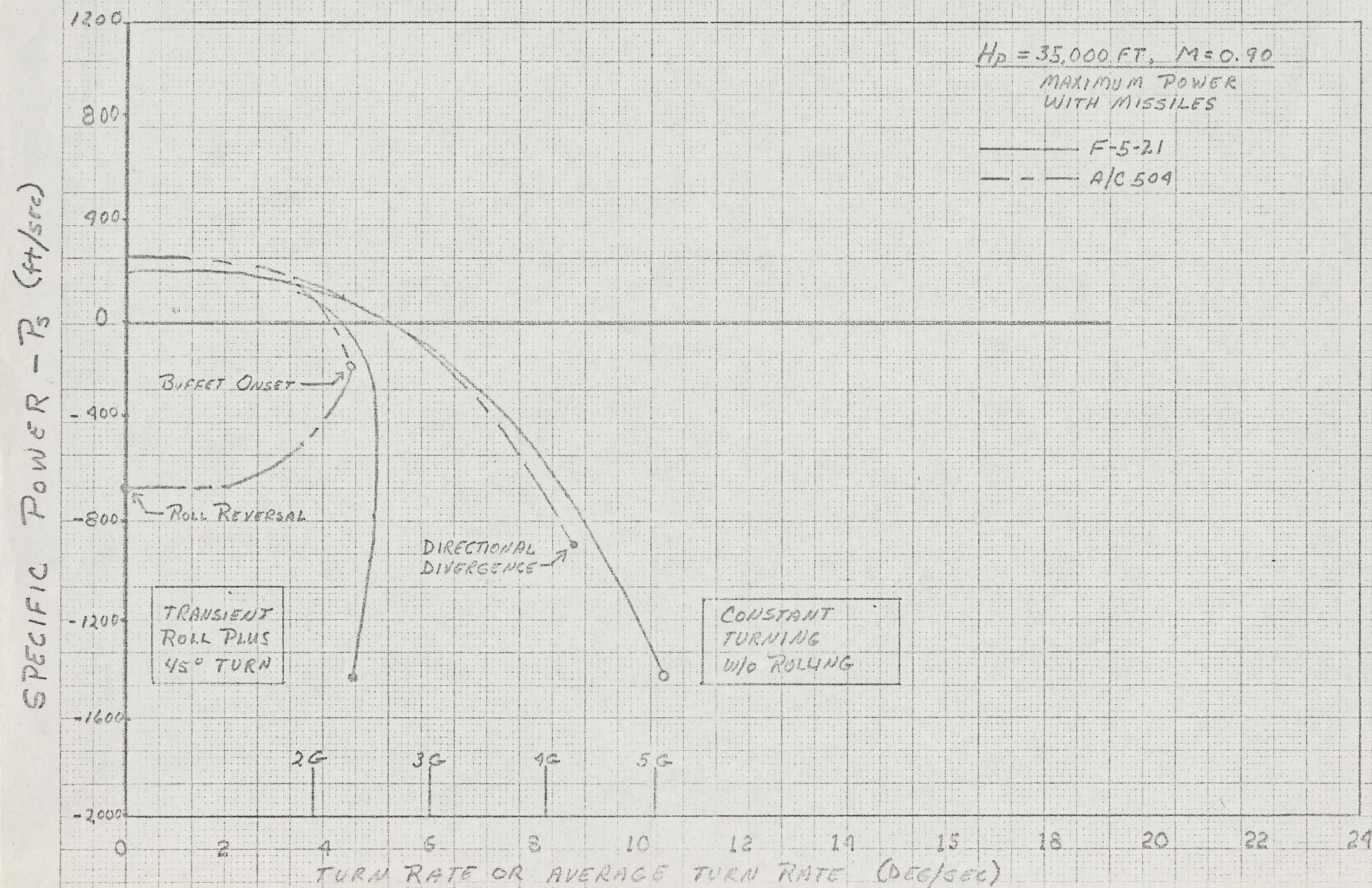


FIGURE B-5

1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40. 41. 42. 43. 44. 45. 46. 47. 48. 49. 50. 51. 52. 53. 54. 55. 56. 57. 58. 59. 60. 61. 62. 63. 64. 65. 66. 67. 68. 69. 70. 71. 72. 73. 74. 75. 76. 77. 78. 79. 80. 81. 82. 83. 84. 85. 86. 87. 88. 89. 90. 91. 92. 93. 94. 95. 96. 97. 98. 99. 100.

Handing Junction

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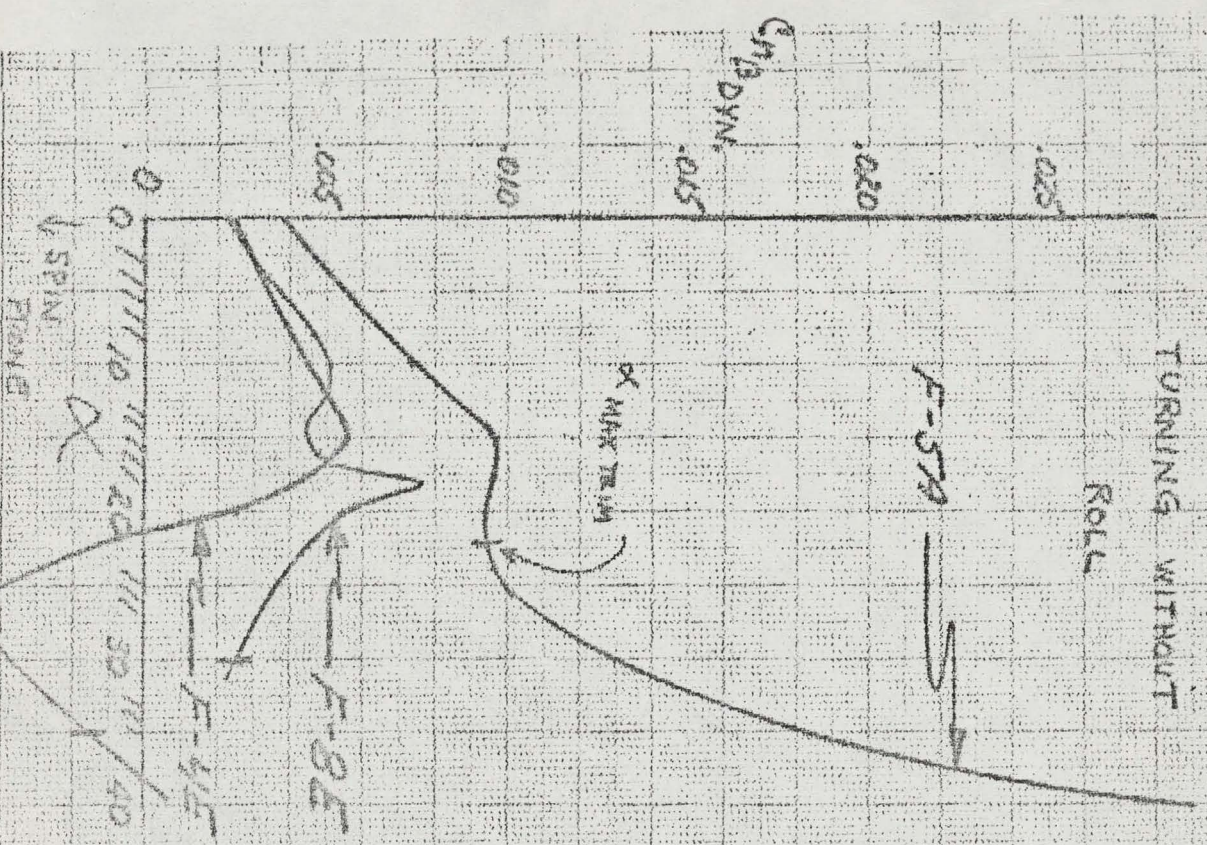
SPIN SUSCEPTIBILITY

TURNING WITHOUT

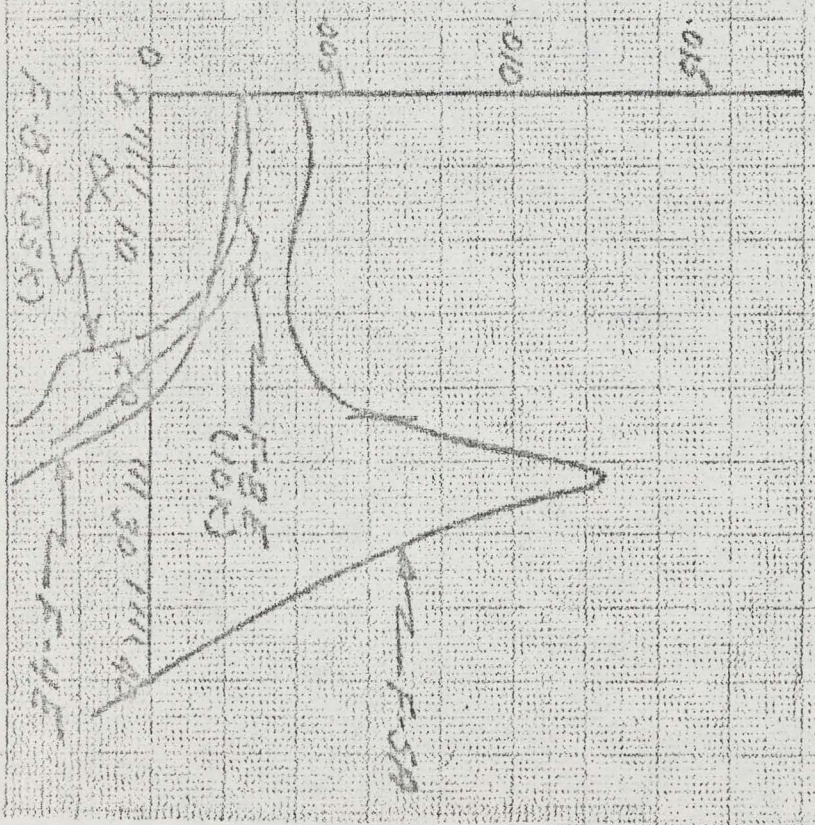
ROLL

F-57A

ROLLING WHILE TURNING



LATERAL CONTROL SPIN PARAMETER

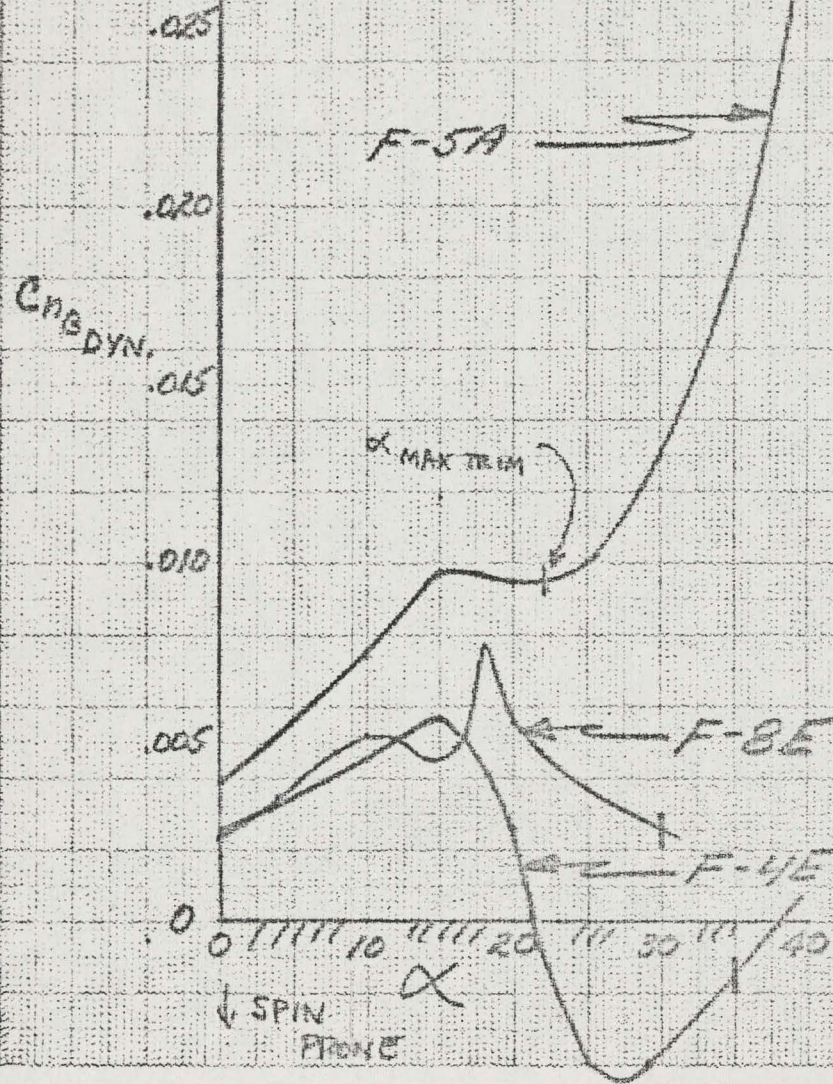


SPIN SUSCEPTIBILITY

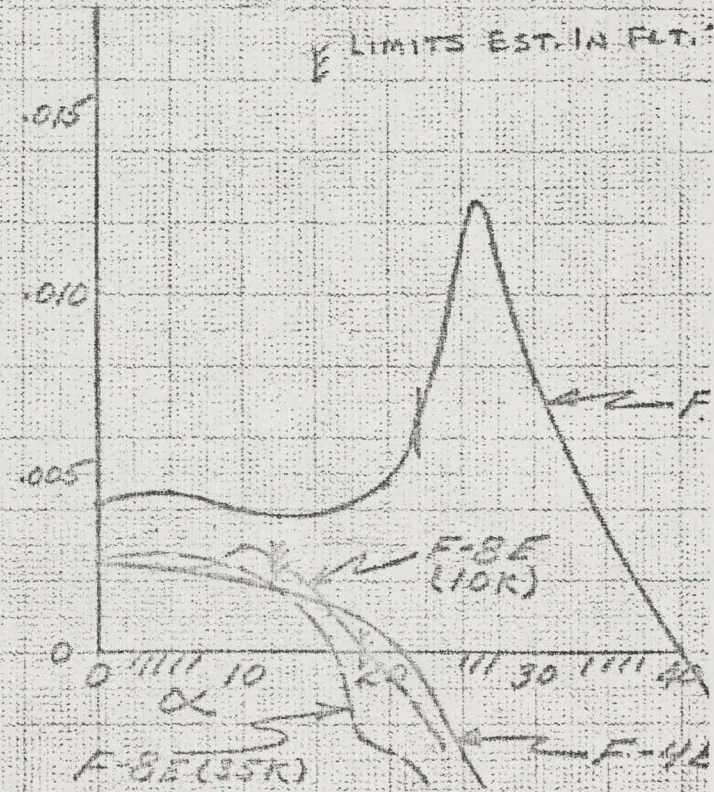
0.6 MACH

TURNING WITHOUT
ROLL

ROLLING WHILE TURNING



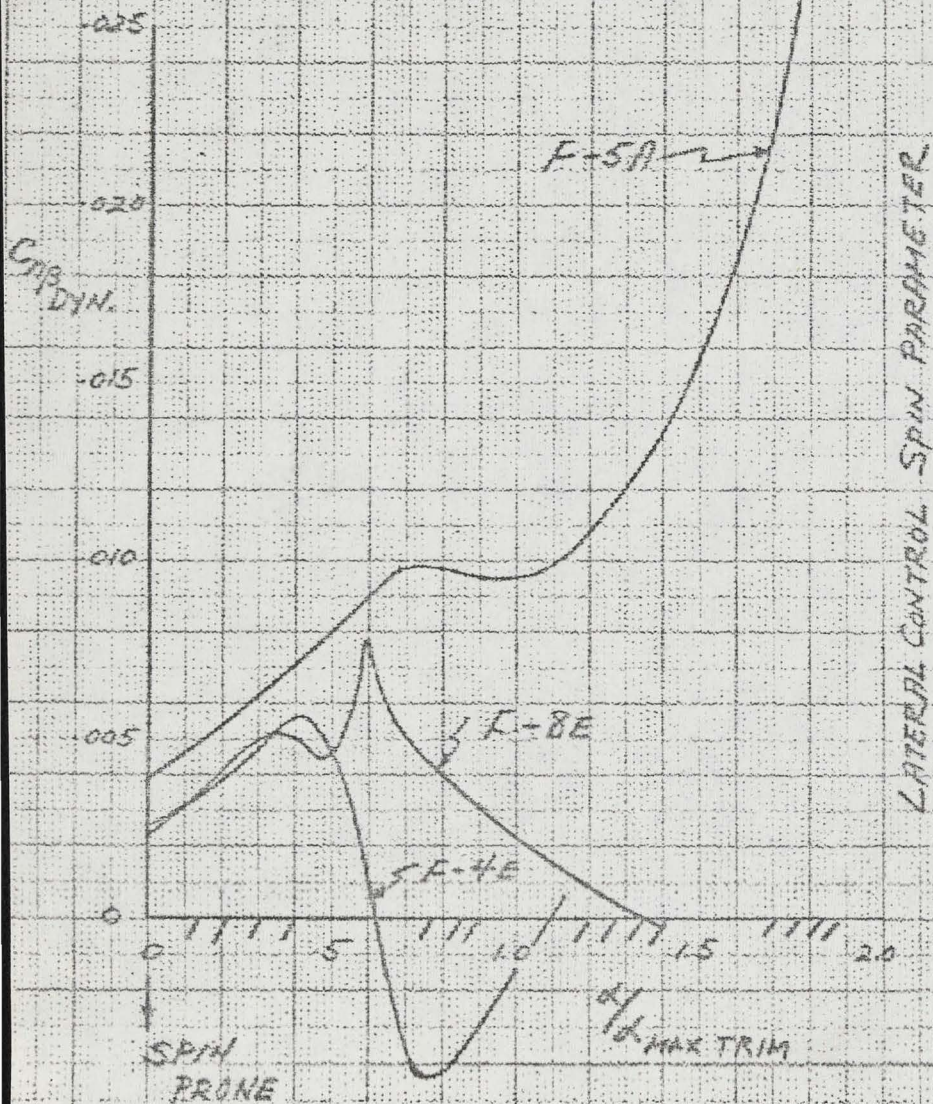
LATERAL CONTROL SPIN PARAMETER



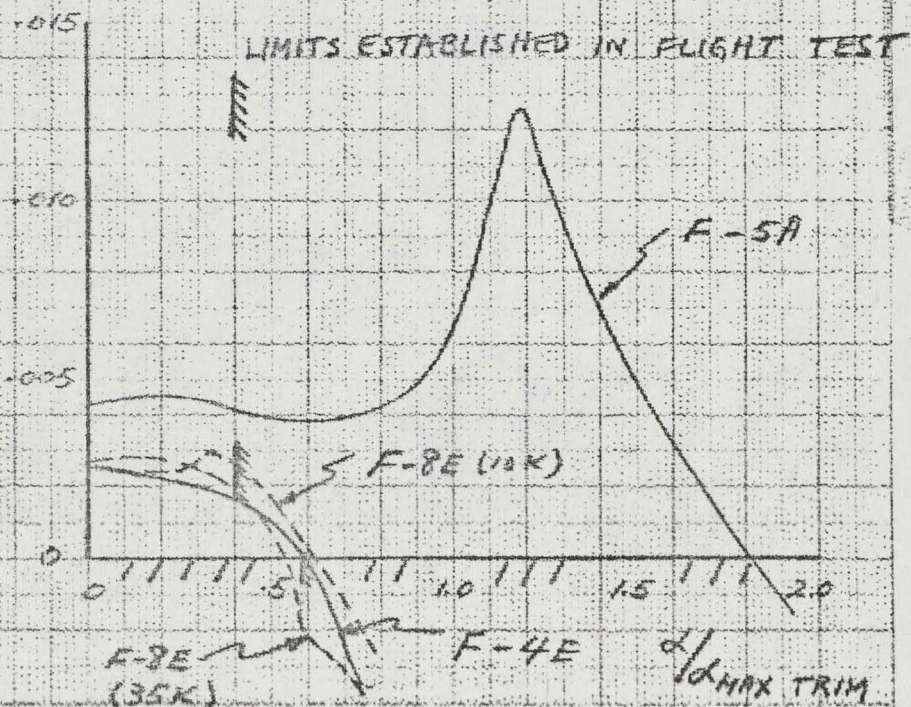
SPIN SUSCEPTIBILITY

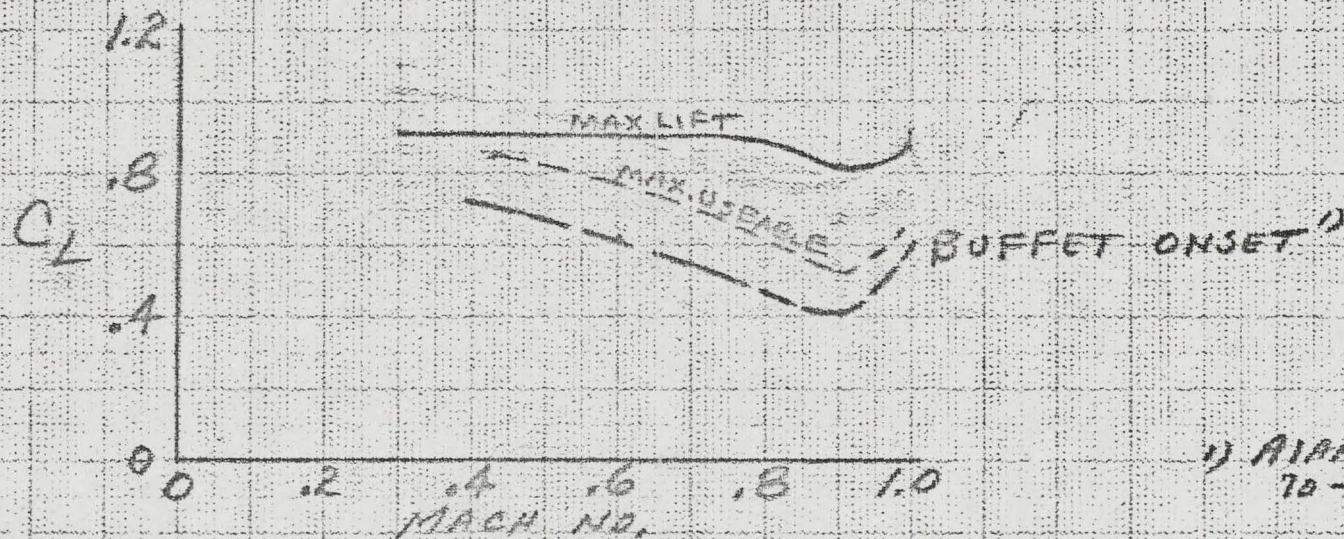
0.6 MACH

TURNING WITHOUT ROLL

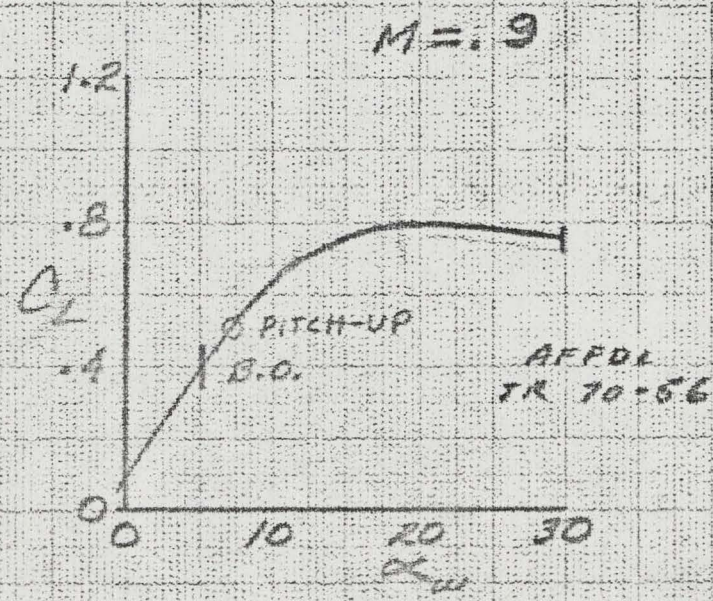
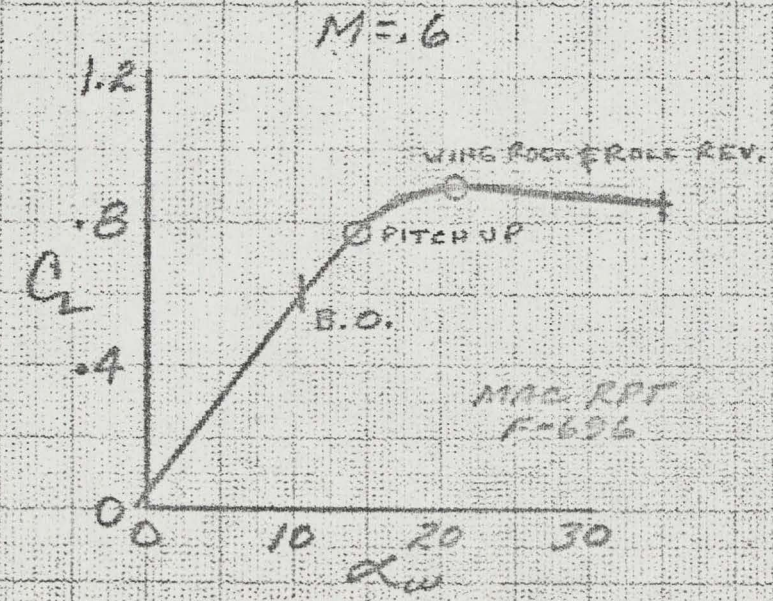


ROLLING WHILE TURNING

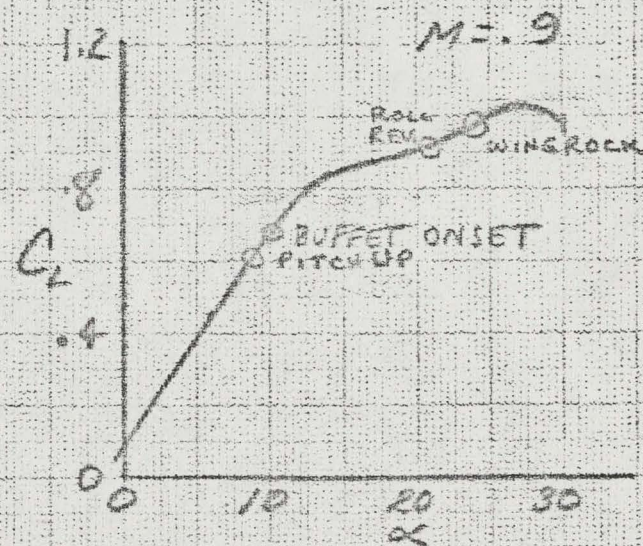
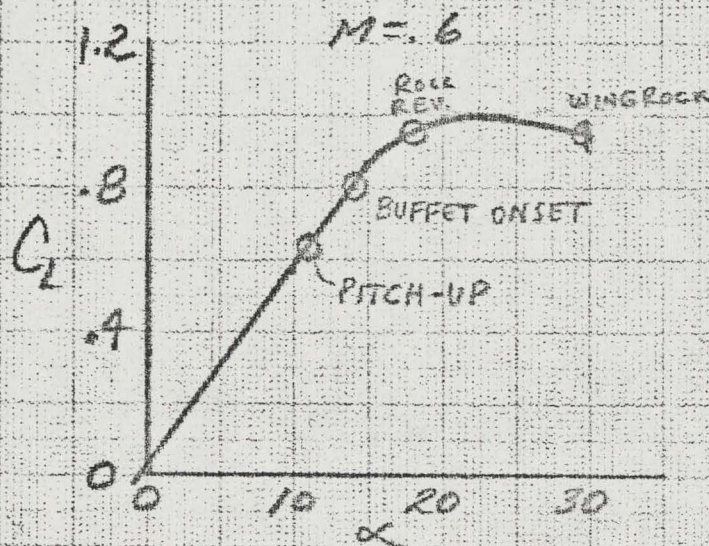
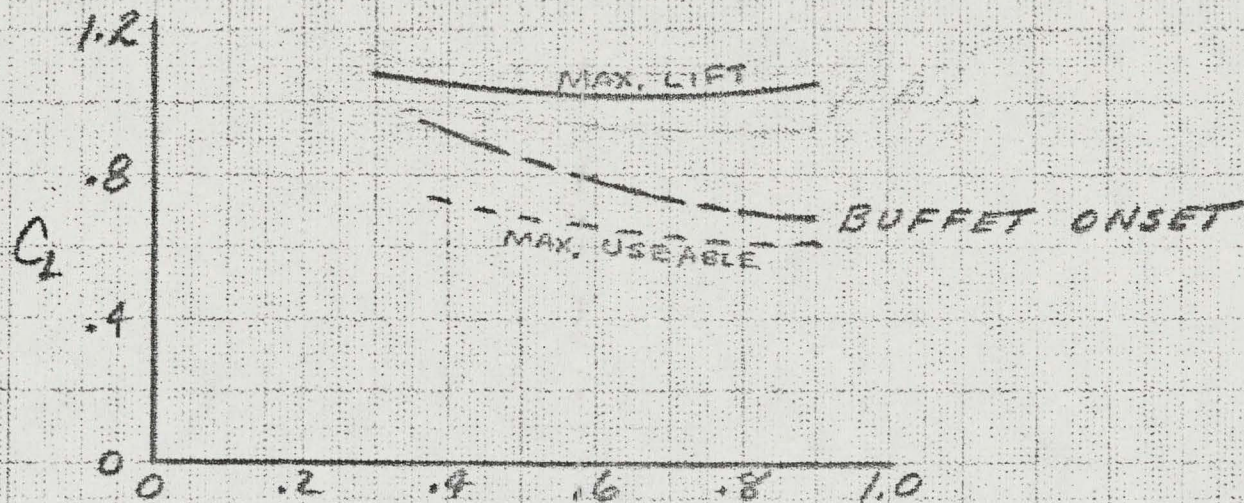




1) AIAA PAPER
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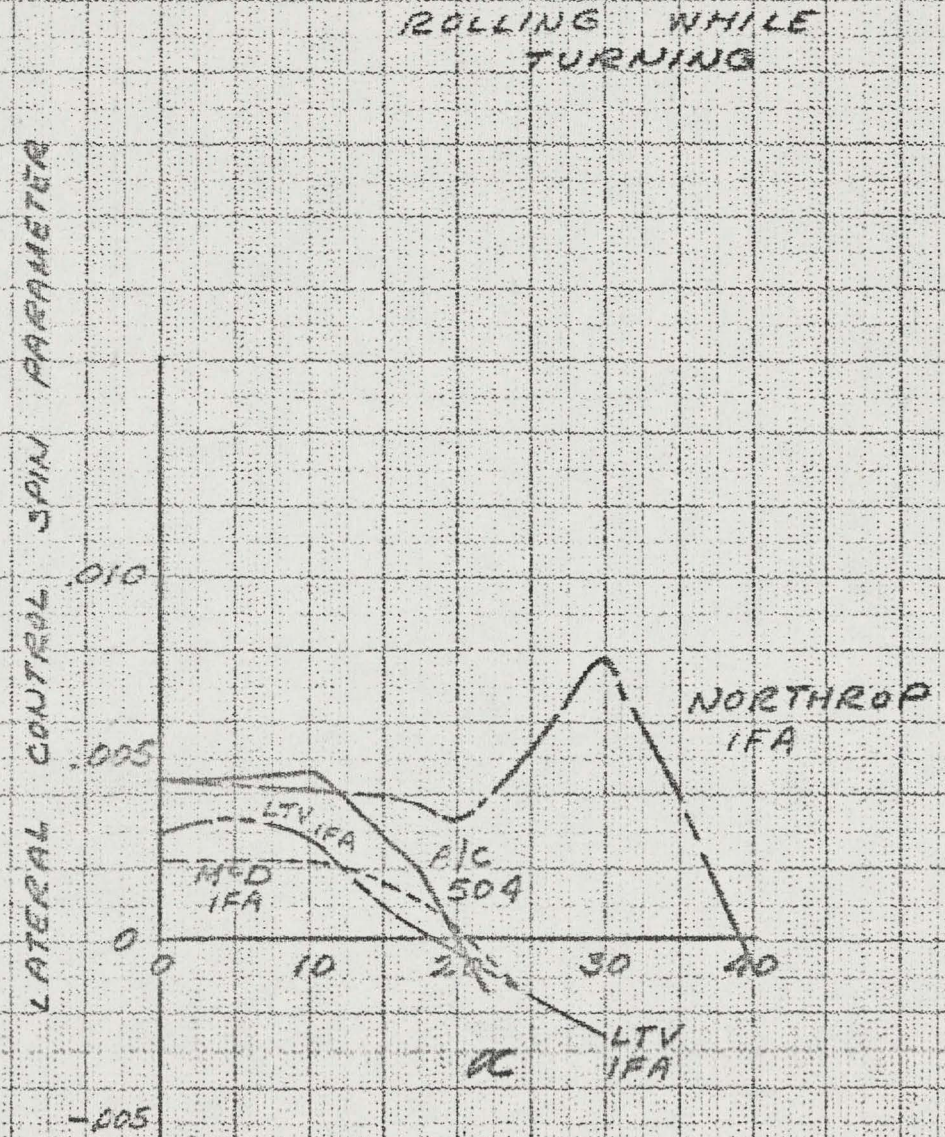
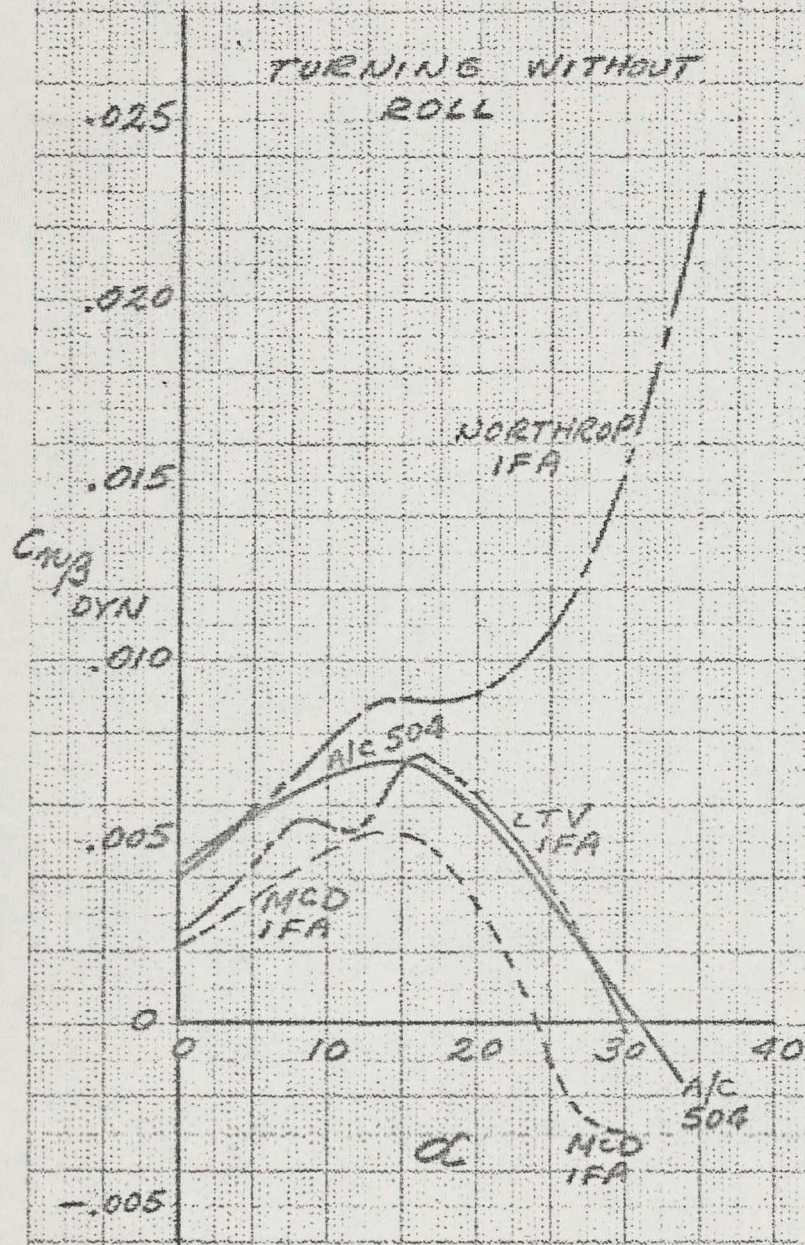


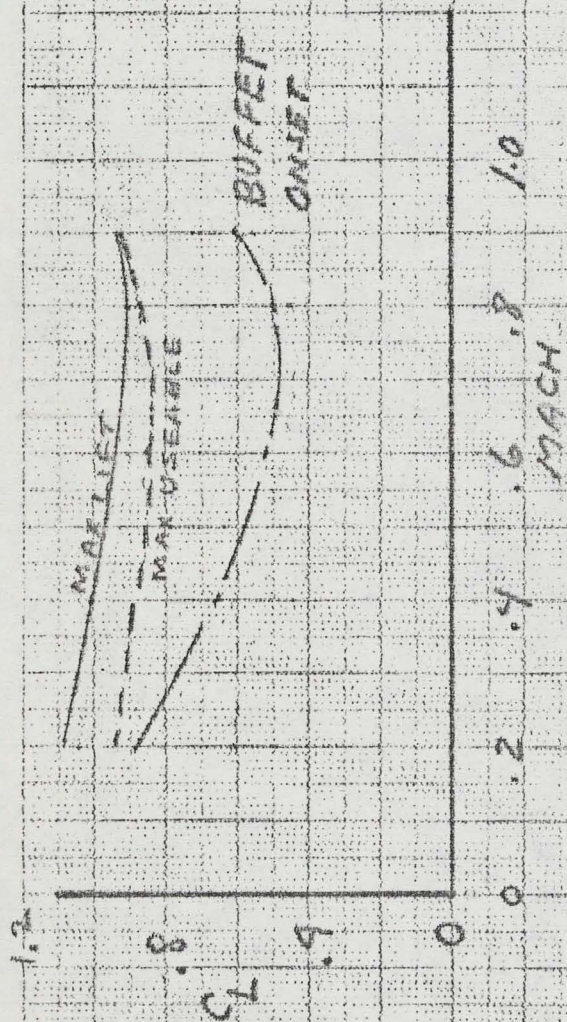
F-4E LIFT CHARACTERISTICS



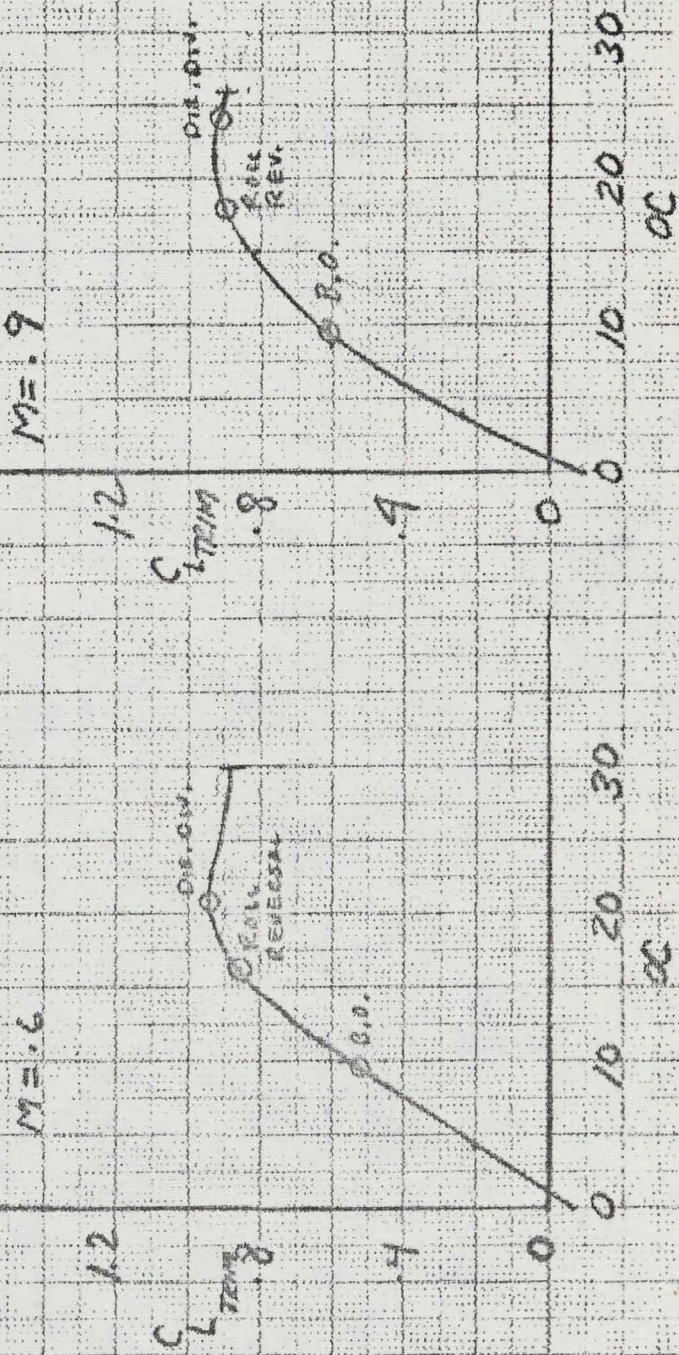
McD IFA LIFT CHARACTERISTICS

SPIN SUSCEPTIBILITY 0.9 MACH

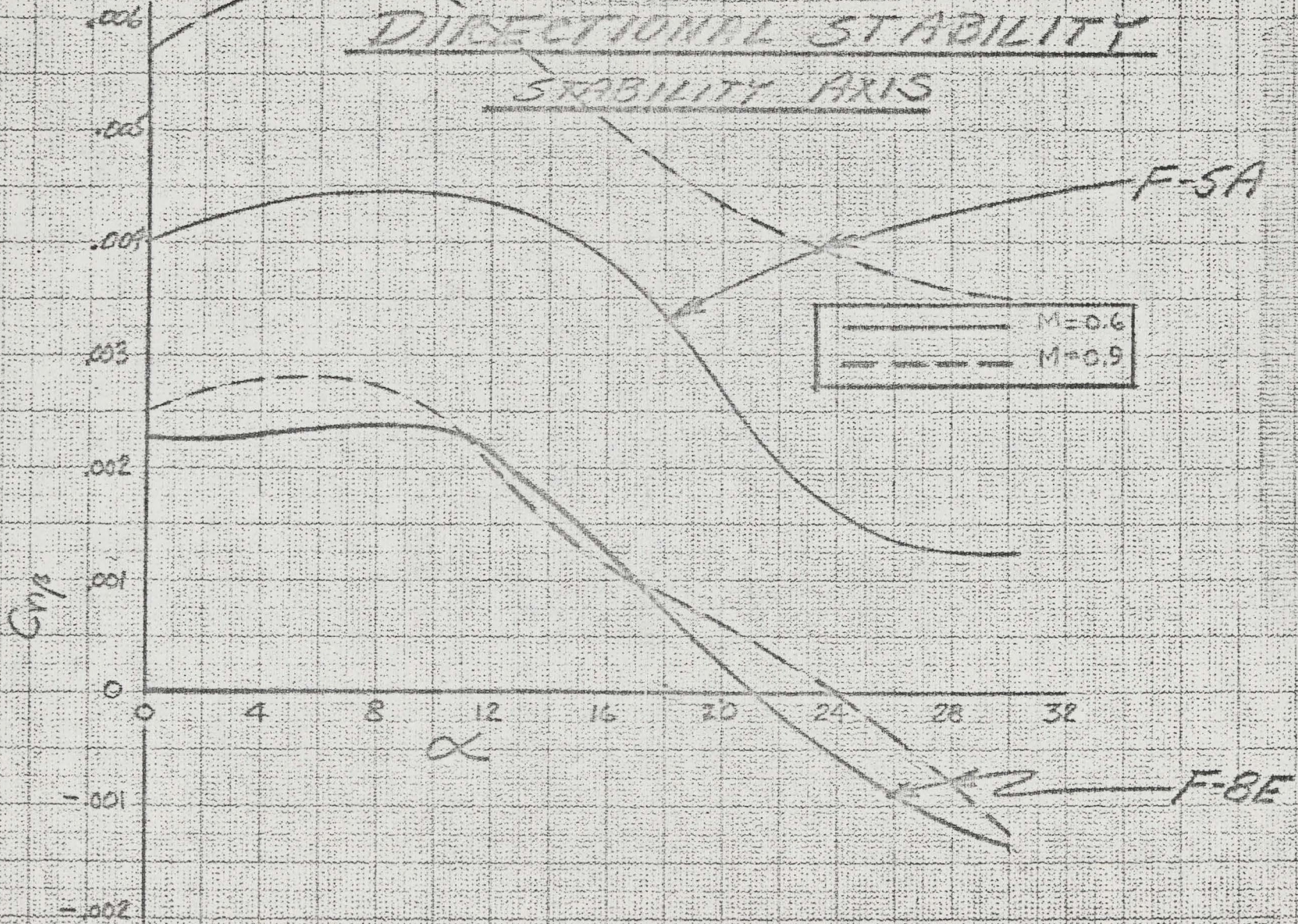




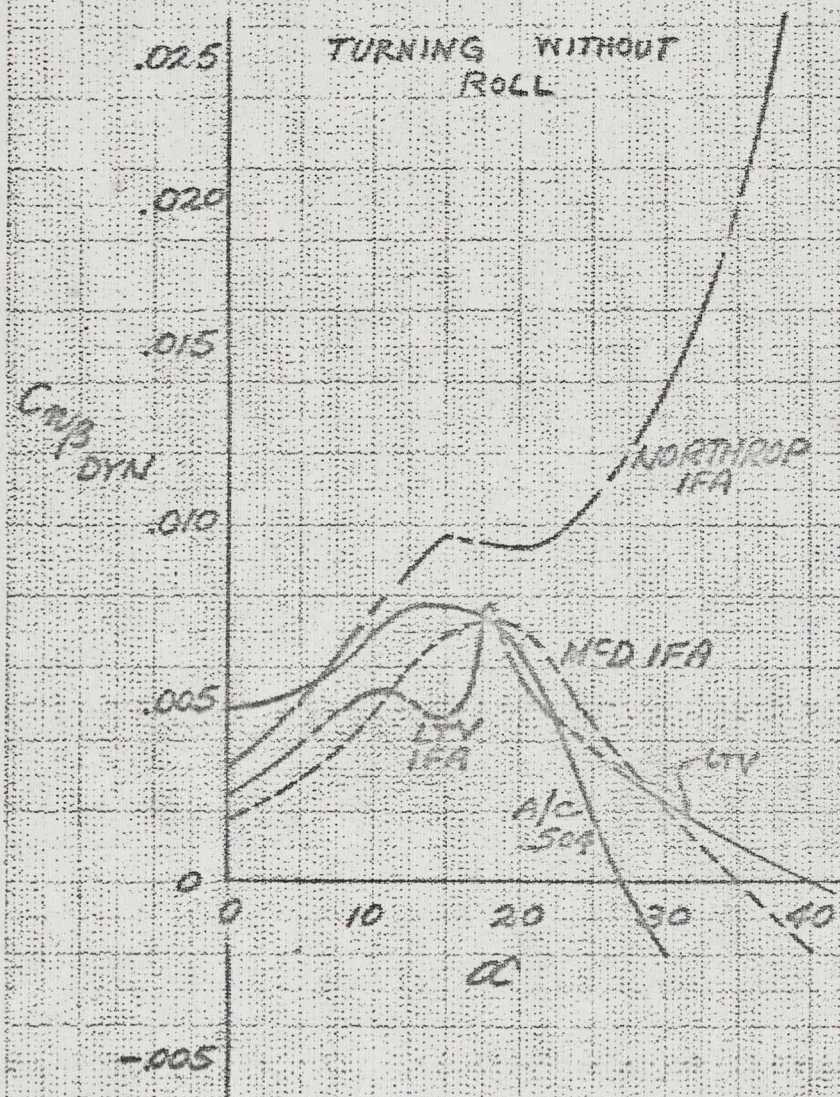
F-8E LIFT CHARACTERISTICS



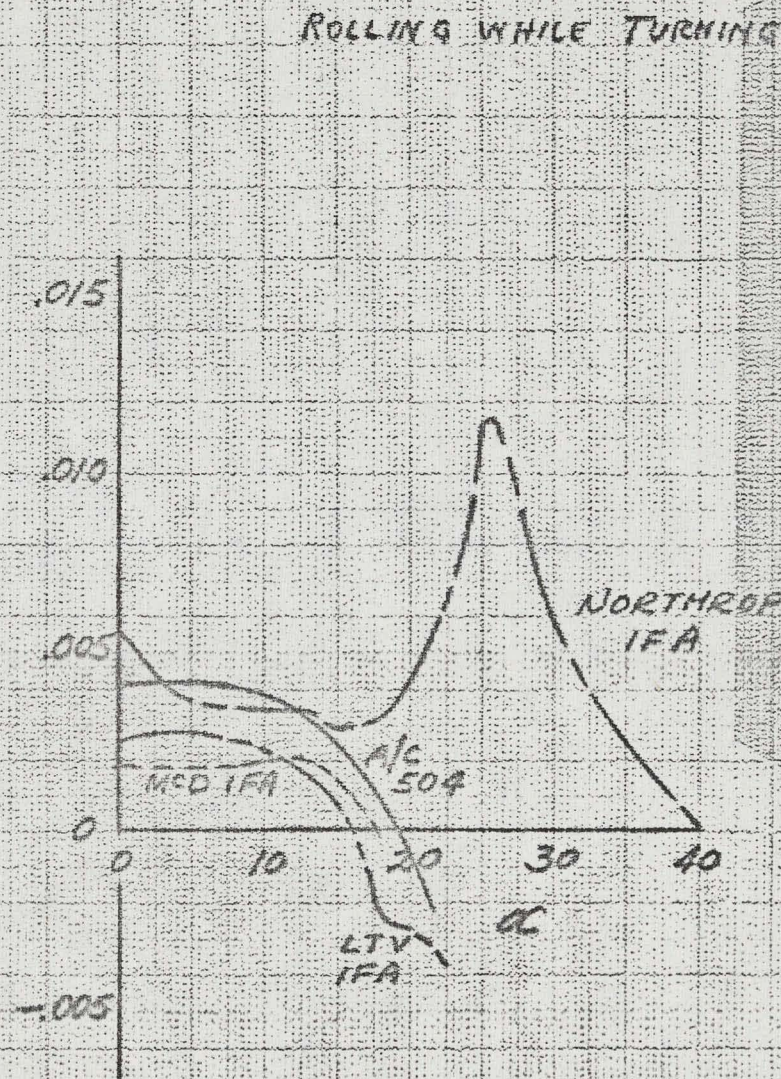
DIRECTIONAL STABILITY STABILITY AXIS

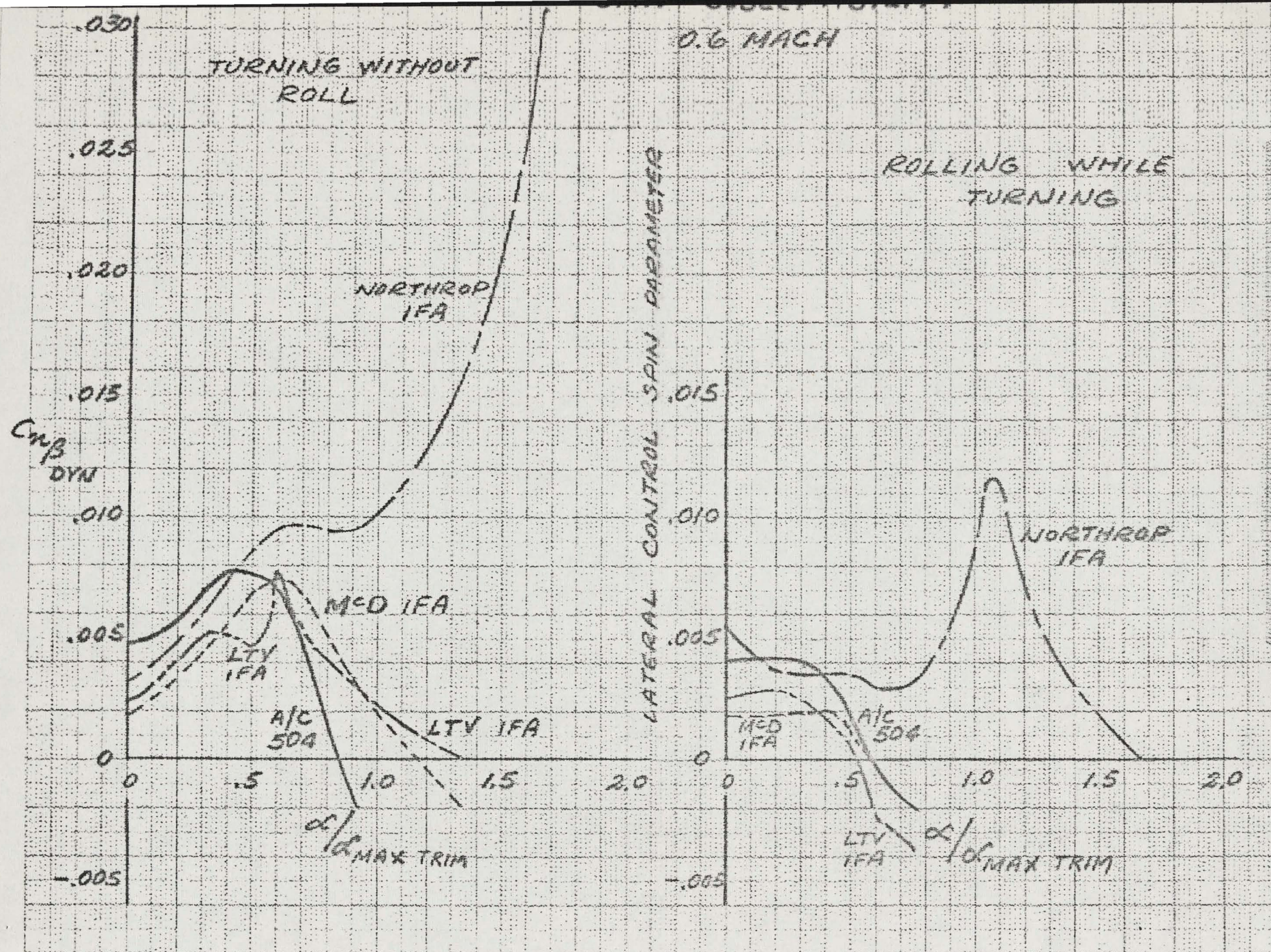


SPIN SUSCEPTIBILITY
0.6 MACH

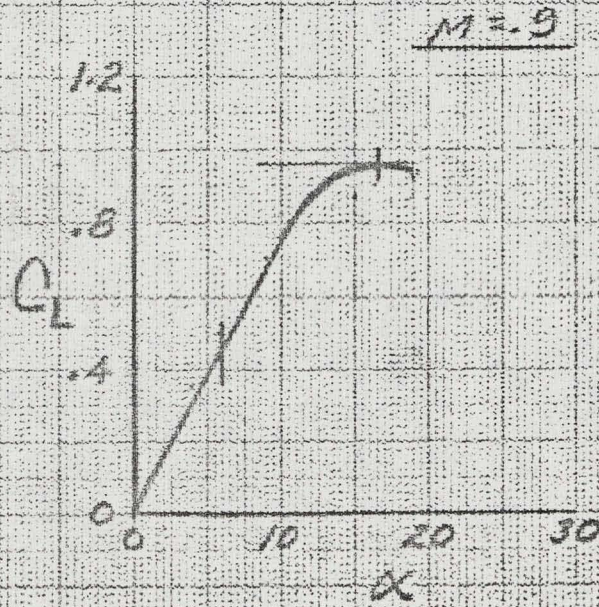
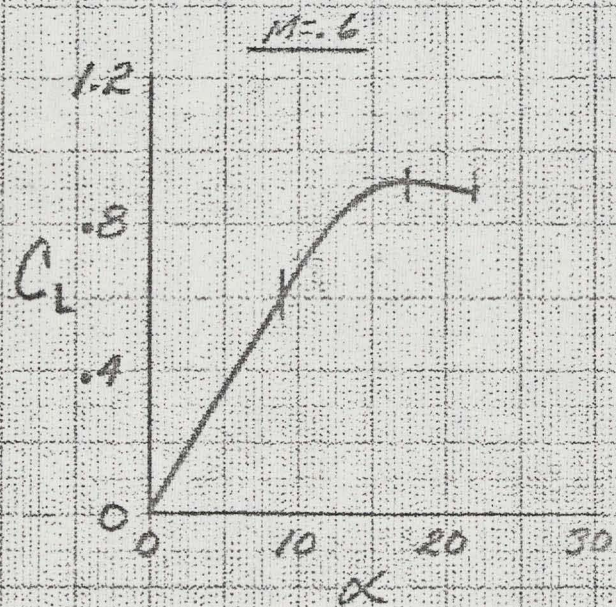
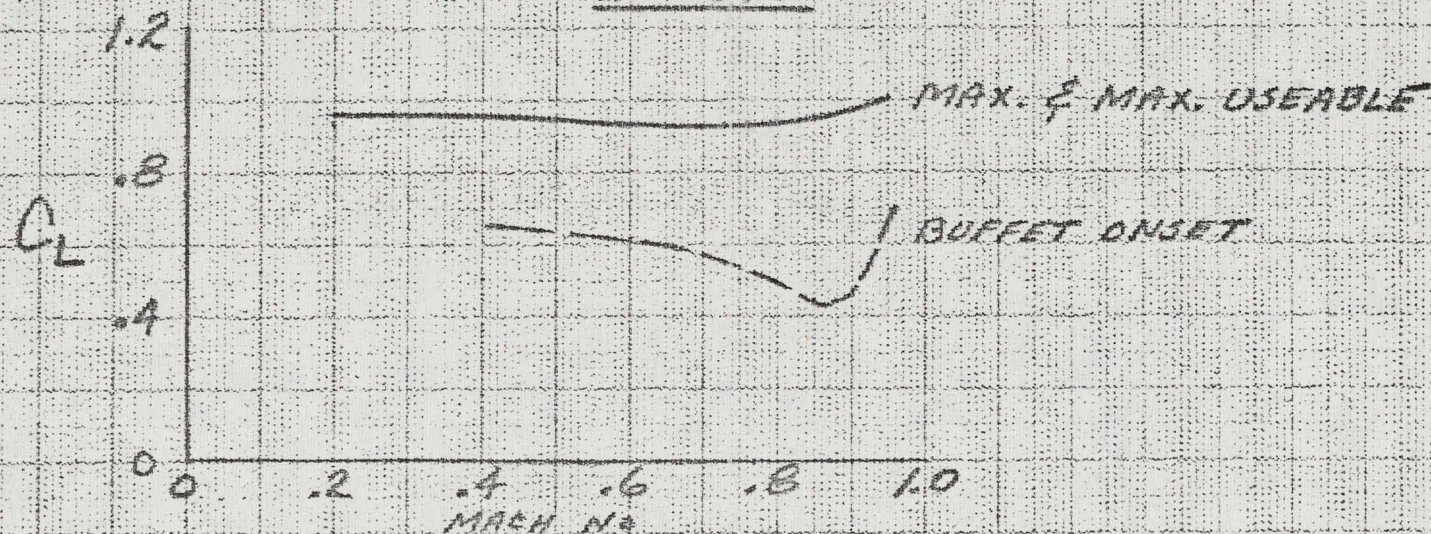


LATERAL CONTROL SPIN PARAMETER

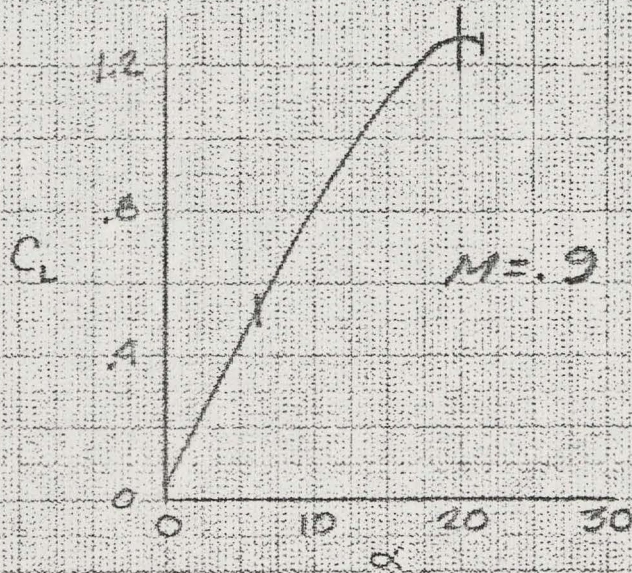
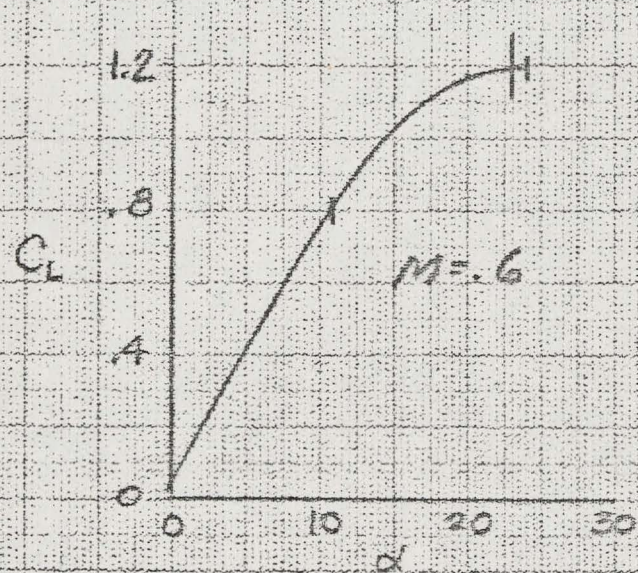
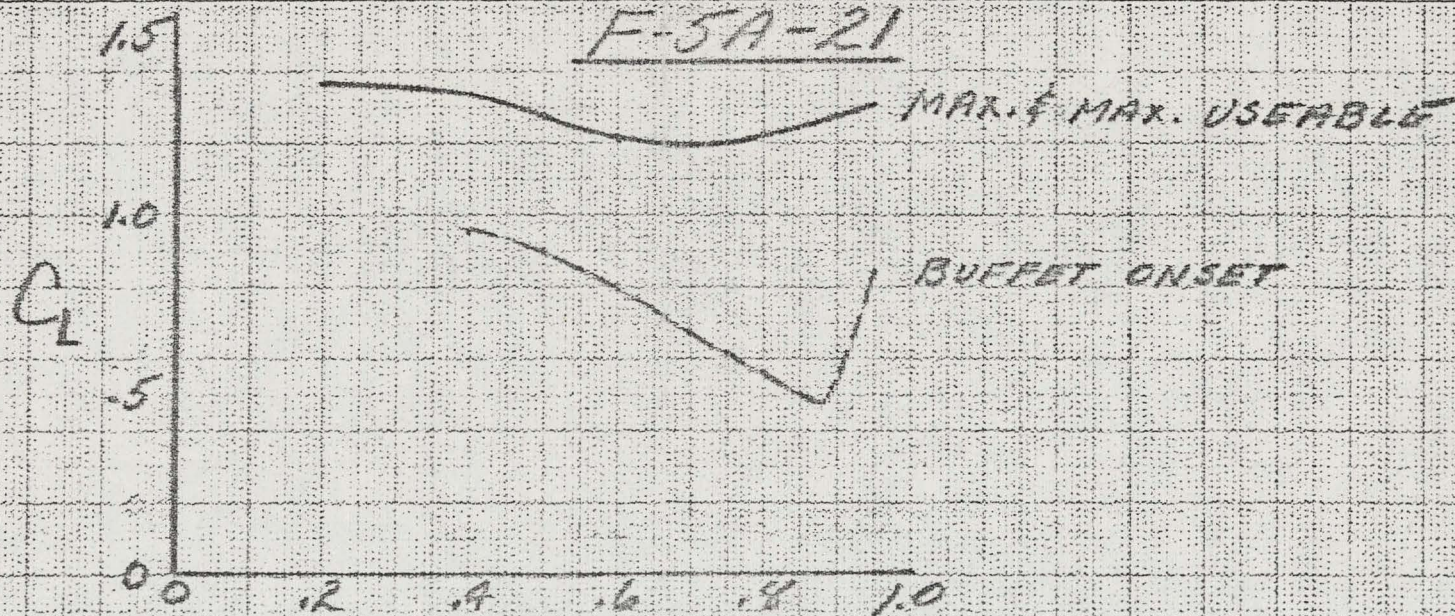




F-5A



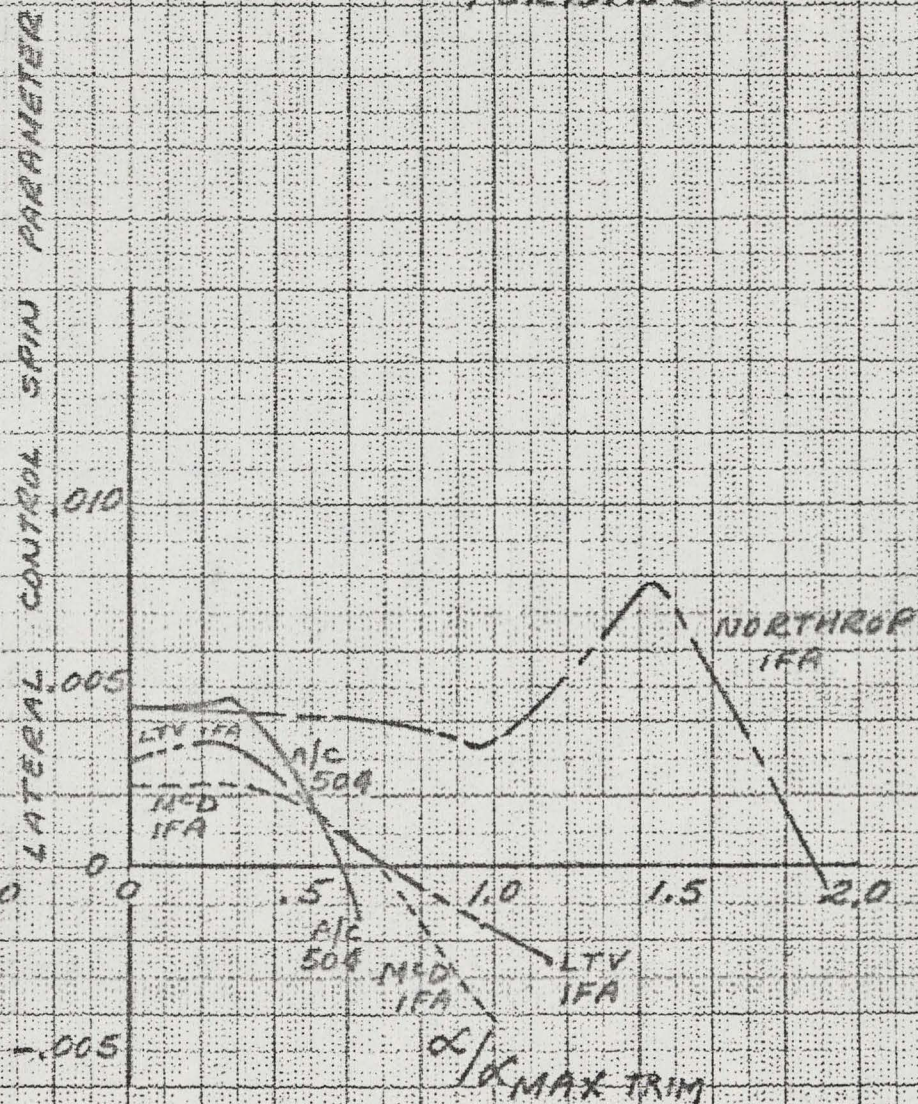
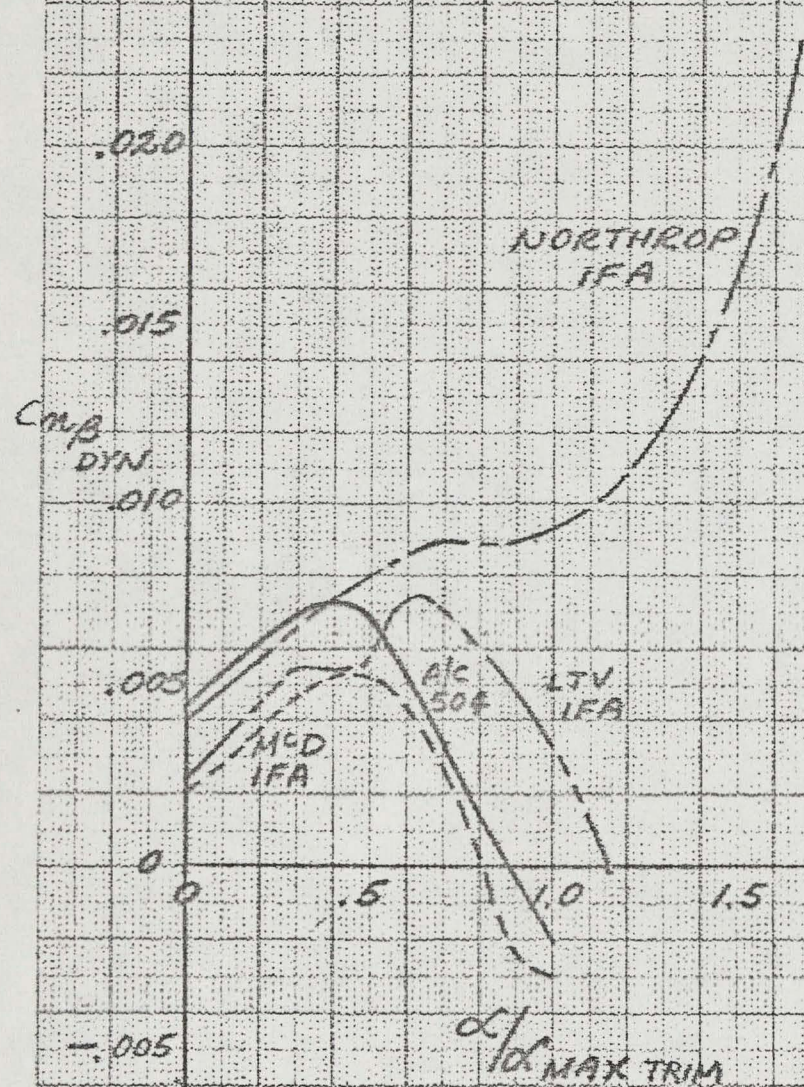
F-5A-21



SPIN SUSCEPTIBILITY 0.9 MACH

TURNING WITHOUT
ROLL

ROLLING WHILE
TURNING



ROLL PERFORMANCE

$h = 35,000$ FT $M = 0.9$

AILERON AND RUDDER INPUTS

