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MEMORANDUM

A FLIGHT INVESTIGATION OF THE LOW-SPEED HANDLING QUALITIES OF A TAILLESS DELTA-WING FIGHTER AIRPLANE

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Ames Research Center
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A FLIGHT INVESTIGATION OF THE LOW-SPEED HANDLING QUALITIES OF A TAILLESS DELTA-WING FIGHTER AIRPLANE*

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Carrier landing-approach studies of a tailless delta-wing fighter airplane disclosed that approach speeds were limited by ability to control altitude and lateral-directional characteristics. More detailed flight studies of the handling-qualities characteristics of the airplane in the carrier-approach configuration documented a number of factors that contributed to the adverse comments on the lateral-directional characteristics. These were: (1) the tendency of the airplane to roll around the highly inclined longitudinal axis, so that significant sideslip angles developed in the roll as a result only of kinematic effects; (2) reduction of the rolling response to the ailerons because of the large dihedral effect in conjunction with the kinematically developed sideslip angles; and (3) the onset of rudder lock at moderate angles of sideslip at the lowest speeds with wing tanks installed. The first two of the factors listed are inseparably identified with this type of configuration which is being considered for many of the newer designs and may, therefore, represent a problem which will be encountered frequently in the future. The results are of added significance in the demonstration of a typical situation in which extraneous factors occupy so much of the pilot's attention that his capability of coping with the problems of precise flight-path control is reduced, and he accordingly demands a greater speed margin above the stall to allow for airspeed fluctuations.

INTRODUCTION

As a part of a general program being conducted at the Ames Research Center to investigate the landing-approach problems of high-speed airplanes, flight tests were conducted on a number of airplanes, some results of which were reported in reference 1. One of the airplanes included in the study was the Douglas F4D-1, a tailless delta-wing fighter-type airplane, which was indicated to have flight characteristics in the

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*Title, Unclassified

landing approach that were different from those of most of the other airplanes studied. In common with many of the other airplanes the approach speed of the F4D-1 was reported to be limited primarily by ability to control altitude. However, with the addition of external underwing fuel tanks, substantially higher approach speeds were selected, an important limiting factor again being the ability to control altitude. This occurred despite the fact that there were only slight differences in the parameters that are usually assumed to affect ability to control altitude, namely $C_{L_{max}}$, drag variations with lift, thrust margins, etc. A possible explanation for the difference in selected approach speed was the fact that the lateral-directional characteristics of the airplane, which were reported to be a secondary limiting factor for the basic airplane, were considered even worse when the wing tanks were added.

In order to determine quantitatively the factors that resulted in this report by the pilots, a flight investigation was conducted to document the flying-qualities characteristics of the airplane in the landing-approach configuration. The results of this investigation are presented in this report.

NOTATION

$\bar{c}$	mean aerodynamic chord
C_D	drag coefficient
C_L	lift coefficient
C_m	pitching-moment coefficient about center of gravity
$C_{1/2}$	cycles to damp to one-half amplitude
F	control force, lb
$\frac{L}{D}$	lift-drag ratio
p	static pressure, lb/sq ft
p_o	ambient static pressure, lb/sq ft
q_c'	impact pressure, lb/sq ft
$T_{1/2}$	time required for oscillation to damp to one-half amplitude, sec
T_2	time required for oscillation to double amplitude, sec
v_e	$V_t \sqrt{\sigma} \sin \beta \approx V_t \sqrt{\sigma} \frac{\beta}{57.3}$ for small values of β

V	indicated airspeed, knots
V_t	true airspeed, ft/sec
α	angle of attack, deg
β	sideslip angle, deg
δ	control-surface angle, deg
φ	angle of bank, deg
$\dot{\psi}$	rate of change of yaw angle, radians/sec
σ	ratio of air density at test altitude to that at sea level
$\frac{\lvert\varphi\rvert}{\lvert v_e\rvert}$	$\frac{\lvert\varphi\rvert}{\lvert\beta\rvert}\frac{57.3}{V_t\sqrt{\sigma}}$ ratio of bank-angle amplitude to equivalent side velocity amplitude for the oscillatory mode, $\frac{\text{deg}}{\text{ft/sec}}$

Subscripts

a	aileron
e	elevator
r	rudder

AIRPLANE

The Douglas F4D-1 airplane is a tailless delta-wing jet-propelled fighter-type airplane. A three-view drawing and a photograph of the airplane are shown in figure 1, and pertinent physical characteristics are listed in table I. The airplane was equipped with two 300-gallon externally mounted (underwing) fuel tanks, which were removed for the configuration described as the basic airplane. The engine is a Pratt and Whitney J57-P8-A, performance characteristics of which are presented in table I and figure 2.

Longitudinal and lateral control is obtained by actuation of power-boosted elevons on the wings together (longitudinal) or differentially (lateral). Typical variations of stick force and position with control deflection for an F4D-1 airplane as extracted from reference 2 are shown in figures 3(a) and 3(b).

Directional control is obtained by actuation of two rudder segments. The basic segment is moved by direct linkage to the rudder pedals. The variations of pedal force and position with rudder deflection from reference 2 are shown in figure 3(c) with the yaw damper inoperative. The servo segment of rudder is slaved to the basic segment by an electrical sensing system and hydraulic drive. In the damper-on mode of operation the servo segment is also actuated by the following functions at the gearings indicated:

(1) Yaw rate: 3° rudder per degree of yaw per second

(2) Aileron position: As shown in figure 3(d) at speeds below about 200 knots

(3) Side acceleration, as indicated by pendulum unit located behind pilot's headrest: gearing as shown in figure 3(e)

INSTRUMENTATION

Except as noted, the following items were obtained from transducer signals recording continuously on Consolidated oscillographs:

Item	Transducer element
Airspeed and altitude	Pressure sources on swivelling pitot-static head on nose boom
Angles of attack and sideslip	Swivelling vanes on nose boom
Stick, rudder-pedal, and control surface deflections	Control position transducers
Stick and rudder-pedal forces	Strain-gage transducers
Vertical and longitudinal accelerations	NACA recording accelerometer
Rates of roll, pitch, and yaw	NACA recording turnmeters

To calibrate the position error of the recording static-pressure source the airplane was flown by a ground installation for which the correct static pressure was simultaneously observed. The calibration curve obtained is shown in figure 4. The airspeed indicator which was connected to the service static-pressure source was calibrated by the same procedure, and the airspeeds reported by the pilot were corrected and rounded off for presentation in this report.

The elevator deflections presented are the average of the individual surfaces on the left- and right-wing panels.

TESTS, RESULTS, AND DISCUSSION

Landing-Approach Investigations

Flight tests to determine the minimum comfortable approach speeds in carrier-type landings were conducted at Crows Landing Auxiliary Landing Field as described in reference 1. Four Ames test pilots participated in the tests, and their selected approach speeds and reasons for limiting as extracted from reference 1 are shown in table II. A description of the characteristics of the airplane that influenced the choice of approach speed is given here in more detail than in reference 1.

The primary reason for limiting the approach speed of the basic airplane (tanks off) was the ability to control altitude. Although all the pilots did not comment specifically on it, it was generally agreed that the lateral-directional stability and control characteristics of the airplane, which deteriorated with decreasing speed, were factors in the determination of the minimum comfortable approach speed. This was because the attention required to maintain lateral-directional control of the airplane diverted some pilot effort from the task of controlling flight-path angle precisely. With the addition of the external wing tanks, the pilots felt that the lateral-directional characteristics deteriorated considerably as indicated in table III. This factor then assumed about equal importance with the ability to control altitude in the pilots' determination of a minimum comfortable approach speed, and as a result, the pilots increased their approach speed by an average of about 9 knots. The main objection to the lateral-directional characteristics lay in the low directional stability and the excessive adverse yaw coupled with the high dihedral effect. This behavior resulted in the lateral control producing considerable sideslip, but being ineffective as a roll control. On the other hand, the application of rudder produced considerable roll in relation to the sideslip generated.

Lift-Drag Characteristics

In figure 5 are shown the variations with lift coefficient of drag coefficient, angle of attack, and lift-drag ratio. Curves of drag against airspeed, as derived from the data of figure 5, are presented in figure 6. The data show no differences between the basic configuration and the tanks-on configuration that appear important enough to account for the observed differences in approach speed.

Static-Longitudinal Stability

The variations of elevator angle and stick force with airspeed and with C_L, as obtained from static measurements at varying speeds, are shown in figure 7. The stick forces parallel the variations in elevator deflection because they are produced by a bungee which parallels the power driven, irreversible control system. This bungee is nonlinear, having different gradients for different control positions (fig. 3).

From the curves of elevator angle against C_L, curves of C_m against C_L were computed with an assumed constant value of $C_{m_{\delta_e}}$ of -0.00145 per degree (fig. 8). The validity of the constant $C_{m_{\delta_e}}$ assumption is indicated by the good agreement of the above-mentioned curve of C_m against C_L with the curve of C_m against C_L constructed from values of C_{m_α} as derived from the periods of short-period oscillations. Since the comparison with period data was possible only for the tanks-on case, it was necessary to make the reasonable assumption that the same constant value of $C_{m_{\delta_e}}$ of -0.00145 was applicable to the basic configuration in determining the C_m versus C_L curve of figure 8.

With tanks on, the variations of elevator angle or pitching-moment coefficient with lift coefficient (figs. 7 and 8) are reasonably smooth, but indicate a slight decrease in stability for a range of values of C_L above about 0.5. For the basic configuration, the smooth variation is broken by a small reversal in slope at lift coefficients above 0.75. Neither of the aforementioned disturbances in the stability curves bothered the pilots significantly because of the small magnitude of the decrease in stability in the tanks-on cases and because the C_L at which the slope reversal occurred with tanks off was well above the range of lift coefficients that would be used in an approach.

Dynamic Longitudinal Stability

The results of limited tests of the short-period oscillation characteristics are shown in figure 9, where the period and damping variations with airspeed are plotted for the tanks-on configuration. A noteworthy characteristic shown by the data is the low degree of damping, damping ratios being of the order of 0.2. The damping ratio, however, does not vary appreciably with C_L or airspeed. No data were obtained for the basic configuration; however, in view of the similarity of the other longitudinal characteristics over the operating range, it appears likely that the dynamic stability characteristics of the basic configuration would not be greatly different from those of the tanks-on configuration shown in figure 9 which, in turn, show no outstanding feature that would limit the approach speed.

Trim Change Due to Thrust

As noted in reference 3, one of the factors that has recently come under scrutiny as possibly influencing the pilot's choice of approach speed is the trim change due to throttle application. It has been noted that airplanes differ in their initial response to throttle application as a result of differences in trim changes due to thrust. In some cases the added energy due to thrust is manifested primarily as a speed increase; in other cases, there is predominantly a flight-path angle increase, with little speed increase, or conceivably even a speed decrease. Intermediate degrees of response between these extremes are also possible, the ideal being a response with no speed changes whatsoever. This particular characteristic would assume increased importance for airplanes of the class of the F4D-1 in which landing approaches are made on the "back side" of the drag-velocity curve, where considerable throttle activity would be required in making flight-path adjustments.

Unpublished data show that the F4D-1 responses to throttle movement were strong in speed changes and only moderate in flight-path angle changes. While the pilots would have preferred that the trim changes produce smaller speed variation, the over-all response characteristics were considered acceptable because of a different compensating factor, namely, the unusually large thrust margin available for maneuvering (ref. 1).

Lateral-Control Characteristics

Rapid control motions.- Time histories of the airplane response to abrupt aileron applications initiated from level flight at a speed of 125 knots are shown in figure 10 for the basic airplane and the airplane with tanks on. Data are shown both for the yaw damper on and off. The data show that for all the configurations the roll rate actually reverses after the first peak is attained, and is thereafter oscillatory about a level lower than that of the first peak. The resulting average or effective roll rate is, of course, greatly reduced, but the amount of the reduction is not affected by the configuration.

The roll-rate reversals are attributed to rolling moments due to sideslip angle, which have been shown to be very large for wings with swept leading edges operating at high angles of attack. Normally, the yawing moments that generate sideslip angles in this condition arise mainly from the adverse yaw characteristics of the ailerons. In the present instance, the sideslip angles result from another factor, namely, the tendency of the airplane to roll around its inclined longitudinal axis, so that sideslip would build up, at least initially, in accord with the relationship $\beta = \alpha \sin \Delta\varphi$. In figure 11, time histories of the function $\alpha \sin \Delta\varphi$, as computed from flight data, are plotted for comparison with the recorded sideslip angles from figure 10. The agreement between the recorded sideslip angles and the sideslip angles computed as $\alpha \sin \Delta\varphi$ is seen to be good for all the cases considered. Further verification of the dominant role of the kinematics in generating sideslip is given by the time histories of the function $\int \dot{\psi}\, dt$ included in figure 11. In the initial part of the time history, this function would indicate the main contribution of a yawing moment such as would be produced by aileron adverse yaw. It is apparent that, initially, the sideslip angles resulting from this source are much smaller than those arising from kinematic considerations, which indicates that the adverse yaw of the ailerons is of minor importance in defining the initial rolling responses to abrupt aileron control. It was necessary to confine these comparisons to the earlier stages of the maneuvers because the effects of side accelerations were not available to include in the comparisons. It is of interest to note that the pilots could not detect from the airplane motions the true source of the sideslips developed, but instead attributed it to aileron adverse yaw.

Slow control motion.- The test pilots reported that when the ailerons were moved slowly at low speeds the sideslip angle tended to increase with little or no roll motion. This confirms the results of the abrupt aileron responses that the ailerons do produce some adverse yaw. Various combinations of aileron adverse yaw, static directional stability, and dihedral effect could result in the observed responses, which were, unfortunately, not documented in flight. As indicated by the variations of rudder deflection with steady sideslip angle in figure 12 and the derived curves of $d\delta_r/d\beta$ in figure 13, the static directional stability of the airplane decreases with decreasing airspeed, so that the tendency of the airplane to yaw and not to roll in response to slow aileron movements would become more annoying at lower speeds as a result of this factor alone.

Steady Sideslips

The variations of aileron, elevon, and rudder forces and deflections with steady sideslip are shown in figure 12 for the basic airplane and for the airplane with tanks on. The variations of rudder angle with sideslip in figures 12 and 13 show a decreasing slope with decreasing speed, although the slopes indicate positive stability at speeds as low as 125 knots. The rudder force gradients show similar trends except for the tanks-on case at 125 knots where a rudder force reversal is indicated for sideslip angles greater than about 6°. Sideslip angles of this order are attained in moderate aileron rolls (see fig. 10). The reason for this difference in rudder force variation at 125 knots between the basic configuration and the tanks-on configuration is not readily apparent. It can only be surmised that the slightly lower rudder position gradient is sufficient to produce this effect, or that there is a difference in air flow over the tail due to the tanks that might account for it. In any case the pilots considered this characteristic dangerous enough that they were reluctant to extend the steady sideslip tests to higher sideslip angles for fear of producing a spin. It should be apparent that the need to maneuver the airplane with such considerations present would force the pilot to select higher approach speeds.

Lateral Stability

In figure 14 are shown the variations with airspeed of the dynamic lateral stability parameters, period, damping, and roll-to-yaw ratio $|\varphi|/|v_e|$. Generally, there is a deterioration in damping (in terms of $C_{1/2}$) as speed is reduced below 150 knots. In reference 4 the relationship of these plotted values to acceptable boundaries is indicated. The comparison, reproduced here in figure 15, indicates that in the approach-speed region the damping is poorer than the acceptable values. It is also noteworthy that with decreasing speed the beneficial effects of the yaw-damper installation tends to diminish until at approach speeds the effect is quite small, the damping being poorer than acceptable with or without the damper. This is consistent with the opinions of the pilots that the dampers were relatively ineffective in this region.

It does not appear that the differences in damping between the basic airplane and the airplane with tanks on are large enough to have affected the approach speed greatly. In particular, the fact that the damping was better with tanks on than off at 125 knots (damper off) combined with the fact that the pilots did not discern an improvement with the damper on argues that damping could not have been a primary factor in influencing approach speed.

CONCLUSIONS

Flying-qualities studies were conducted in flight on a tailless delta-wing fighter-type airplane in the landing-approach configuration in order to investigate in more detail the factors that contributed to the pilots' selection of a landing-approach speed. The following factors were found to be significant:

1. In abrupt aileron rolls the airplane tended to roll around the highly inclined longitudinal axis so that significant sideslip angles developed in the roll as a result only of this kinematic effect. This would augment the usual adverse yaw characteristics of the ailerons which were powerful enough that the airplane would yaw and not roll in response to slow aileron movements.

2. The rolling response to the ailerons was greatly reduced as a result of the dihedral effect operating at the kinematically developed sideslip angles.

3. With tanks installed the landing-approach speed was higher than it was for the basic airplane. With tanks, rudder-free directional instability (i.e., a rudder-lock) occurred at a sideslip angle of 6° as the airspeed was reduced from 135 to 125 knots, a condition that was not experienced on the basic airplane. This sideslip angle of 6° could be generated in moderate aileron rolls as a result of kinematic effects mentioned above.

4. The special significance of these factors lies in the fact that collectively they can occupy so much of the pilot's attention that he has reduced capability of coping with the problems of precise flight-path control and, accordingly, he demands a greater speed margin above the stall to allow for airspeed fluctuations.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Jan. 15, 1959

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1. White, Maurice D., Schlaff, Bernard A., and Drinkwater, Fred J., III: A Comparison of Flight-Measured Carrier-Approach Speeds With Values Predicted by Several Different Criteria for 41 Fighter-Type Airplane Configurations. NACA RM A57L11, 1958.

2. Miller, J. C.: Control System Calibration of F4D-1 Airplane, BUAER No. 130740. Rep. CG-MR-160, Douglas Aircraft Co., Inc., El Segundo Division, Aug. 1954.

3. Drinkwater, Fred J., III, and Cooper, George E.: A Flight Evaluation of the Factors Which Influence the Selection of Landing Approach Speeds. NASA MEMO 10-6-58A, 1958.

4. McNeill, Walter E., and Vomaske, Richard F.: A Flight Investigation to Determine the Lateral Oscillatory Damping Acceptable for an Airplane in the Landing Approach. NASA MEMO 12-10-58A, 1959.

TABLE I.- TEST AIRPLANE CHARACTERISTICS

Engine	
Type	J57-P8-A
Maximum thrust without afterburner (nominal), lb	10,200
Maximum thrust with afterburner (nominal), lb	16,000
Fuel regulator	JFC 12-2
Airplane	
Fuselage	
Length, ft	38.63
Wing	
Airfoil section	
Root	NACA 0007-63/30 -9°30' Modified
Tip	NACA 0004.5-63/30 -9°30' Modified
Span, ft	33.5
Area, sq ft	557.0
Taper ratio	0.332
Aspect ratio	2.02
Mean aerodynamic chord, ft	18.25
Leading-edge sweep, deg	52.5
Elevon	
Area, sq ft (total)	45.14
Pitch trimmer	
Area, sq ft (total)	26.84
Vertical tail	
Area, sq ft	47.7
Span, ft	7.58
Rudder	
Manual	
Area, sq ft	10.7
Yaw damper	
Area, sq ft	5.5
Gross weight as tested without external wing tanks	
Empty	15,870
Landing (1000 lb fuel)	16,870
Gross weight as tested with external wing tanks	
Landing (1000 lb fuel)	17,260

TABLE II.- CARRIER LANDING-APPROACH SPEEDS AND REASONS FOR LIMITING AS DETERMINED FROM FLIGHT EVALUATIONS

Configuration	Calibrated approach speed, knots, and primary reason for limiting approach speed				Average of pilots			Remarks
	Individual pilot				Approach speed	Reason for limiting approach speed		
	A	B	C	D		Primary	Secondary	
Basic airplane (Tanks off)	120 (1)	118 (1)	124 (1)	122 (1)	121	(1)	(2)	Poor lateral-directional characteristics at low speeds affect approach speed. Powerful thrust margin
Tanks on	135 (1)	128 (1)	130 (1)	125 (1)	130	(1)	(2)	Lateral-directional characteristics considered even worse with tanks on than with tanks off. Powerful thrust margin

[1] Ability to control altitude or arrest rate of sink

[2] Lateral-directional stability or control characteristics

TABLE III.- PILOTS' RATINGS[1] OF LATERAL-DIRECTIONAL CHARACTERISTICS OF F4D-1 AIRPLANE

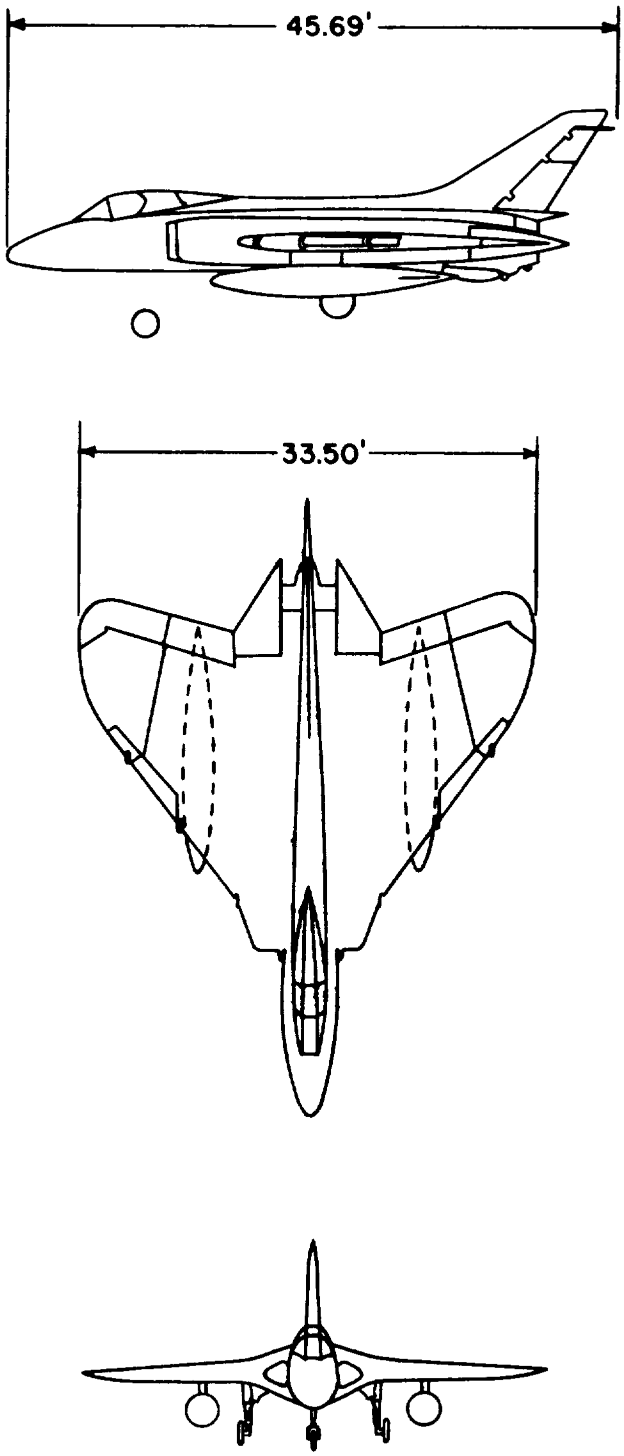
			Basic airplane (Tanks off)				Tanks on				
Indicated airspeed, knots			125	150	175	200	125	135	150	175	200
Directional oscillation	Damping	Damper off	3	3	3	3	5		4	4	4
	$\lvert\varphi\rvert/\lvert v_e\rvert$		4	3	3	3	6		4	3	3
	Damping	Damper on	3	2	2	2	5	4	3	2	2
	$\lvert\varphi\rvert/\lvert v_e\rvert$		4	3	3	3	6	5	4	3	3
Steady sideslip		Damper off	4	3			8	4	3		
Adverse yaw, rudder free		Damper on	5	4			9	6	5		
Roll performance, rudder fixed		Damper on	4	3			6	4	3		
		Damper off					8	6			

[1] Based on rating system in table IV

TABLE IV.- PILOT OPINION RATING SYSTEM

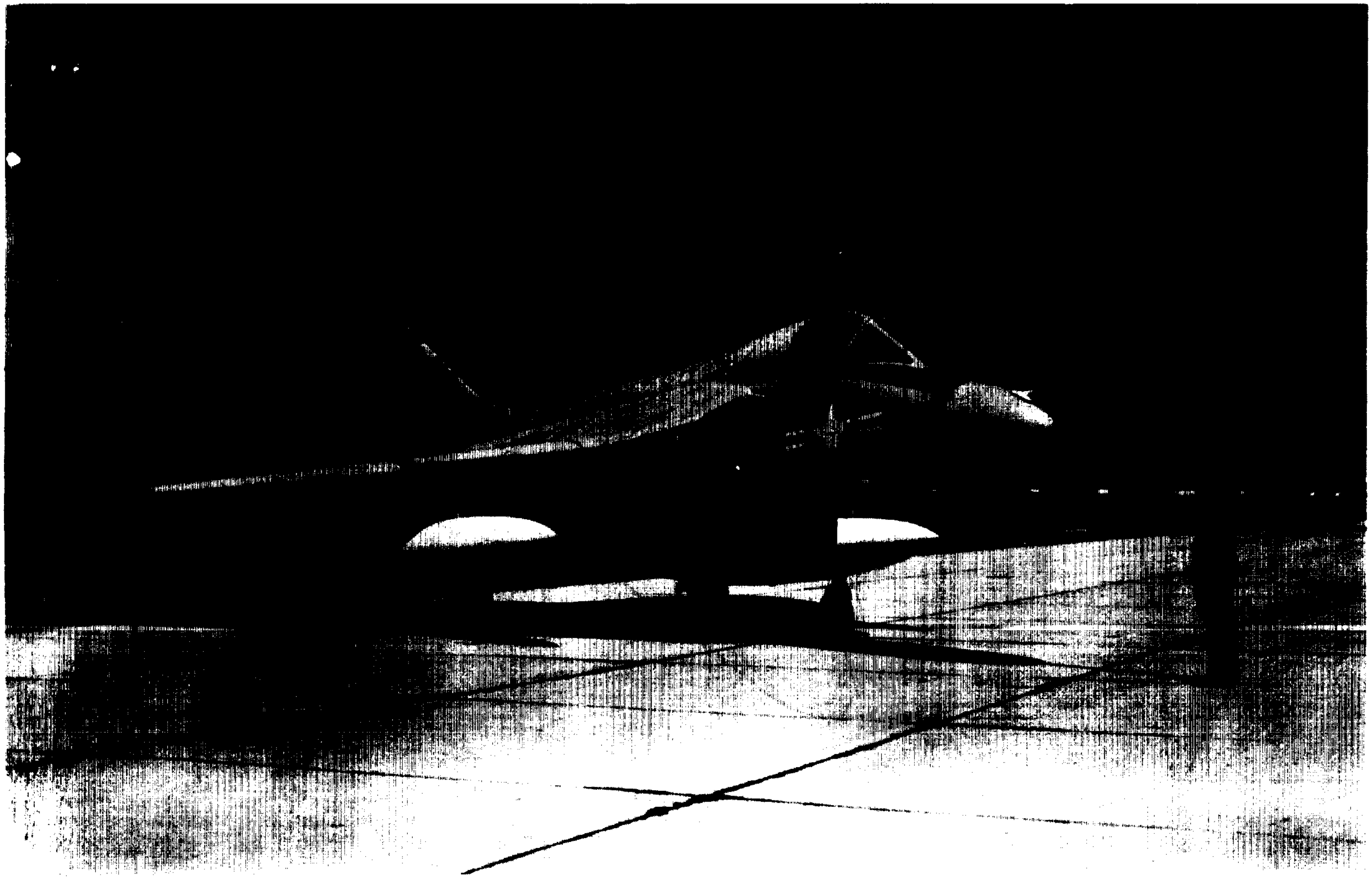
	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No

[1] Failure of a stability augmenter



(a) Three-view drawing.

Figure 1.- Views of the F4D-1 airplane.



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(b) Three-quarter front view; underwing fuel tanks installed.

Figure 1.- Concluded.

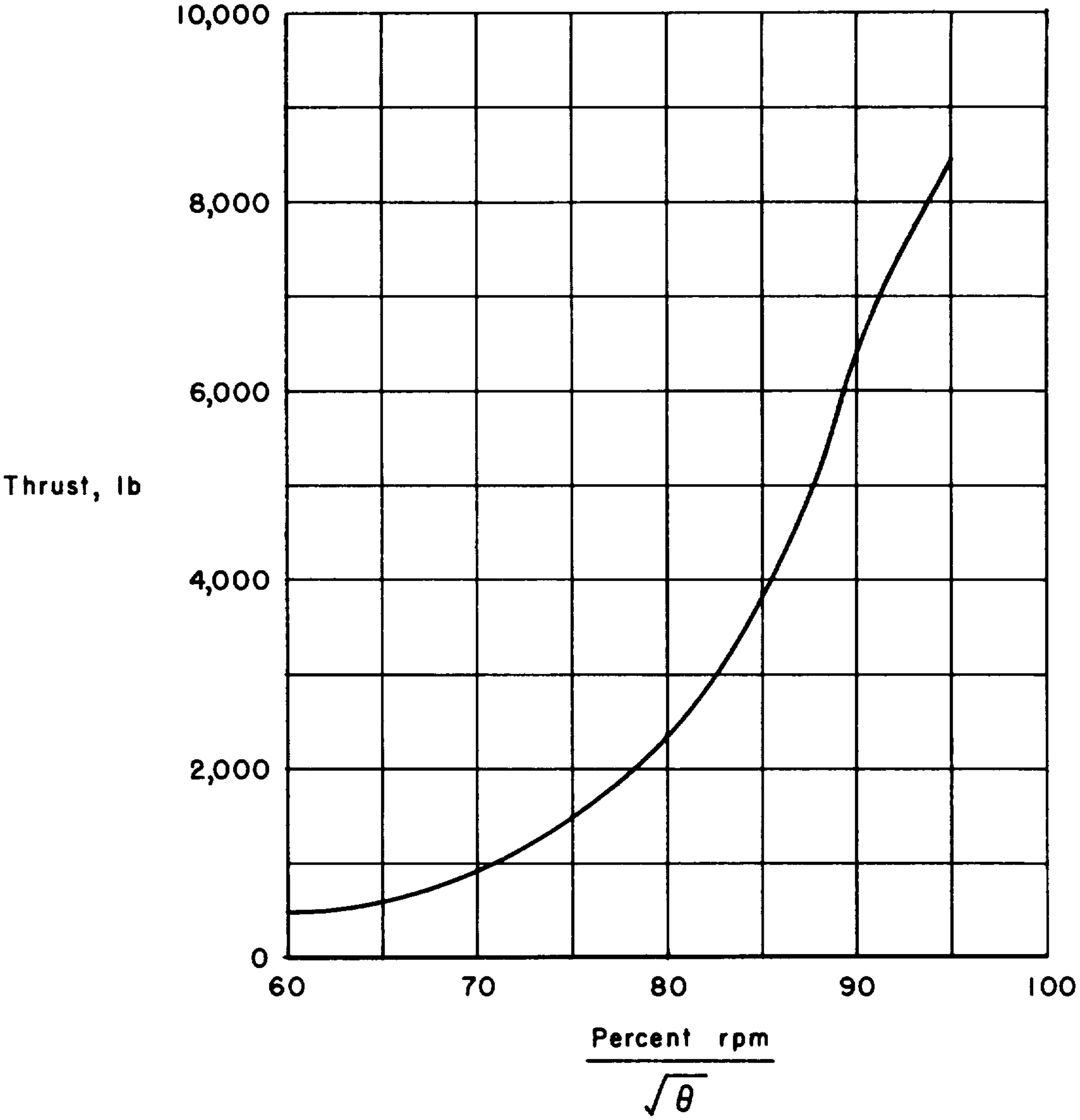
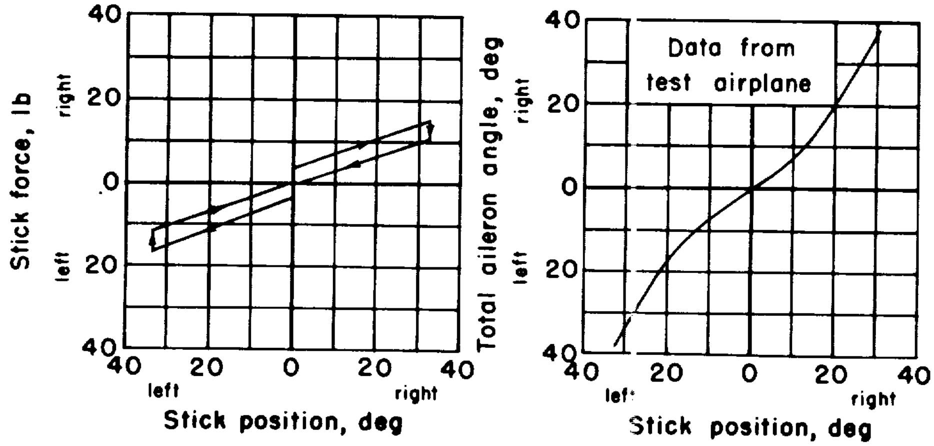
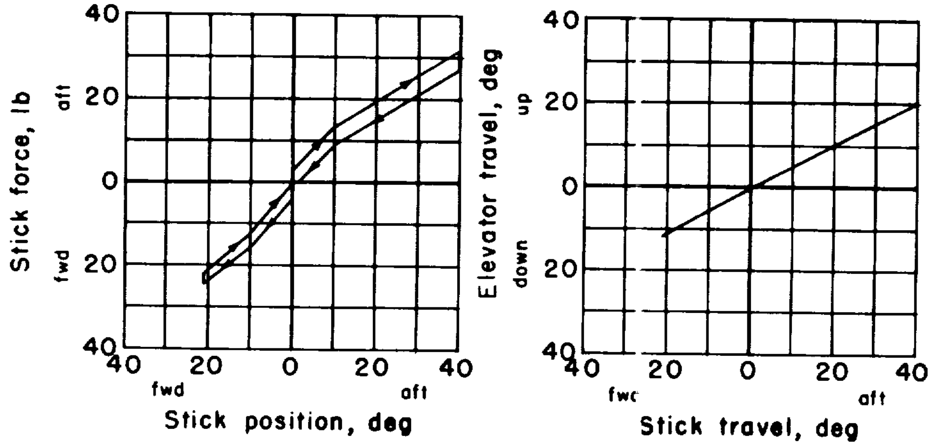


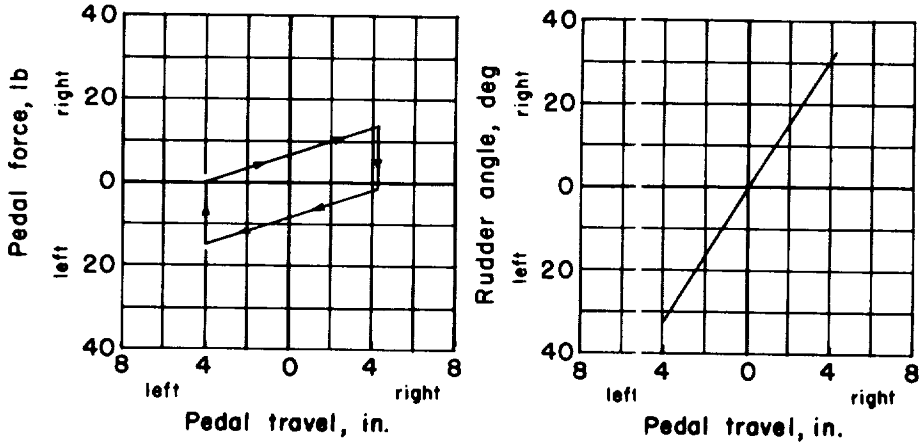
Figure 2.- Variation of installed-engine thrust with rpm for the F4D-1 airplane as measured on thrust stand.



(a) Ailerons.

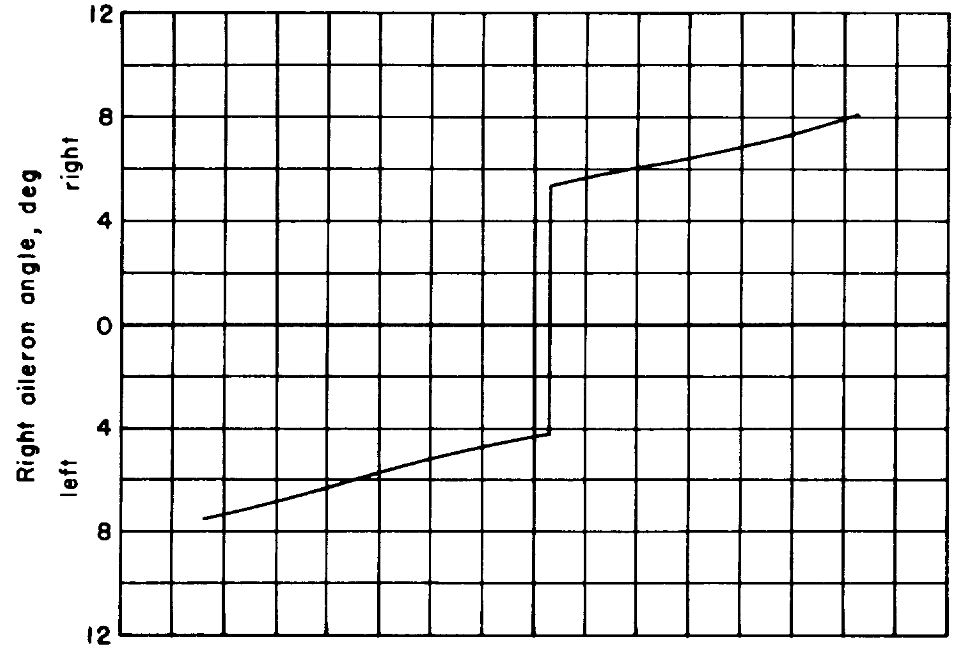


(b) Elevator.

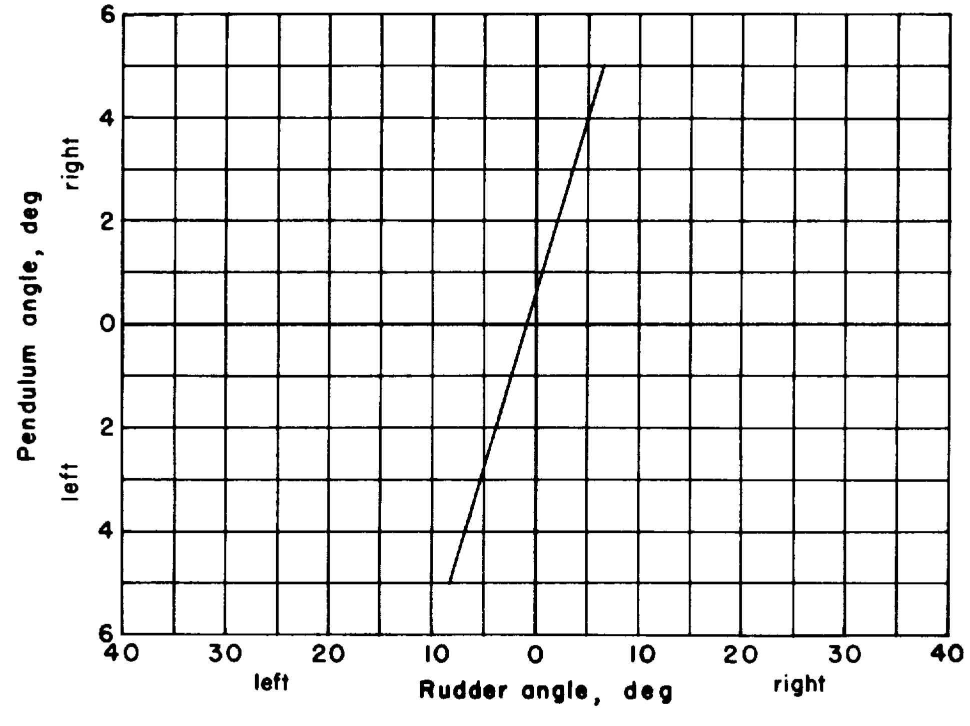


(c) Rudder.

Figure 3.- Control gearings and force variations for a typical F4D-1 airplane; data from reference 3 except as noted.



(d) Servo rudder actuation by aileron.



(e) Servo rudder actuation by side acceleration.

Figure 3.- Concluded.

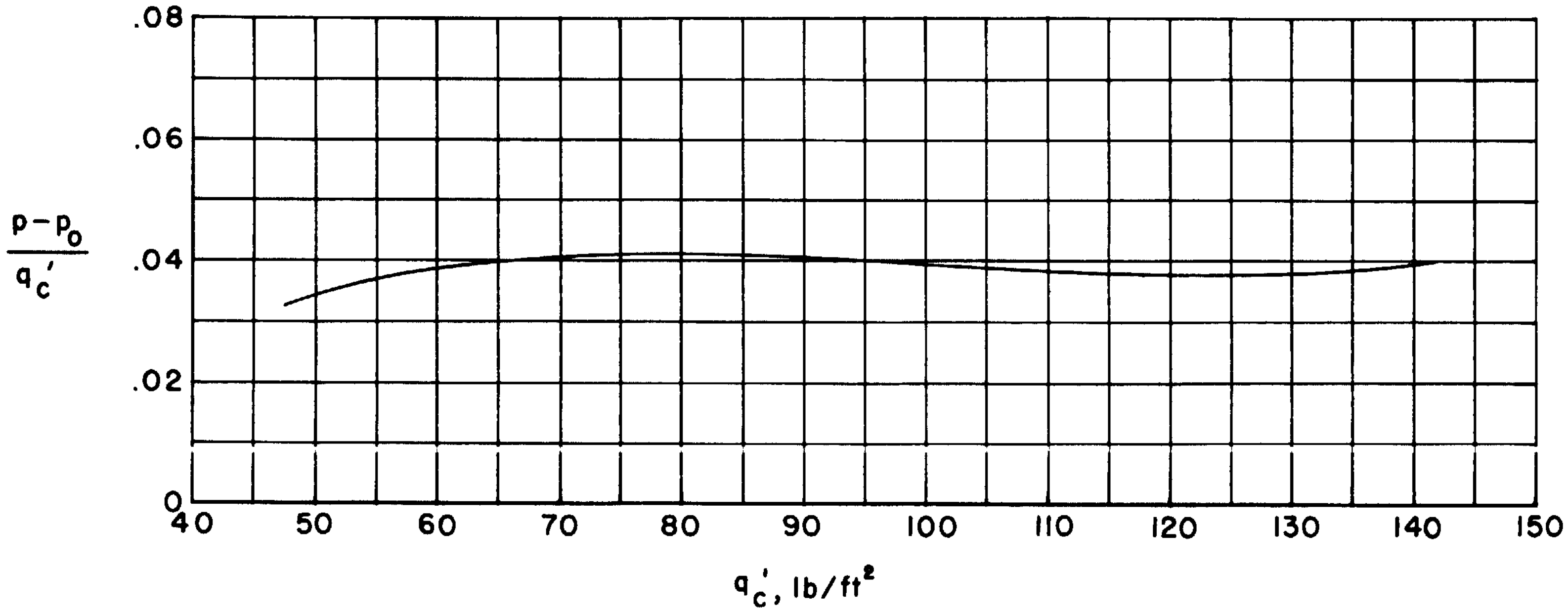


Figure 4.- Airspeed calibration curve for F4D-1 recording airspeed system.

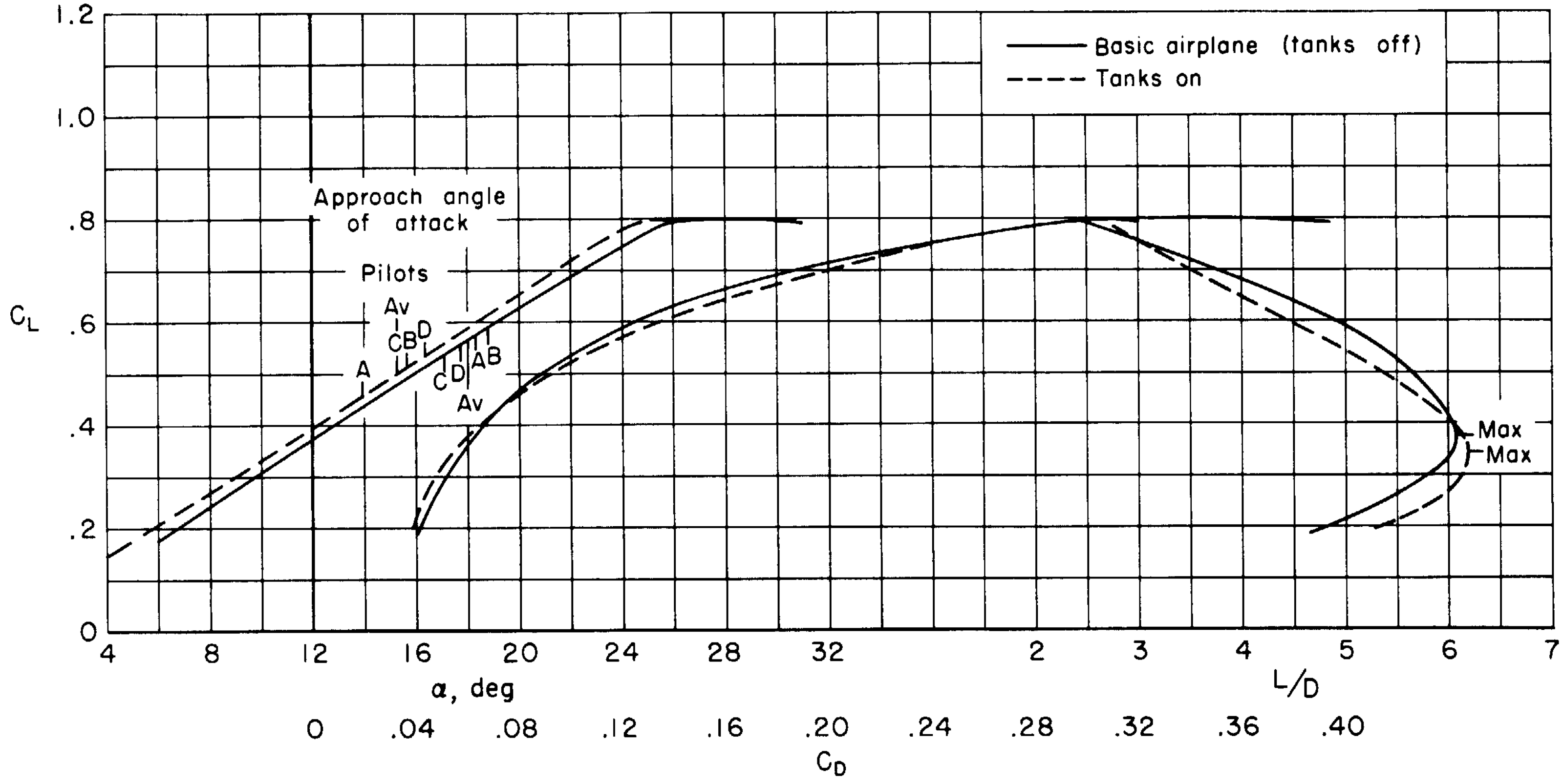


Figure 5.- Aerodynamic characteristics of the F4D-1 airplane.

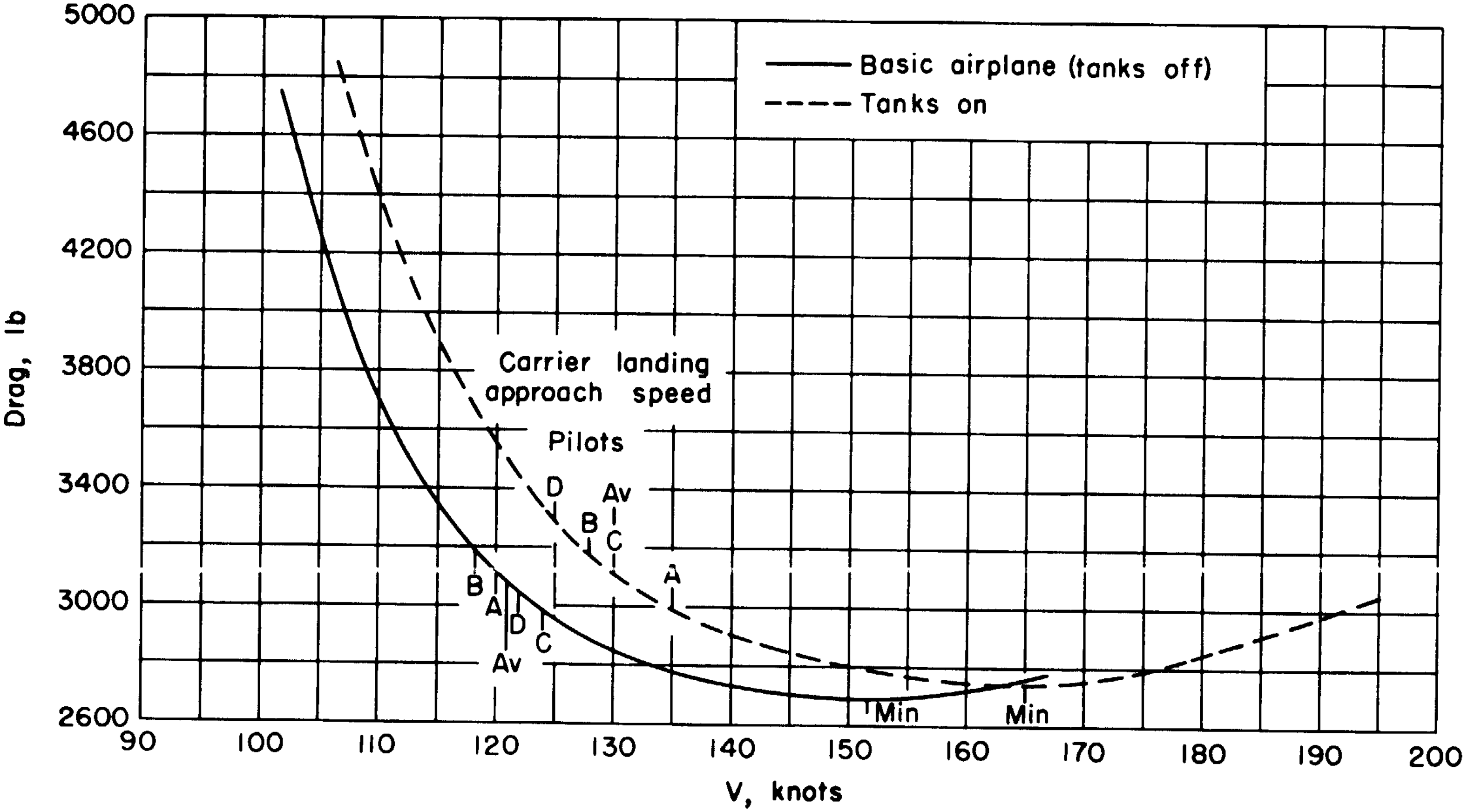


Figure 6.- Variations of drag with velocity for the F4D-1 airplane.

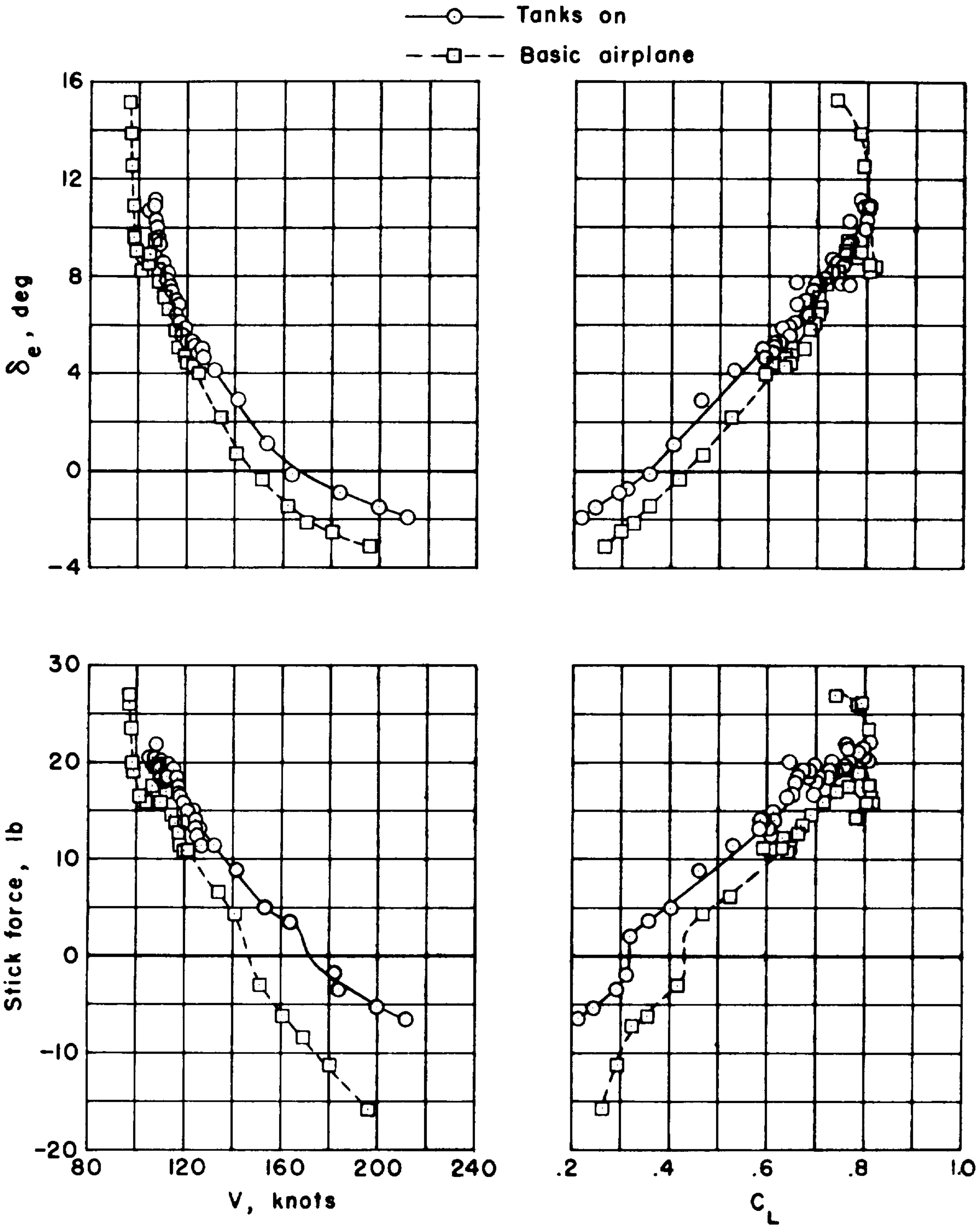


Figure 7.- Stick-force and elevator-angle variations for F4D-1 airplane; gross weight = 19,100 pounds center of gravity at 0.244 $\bar{c}$.

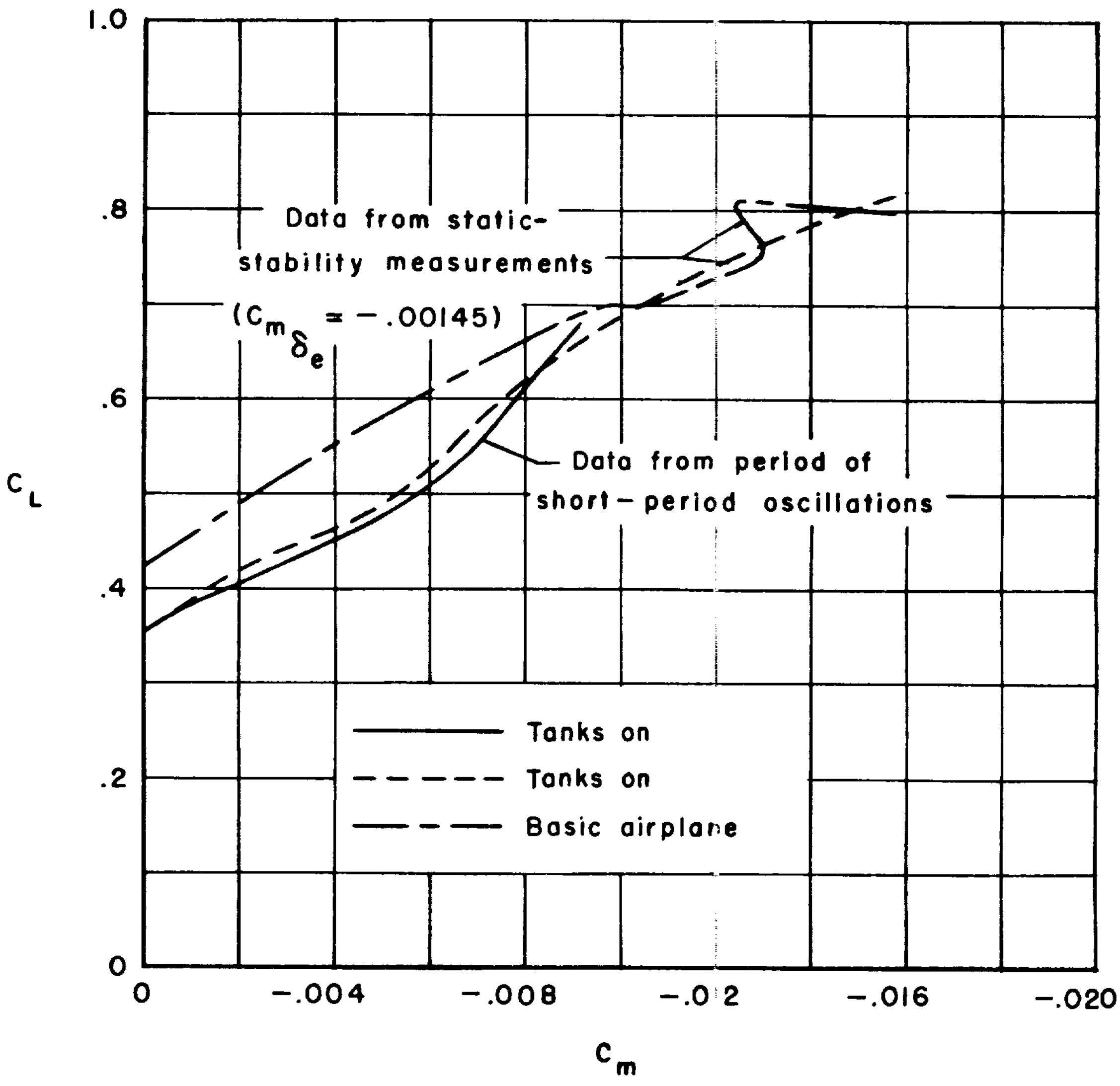


Figure 8.- Variation of C_m with C_L for F4D-1 airplane.

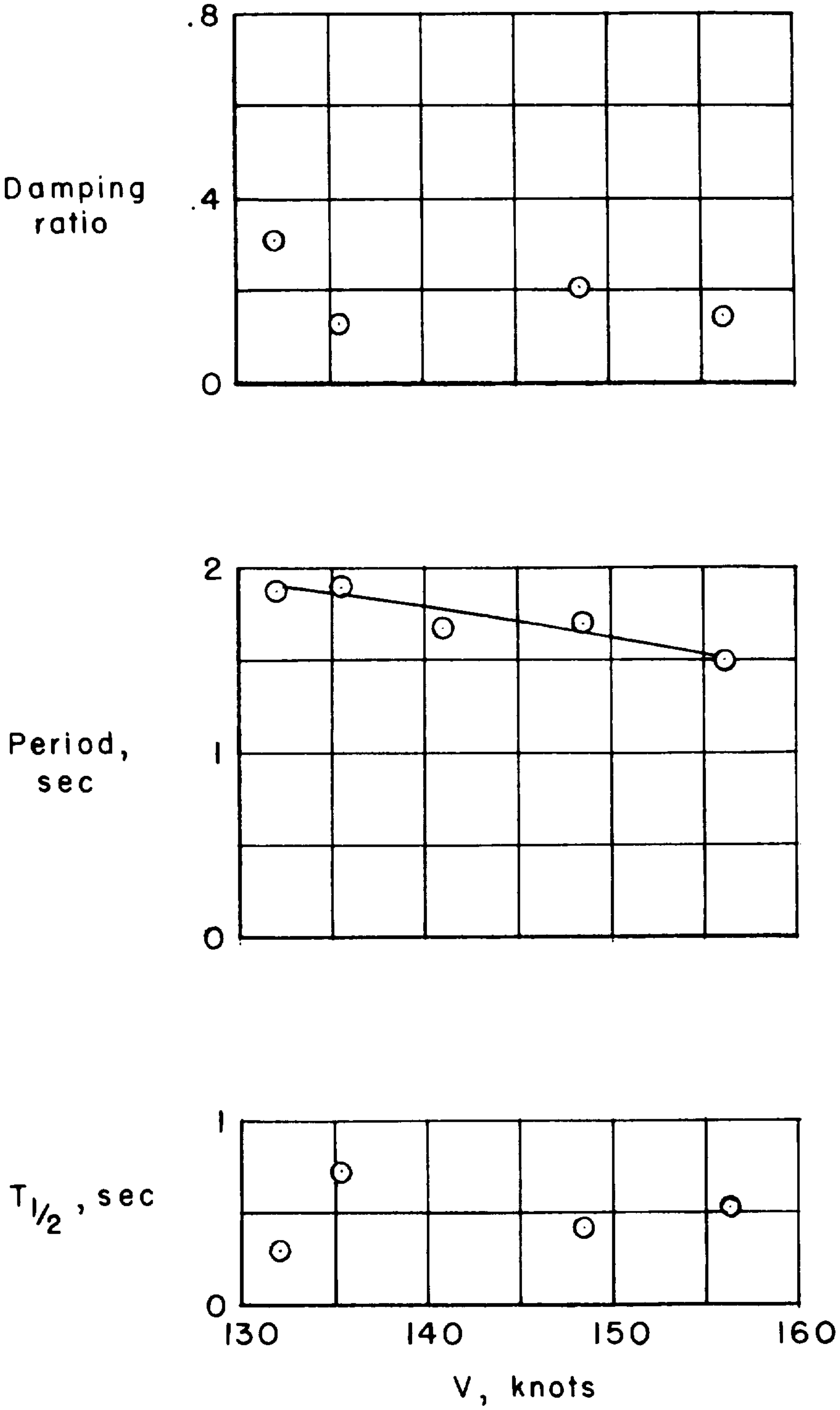


Figure 9.- Short-period dynamic longitudinal stability characteristics of F4D-1 airplane; tanks on.

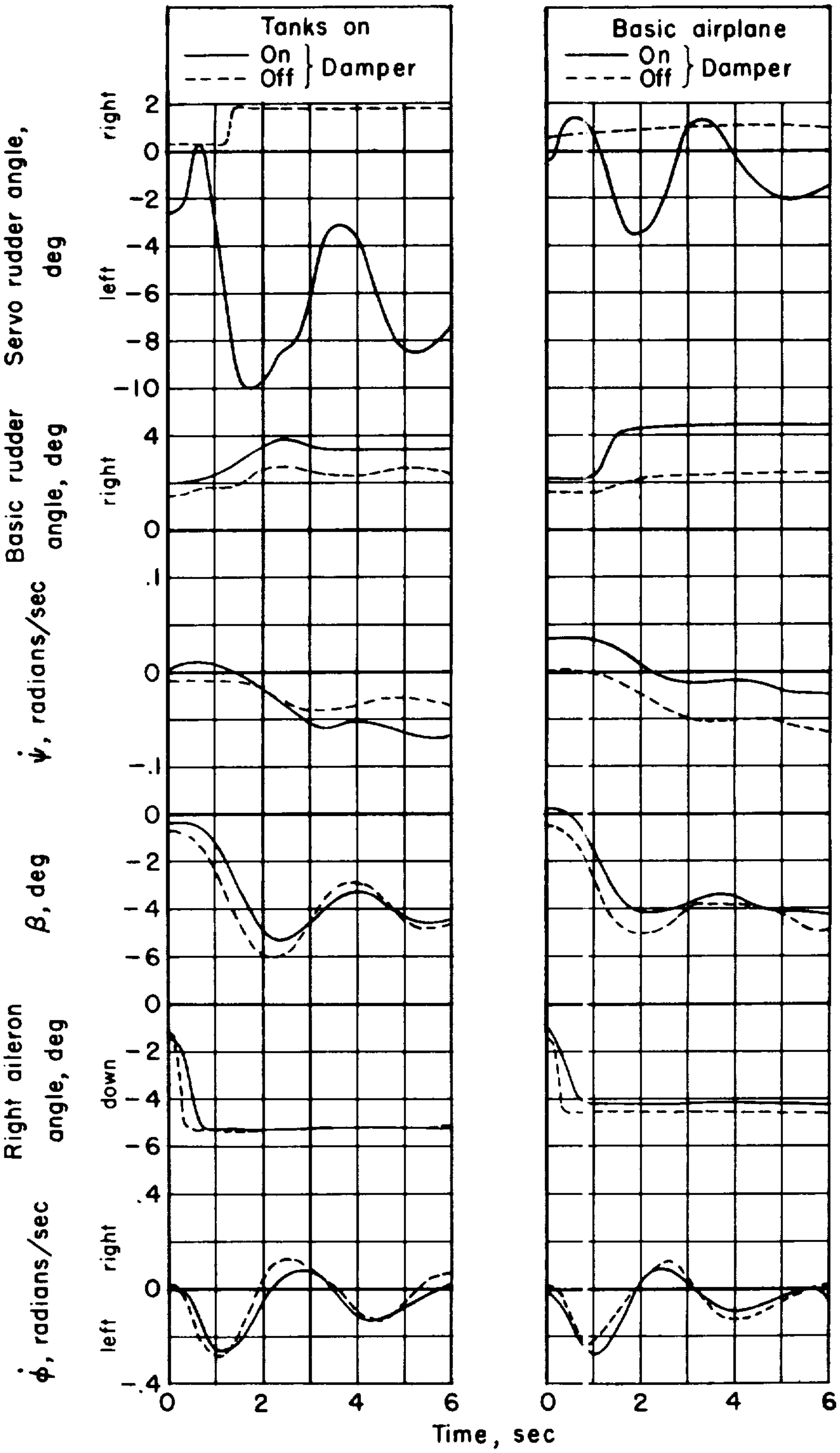


Figure 10.- Responses to abrupt aileron deflections for F4D-1 airplane; V = 125 knots. (Basic airplane, damper-on test was initiated from turn at 45° bank angle.)

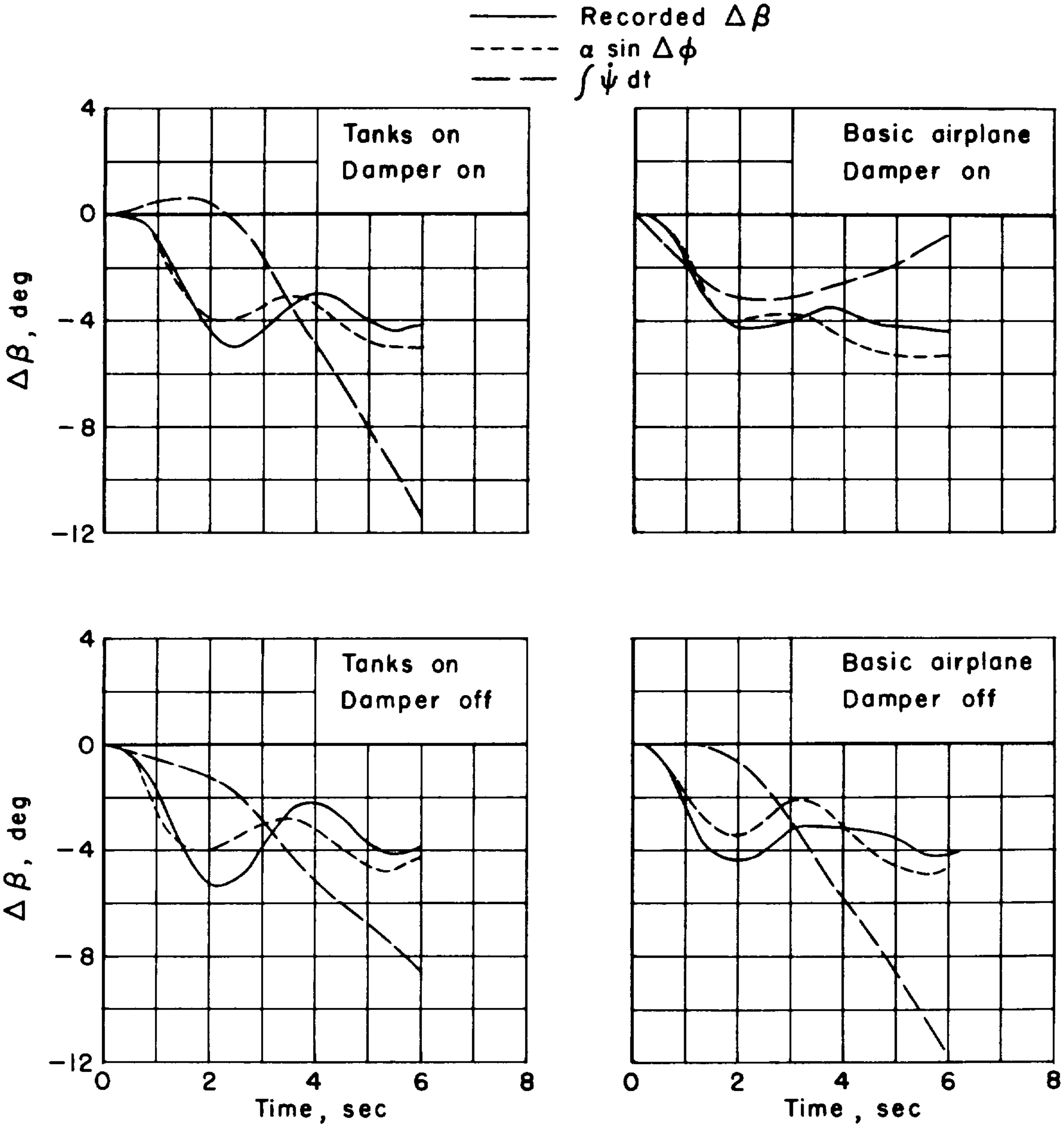
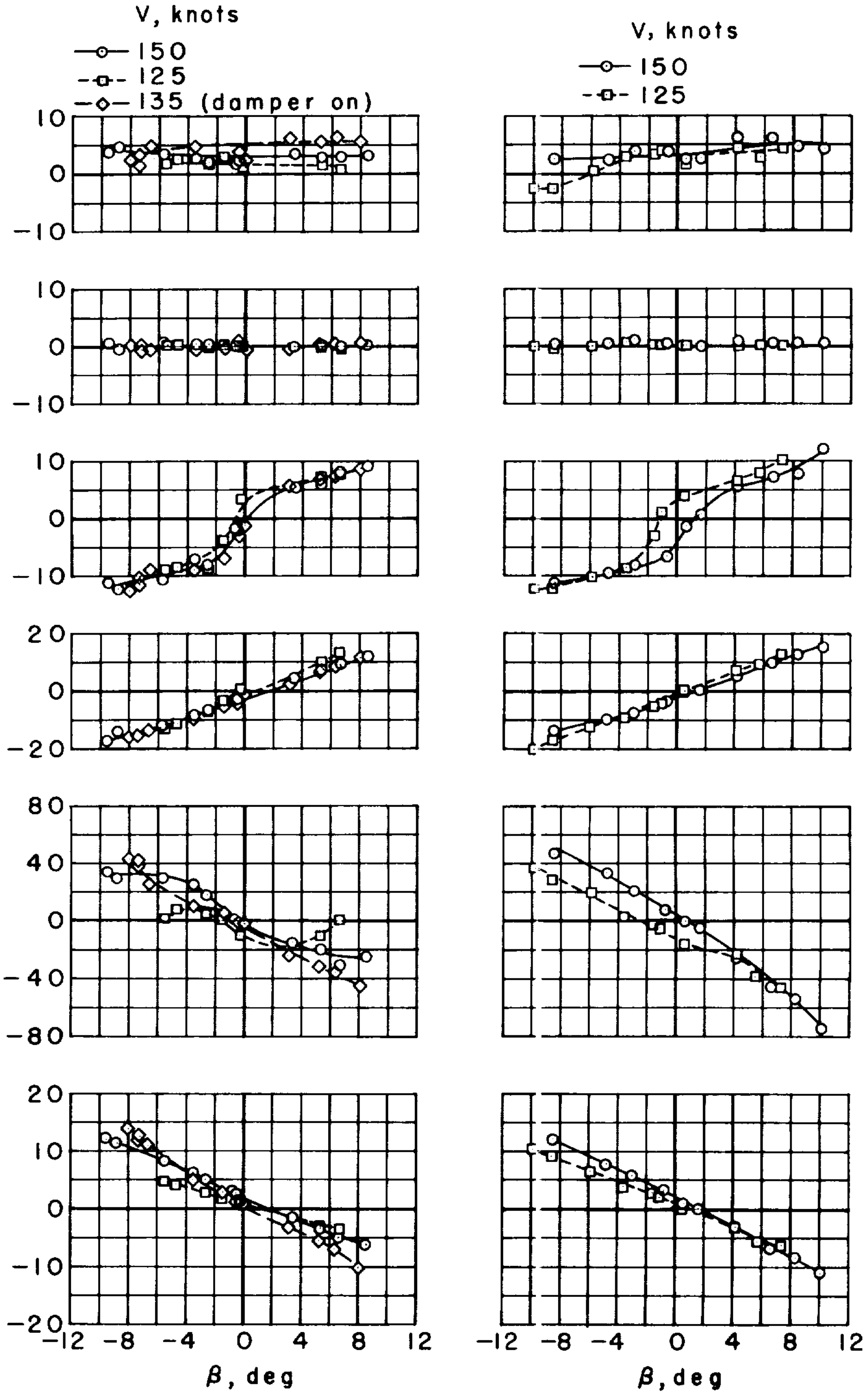


Figure 11.- Comparison of recorded sideslip angles with sideslip angles developed from rolling about inclined axis as determined in abrupt aileron rolls. (Basic airplane, damper-on test was initiated from turn at 45° bank angle.)



(a) Tanks on. (b) Basic airplane (tanks off).

Figure 12.- Steady sideslip characteristics of F4D-1 airplane; data obtained with yaw damper off except as noted.

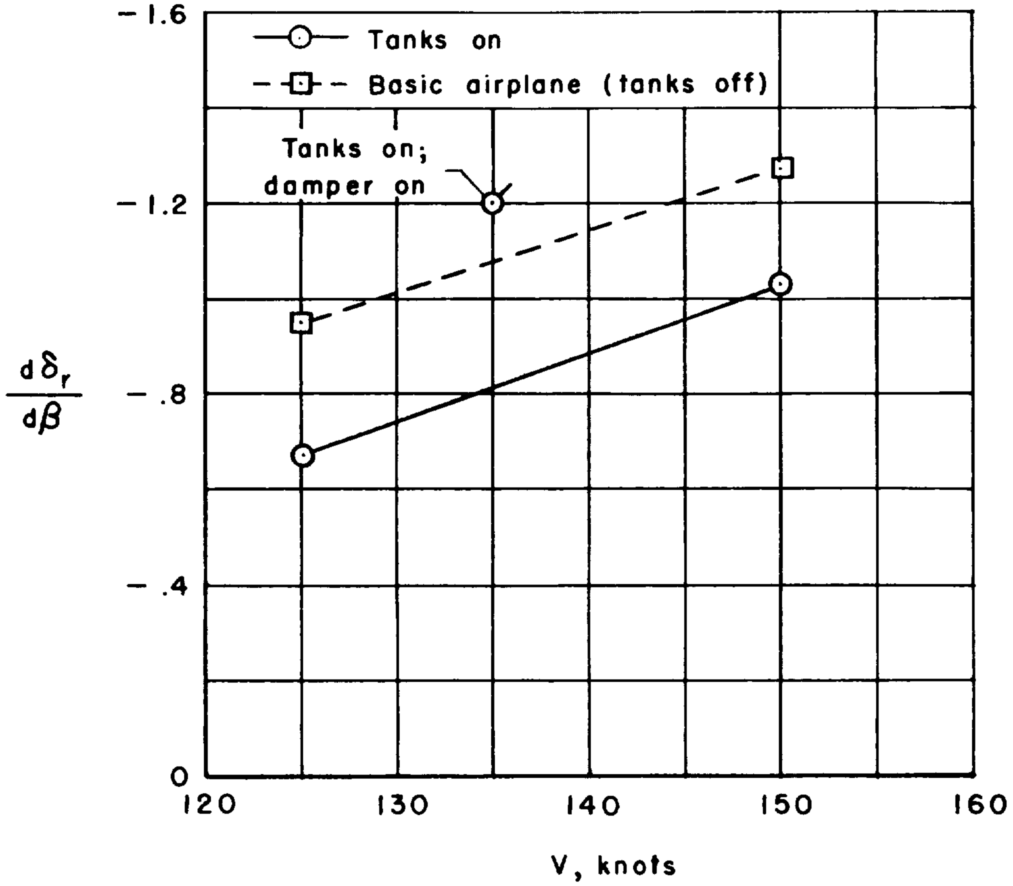


Figure 13.- Variation of directional stability parameter $d\delta_r/d\beta$ with airspeed; data obtained with yaw damper off except as noted.

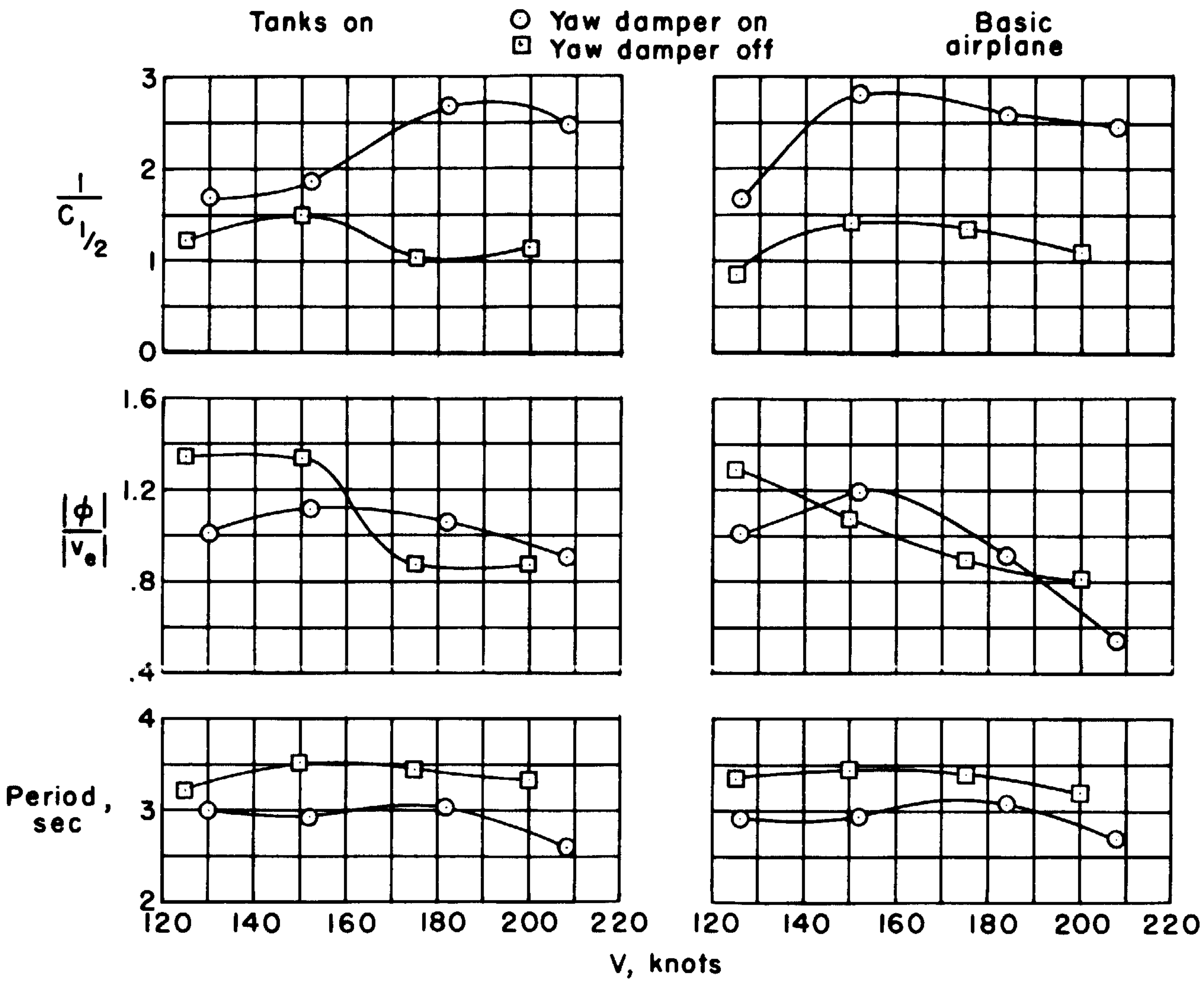


Figure 14.- Dynamic lateral stability characteristics of F4D-1 airplane.

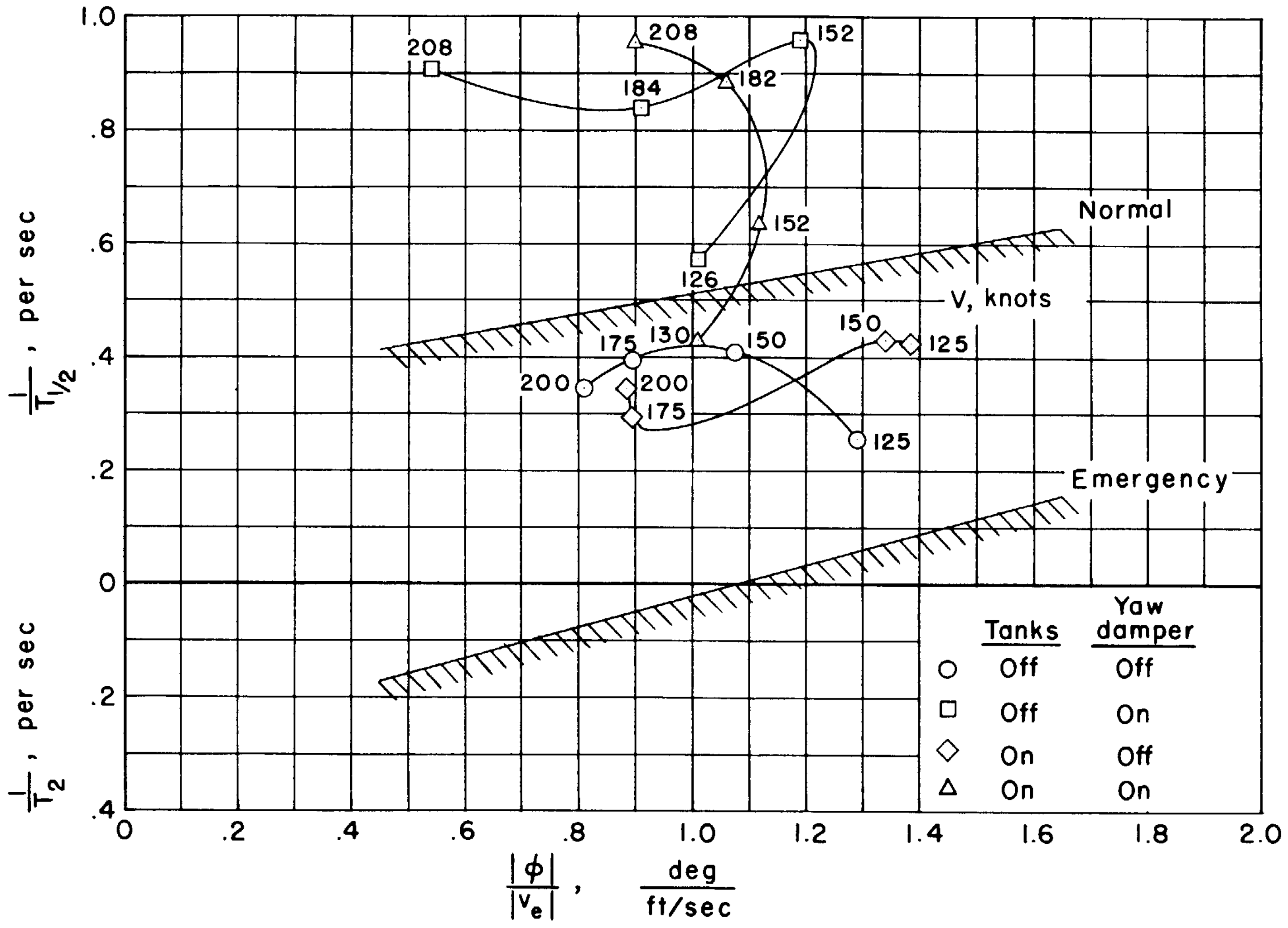


Figure 15.- Comparison of Dutch roll damping variations for F4D-1 with acceptable boundaries; data from reference 4.