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CALCULATION OF VERTICAL AND RAMP-ASSISTED TAKEOFFS FOR SUPERSONIC CRUISE FIGHTERS

Grace C. Liu

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

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AUTH: A/LIU, G. C.

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ABS: A procedure that allows rapid preliminary evaluations of the vertical, short, and normal takeoff performance of supersonic cruise aircraft concepts was developed into a numerical computer program. The program is used to determine the effects on takeoff performance of various parameters, such as thrust-weight ratio, wing loading, thrust vector angle, and flap setting. Ramp-assisted takeoffs for overloaded configurations typical of a ground-attack mission are included. The effects of wind on the takeoff performance are also considered.

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SUMMARY

A procedure that allows rapid preliminary evaluations of the vertical, short, and normal takeoff performance of supersonic cruise aircraft concepts has been developed into a numerical computer program. The program is used to determine the effects on takeoff performance of various parameters, such as thrust-weight ratio, wing loading, thrust vector angle, and flap setting. Ramp-assisted takeoffs for overloaded configurations typical of a ground-attack mission are included. The effects of wind on the takeoff performance are also considered.

Vertical takeoff causes negligible range penalty. Ramp-assisted takeoff provides substantial reduction in takeoff ground run, even with extreme overloads, if control power is available. Head winds improve the flight trajectory. Wing loading has a slight effect on takeoff performance, but high thrust-weight ratios combined with nozzle vectoring is the main factor for a successful vertical and short takeoff.

INTRODUCTION

Recent improvements in engine efficiency and thrust-weight ratio, together with improvement in material and aerodynamics lead to the possibility of sustained supersonic cruise fighters. Such fighters will inevitably have thrust-weight ratios much greater than 1. With such thrust-weight ratios, it is no longer necessary to be concerned with runway length. Provided that the configuration can be arranged such that the center of gravity, aerodynamic center, and nozzle centerlines closely coincide (such as the concept of ref. 1), short, vertical, or ramp-assisted takeoff are completely feasible.

The investigation of the low-speed flight of such configurations requires a simple rapid method of calculation which can be applied in the early design stages. Such a method is presented herein. This method uses simple point-mass assumptions. Moment trim is not included since the necessary moment information is not generally available for low-speed high-angle-of-attack conditions in the preliminary design.

This method has been applied to the configuration of reference 1 and several different types of takeoff and several different sets of conditions are considered. The results given indicate the effect of thrust-weight ratio, wing loading, initial thrust-vector angle, ramp geometry, and wind.

SYMBOLS

a	acceleration, ft/sec^2
D	drag, lbf
g	gravitational acceleration, ft/sec^2
h	height of the top edge of the ramp, ft
H	altitude, ft
L	lift, lbf
R	range, n. mi.
S	reference wing area, ft^2
t	time, sec
T	thrust, lbf
V	velocity, knots
V_W	wind velocity, positive for head wind, knots
W	weight of airplane, lbf
W_f	fuel weight, lbf
x	length of the ramp base, ft
α	angle of attack, deg
β	ramp angle, the angle between the base of the ramp and a tangent line at the end of the ramp, deg
θ	flight path angle, deg
$\dot{( )}$	total derivative with respect to time

ANALYSIS

Given the airplane flap and thrust vector angle settings and the angle of attack, the lift, drag, and thrust are established. The flight path angle, altitude, range, and weight are obtained by integrating the differential equations of motion for take-off.

The governing equations of motion for a point mass, with horizontal wind effect, are obtained by using the equations of references 2 and 3.

$$\dot{V} = g \left[\frac{T \cos\alpha - D}{W} - \sin\theta\right] \tag{1}$$

$$\dot{\theta} = \frac{g}{V} \left[\frac{T \sin\alpha + L}{W} - \cos\theta\right] \tag{2}$$

$$\dot{H} = V \sin\theta \tag{3}$$

$$\dot{R} = V \cos\theta - V_W \tag{4}$$

$$\dot{W} = -W_f \tag{5}$$

This system of ordinary differential equations of motion (eq. 1-5) is integrated by a Runge-Kutta scheme. The computational procedures are written as a computer program. Input and output variables, and their descriptions, are given in the Appendix. No optimization routines are included in the program.

CONCEPT DESCRIPTION

Baseline Configuration

The baseline configuration is fully described in reference 1. The aircraft has a thrust-weight ratio of 1.4, and a takeoff wing loading of 70 psf. The total length of the aircraft is about 66 feet. It has a takeoff gross weight of 42,750 pounds, including 4,560 pounds of weapons payload. The feature of the aircraft which provides good V/STOL potential is that the thrust line passes through the coincident aerodynamic center and center of gravity.

The mission profile consists of supersonic cruise, supersonic sustained turns, and supersonic return cruise as shown on figure 1.

Takeoff Procedure

Four different takeoff procedures are discussed here. These are normal takeoff, short takeoff, vertical takeoff, and ramp-assisted takeoff. Takeoff procedure includes the transition to normal cruise climb, where the thrust vector angle is zero, and the airplane has a small angle of attack. Maximum thrust is assumed for takeoff.

The airplane normal takeoff configuration is with flaps and thrust vector angle at zero degrees. The airplane accelerates from zero velocity until it reaches a rotational speed which is a function of T/W, W/S, and the aerodynamic characteristics. There it starts rotation by increasing angle of attack and nozzle and flap deflection. The airplane lifts off when the combined vertical components of the thrust and aerodynamic lift exceed the weight of the airplane. The airplane rotates to takeoff angle-of-attack, and remains in this configuration until it clears the obstacle. Whenever aerodynamic lift alone can support the weight of the airplane, transition starts with the nozzles gradually rotated back to zero. In the interim, whenever the pitch rate becomes greater than 1 deg/sec, angle of attack rotates to a small angle, and stays at this angle until the end of takeoff.

Short takeoff starts with large nozzle and flap deflections. Since the vertical component of thrust cannot support the weight of the airplane at the beginning of the takeoff, a short ground run is required. Whenever lift exceeds the weight of airplane, liftoff occurs, and the angle of attack starts to rotate to the takeoff value. The takeoff flight path is greatly affected by the combination of takeoff angle of attack and the nozzle deflection angle. The airplane maintains the same nozzle and flap deflections until it reaches the obstacle altitude; after that, the airplane will gradually reduce the nozzle deflections as it increases forward velocity. Transition to cruise-climb is done as for normal takeoff.

Vertical takeoff is only possible when the thrust-weight ratio of the airplane is greater than unity, and the vertical component of the thrust is in excess of the weight of the airplane. Vertical takeoff requires large enough nozzle deflections so that the airplane lifts off immediately. Liftoff velocity is zero; thus, a reaction control system is essential. The airplane maintains constant attitude until it passes the obstacle altitude. After achieving obstacle altitude, the airplane rotates in angle of attack so as to fly along the direction of flight path with the normal takeoff angle of attack, and it also decreases the nozzle deflections to increase the forward velocity. The means of changing the thrust vector angle and angle of attack for transition are the same as for a normal takeoff.

When the thrust-weight ratio of the airplane is less than one, a ramp-assisted takeoff can be used to achieve a short takeoff (refs. 4 to 7). Ramp-assisted takeoffs for overloads have been studied for this configuration. The surface of the ramp is assumed to be a circular arc (fig. 2). At the beginning of the ramp, the slope is zero, so the airplane has a horizontal entry to the ramp. The relationship between the radius and the height of ramp are

$$r = x \csc \beta \tag{6}$$

$$h = x \tan (\beta/2) \tag{7}$$

For ramp-assisted takeoffs, the airplane starts some distance ahead of the ramp. The thrust vector angle and flap deflection are set at zero to allow the greatest possible acceleration before the ramp is reached. The airplane lifts off at the end of the ramp. Lift-off velocity, flight path angle, available thrust, and thrust vector angle are the main factors determining the trajectory of the flight path. Rotation can start when entering the ramp or when leaving the ramp. The first case results in a lower lift-off velocity, while the second case requires an undesirably fast response of the pilot, and the flaps and nozzle. The procedures of rotation and transition are the same as normal takeoff.

Results and Discussion

For all of the results presented herein, maximum thrust is used and transition to cruise-climb is included. The flight paths appear distorted because of the different scales used for the horizontal and vertical axes. The tiny airplanes shown on the figures indicate the airplane attitude and the thrust vector angle setting.

Effect of Initial Thrust-Vector Angle on Takeoff for Baseline Configuration

When the thrust-weight ratio is greater than unity, vertical takeoff is possible. For the baseline configuration, with thrust-weight ratio of 1.4, and a weapon payload of 4,560 pounds, the takeoff performance is shown on figure 3. Flight paths and velocity profiles with different initial thrust-vector angles are shown on figures 3(a) and 3(b). The normal takeoff procedure is used for an initial thrust-vector angle of 0°, the short takeoff uses a 45-degree angle and vertical takeoff uses an 80-degree angle. Figure 3(c) summarizes the results. When the initial thrust-vector angle is over 50 degrees, the airplane lifts off immediately; however, the low airspeed at liftoff indicates a problem of aerodynamic control. A reaction control system is assumed to provide adequate control.

A mission program was run to determine the loss of range because of the vertical takeoff. The percentage change in mission radius is compared to the normal takeoff in figure 3(d). The reduction of mission radius for an 80-degree deflection takeoff is only 2 percent.

A different procedure for transition would affect the flight path and velocity profile. It is possible that other transition procedures could lead to better results since no optimization procedure is included in the present computer program.

Effect of Ramp Geometry on Takeoff for Overloaded Configuration

The effect of ramp geometry on takeoff is shown in figure 4 for the airplane overloaded with extra weapon payload such that the gross weight of the airplane is 60,000 pounds. The thrust-weight ratio of airplane is close to unity. In order to have a successful takeoff with a 100-foot ramp, that ramp is placed 150 feet ahead of the initial airplane position. The flight paths and velocity profiles for ramps with different ramp angles are shown here. Since all of ramps are 100 feet long, the lift-off distance is 250 feet for all these ramp-assisted takeoffs. This distance may be compared to over 1000 feet for a normal takeoff. The distance required to clear the 50-foot obstacle is only 312 feet for a 25-degree ramp angle, which may be compared to 2,000 feet for a normal takeoff. The reduction of mission radius for the 25-degree ramp is only 4.2 percent. Ramp-assisted takeoff results in a major improvement in takeoff performance, provided that a reaction control system is available.

Effect of Wind on Takeoff

Head winds can have positive effect on takeoff performance by providing a higher relative airspeed. The effect of wind on the takeoff is shown in figure 5, for an airplane loaded with a weapon payload of 41,810 pounds, and a gross weight of 80,000 pounds. The payload itself is greater than the weight of the airplane and fuel together. The thrust-weight ratio of the airplane is reduced to about 0.75. A short takeoff distance is achievable for this configuration by using an 100-foot ramp sitting 250 feet ahead of the initial airplane position. Head wind causes a more desirable flight path and greater airspeed for aerodynamic control. For the no-wind case, the flight path has an undesirable altitude loss which is not present for reasonable head winds. Only small reductions in mission radius are found (fig. 5(d)).

Effect of Thrust-Weight Ratio on Normal Takeoff

The normal takeoff performance for different thrust-weight ratios are shown on figure 6. The flight procedure starts with quick acceleration by having no flap and thrust vectoring until rotational speed (which is a function of T/W, W/S, angle of attack, and thrust vector angle) is reached. Then the airplane instantaneously deflects the flap to 30-degrees and deflects the thrust vector angle to 30 degrees in one-half second. Angle of attack rotates at 4 degrees per second to 8 degrees. When the lift exceeds the weight, the airplane lifts off. The airplane starts transition when the aerodynamic lift alone can support the weight of the airplane. Transition includes rotating the flaps and thrust vector to zero and the angle of attack to 2 degrees. The flight paths are shown on figure 6(a), while figure 6(b) is a summary showing the distance and velocity to lift-off and to clear a 50-foot obstacle. Thrust-weight ratio has a major effect on takeoff performance. Takeoff distance for T/W = 0.5 is over 2,000 feet, whereas it is less than 450 feet for T/W = 1.4.

Effect of Wing Loading on Vertical Takeoff

The effect of wing loading has been studied for the baseline configuration by varying the wing size while keeping thrust-weight ratio and gross weight constant. The thrust-weight ratio is 1.4, and the vertical takeoff is performed with a 60-degree initial vector angle setting. The flight paths, times, and velocities are shown on figures 7(a) to 7(c). The distance and velocity to clear a 50-foot obstacle are shown on figure 7(d). Wing loading has little affect on takeoff performance.

CONCLUDING REMARKS

A computer program that allows rapid, preliminary, evaluations of the vertical, short, and normal takeoff performance of supersonic cruise aircraft concepts has been developed. The program is used to determine the effects on takeoff performance of various parameters, such as thrust-weight ratio, wing loading, thrust vector angle, and flap setting. Ramp-assisted takeoffs for overloaded configurations are included. The effect of wind on the takeoff performance has also been considered.

The program requires the description of the configuration in terms of thrust-weight ratio, wing loading, gross weight, and ground run angle of attack. The aerodynamic data, engine data, and flight procedures are also required. Results of the program are expressed as flight history data for takeoff.

The program has been used to evaluate the takeoff performance of a high-performance, supersonic cruise fighter. The results indicate thrust-weight ratios combined with nozzle vectoring has a major effect for vertical and short takeoffs. There is only a negligible range penalty for such takeoffs. Wing loading has only a slight effect on takeoff performance. Ramp-assisted takeoffs provide substantial reduction in takeoff ground run and allow major increases in payload. Head winds have a positive effect on takeoff performance.

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APPENDIX

INPUT AND OUTPUT OF THE PROGRAM

Input Definitions

The program is coded in FORTRAN Extended (ref. 8). The inputs are in three parts. TAPE5 contains information that relates to the airplane configuration and aerodynamics. TAPE55 is the engine data input. Interactive input through a terminal relates to the flight procedure. Input variables are listed by their means of input. The subsequent listings provide for each variable its definition and the units to be used. Default values, where they exist, are indicated in parenthesis. The parenthesis beside the variables define arrays and their maximum size.

Input Variables on TAPE5

The inputs are divided into two parts. The first part is airplane configuration input through a NAMELIST called COND, the second part is the aerodynamic input through the NAMELIST AIN. The variables in the NAMELIST may be listed in any order.

$COND	Airplane configuration inputs
ALFDOT	Airplane rotational speed during takeoff, deg/sec (2.)
DTEMP	Standard day temperature increments, deg C (0.)
GALPH	Ground run angle of attack, deg (-2.)
HMAX	Maximum altitude for takeoff calculation, ft (400.)
HNOGE	Altitude for disappearance of ground effect, ft (0.)
HSTART	Starting altitude for takeoff calculation, ft (0.)
NENR	The number of baseline engines
OBS	Takeoff obstacle altitude, ft (50.)
TDOT	Rate change of thrust vector angle, deg/sec (60.)
TOW	Thrust-weight ratio of the airplane
TOWREF	The installed sea level thrust to airplane gross weight ratio for the input engine and baseline airplane combination
WG	Gross weight of the airplane, lbf
WGREF	Gross weight of the baseline airplane used in determining TOWREF, lbf

WGSTAR	Takeoff gross weight, lbf
WOS	Wing loading of the airplane, lbf/ft^2
$AIN	Aerodynamic inputs for the aircraft
CDGRT(15)	Array of landing gear drag coefficient increments
CLGRT(15)	Array of landing gear lift coefficient for CDGRT
DCDLG	Landing gear drag increment
DELCD	Increment in total drag coefficient
NFD	Number of flap deflections (maximum of 4)
NLGD	Number of terms in CDGRT and CLGRT tables (15 max)
NTOG	Number of terms in TALPTOG, TCDTOG, TCLTOG arrays (15 max)
NTOP	Number of terms in TALPHTO, TCDTO, TCLTO arrays (15 max)
REFA1	Reference area, ft^2
REFB1	Reference span, ft
TALPHTO(15,4)	Array of angles of attack for TCDTO and TCLTO
TALPTOG(15,4)	Array of in-ground angle of attack for TCDTOG and TCLTOG
TCDTO(15,4)	Array of out-of-ground effect drag coefficients
TCDTOG(15,4)	Array of in-ground effect drag coefficients
TCLTO(15,4)	Array of out-of-ground effect lift coefficients
TCLTOG(15,4)	Array of in-ground effect lift coefficients
TFSET(4)	Array of flap deflections

Input Variables on TAPE55

The TAPE55 input is comprised of two groups of information that contain the baseline engine characteristics. The first part provides full power characteristics, and the second part contains part power values. The input format is the same as reference 9. The full power input contains the Mach number, altitude, gross thrust, ram drag, and fuel flow. The arrangement on each line is as follows.

Column	Description
1-5	Mach number
6-15	altitude, ft
21-30	gross thrust, lbf
31-40	ram drag, lbf
41-50	fuel flow, lbf/hr

Inputs are stacked by increasing altitude (at constant Mach number), and then by increasing Mach number. A maximum of 15 values for both altitude and Mach number is allowed. At least two altitudes at each Mach number are required. For each Mach number-altitude combination, the program expects to read two lines. The first of these contains nonaugmented power values; the second contains augmented values. If the information for one of these is not available, then the available one must be entered in duplicate at each Mach number-altitude combination. The end of the maximum power information is indicated by two successive lines, each containing the characters 9. in columns 1 and 2.

The information for partial power contains the same variables, and is input in the same format, as the full power values. A maximum of 15 partial-power settings and a maximum of 10 Mach numbers are allowed. In contrast to the full power input, the partial power information must contain only one line for each part-power Mach number combination. The last line of this group completes the engine input requirements and the end is indicated with characters 9. located in columns 1 and 2.

Interactive Input Variables

All the variables are related to flight procedures are inputted interactively, and their descriptions are listed below. The default numbers are in the parentheses. The program has the capability to run several cases during one run by input index J, number of cases NP, and values which follow. Four different flight procedures are included: vertical takeoff, short takeoff, ramp-assisted takeoff, and normal takeoff. They are controlled by proper inputs of IVTOL, ISTOL, and IRAMP. Only one can be picked by having value 1 as input; when they are all zero, a normal takeoff is assumed.

ALPHTO	Takeoff angle of attack, deg (8.)
ARRAY(10)	Array for multiple runs
CHKH	Desired altitude at which the data will be recorded on TAPE12 for later comparsion with other cases.
CHKM	Desired Mach number at which the data will be recorded on TAPE12 for comparison with other cases.
DELFIN	Flap deflection after obstacle, deg (30.)
DELFST	Flap deflection at start of takeoff, deg (0.)
HALROT	Altitude for alpha rotation (only if ISTOL=1 or IVTOL=1)
IRAMP	Index for ramp-assisted takeoff (0) =1 ramp =0 no ramp
ISTOL	Index for short takeoff (0) =1 short takeoff =0 not short takeoff

IVTOL	Index for vertical takeoff (0) =1 vertical takeoff =0 not vertical takeoff
ISEGROT	Flight segment for rotation (only if IRAMP=1) (2) =2 starting rotation when airplane reaches ramp =3 starting rotation when airplane leaves ramp
J	Index for looping (0) =1 ramp length =2 ramp angle =3 ramp location from the airplane =4 thrust vector angle and flap deflection after obstacle =5 thrust vector angle and flap deflection at starting =6 takeoff angle of attack (ALPHTO) =7 wing loading with constant gross weight and thrust =8 wing loading with constant wing area and thrust to weight ratio =9 thrust to weight ratio with constant gross weight and wing loading =10 thrust to weight ratio with constant thrust and wing area =11 wind velocity
NP	Number of cases to run (only if J≠0) (1) (maximum of 10)
RAMPL	Ramp length, ft (only if IRAMP=1) (0.)
RAMPS	Ramp angle, deg (only if IRAMP=1) (0.)
RAMPOS	Distance of ramp ahead of airplane, ft (only if IRAMP=1) (0.)
TDFLIN	Thrust vector angle after OBS, deg (30.)
TDFLST	Thrust vector angle at start of takeoff, deg (0.)
TRSDOT	Rate of change of thrust vector angle for transition, deg/sec (10.)
VWK	Wind velocity (head wind is positive), knots (0.)

Output Descriptions

The outputs from the takeoff program have three parts. TAPE6 contains flight history data which is output to the screen for viewing, TAPE10 is the output which includes the time history of the flight data for plotting, and TAPE12 is the output tape which contains summary results for comparing with other cases. The names for variables in the output are listed on the tape; their descriptions are listed here.

Variables on TAPE6 in Order of Output

R	Range, ft
H	Altitude, ft

T	Time, sec
VK	Velocity, knots
FPA	Flight path angle, deg
AL	Angle of attack, deg
DEFL	Flap deflection angle, deg
TDFL	Thrust vector angle, deg
ISEG	Flight segment
M	Mach number
W	Weight of airplane, lbf
VW	Head wind velocity, knots

Variables on Tape10 in the Order of Output

IRUN	Index for case number, maximum is NP
R	Range, ft
H	Altitude, ft
T	Time, sec
VK	Velocity of the airplane, knots
FPA	Flight path angle, deg
AG	Load factor, a/g
W	Weight of airplane, lbf
ALPHA	Airplane angle of attack, deg
TOW	Thrust-weight ratio
WOS	Wing loading, lbf/ft^2
WG	Airplane gross weight, lbf
DEFL	Flap deflection angle, deg
TDFL	Thrust vector angle, deg
THR	Thrust, lbf
ZL	Lift, lbf

DRAG	Drag, lbf
ZM	Mach number
WFB	Fuel burned, lbf
SFC	Specific fuel consumption, lbf/lbf-hr
VWK	Wind velocity, knots

Variables on Tape12

There are 67 variables output for each case. The first integer is always 1; the remaining 66 variables are summary results. They are arranged in matrix form, eight different flight parameters (column) are recorded at seven different events (row). The last 10 variables are related to the flight conditions and airplane configuration that might vary with J. The list of eight parameters are: range, altitude, time, velocity, flight path angle, angle of attack, Mach number and fuel burned. The list of seven events are: liftoff, obstacle, transition, angle-of-attack rotation for transition, altitude check point (input by CHKH), Mach number check point (input by CHKM), and takeoff termination point (input by HMAX). The remaining 10 variables are: ramp length, ramp angle, distance between the airplane and ramp, thrust-weight ratio at beginning of takeoff, wing loading, thrust-vector angle and flap deflection after obstacle, thrust vector angle and flap deflection at beginning of takeoff, takeoff angle of attack, and wind velocity (head wind is positive).

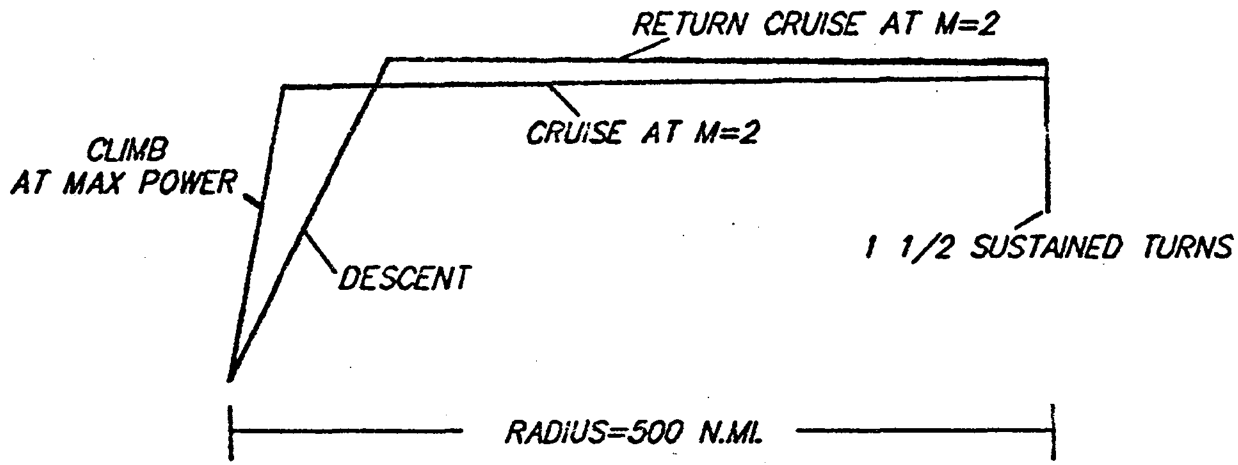


Figure 1.- Mission profile of the supersonic cruise fighter concept.

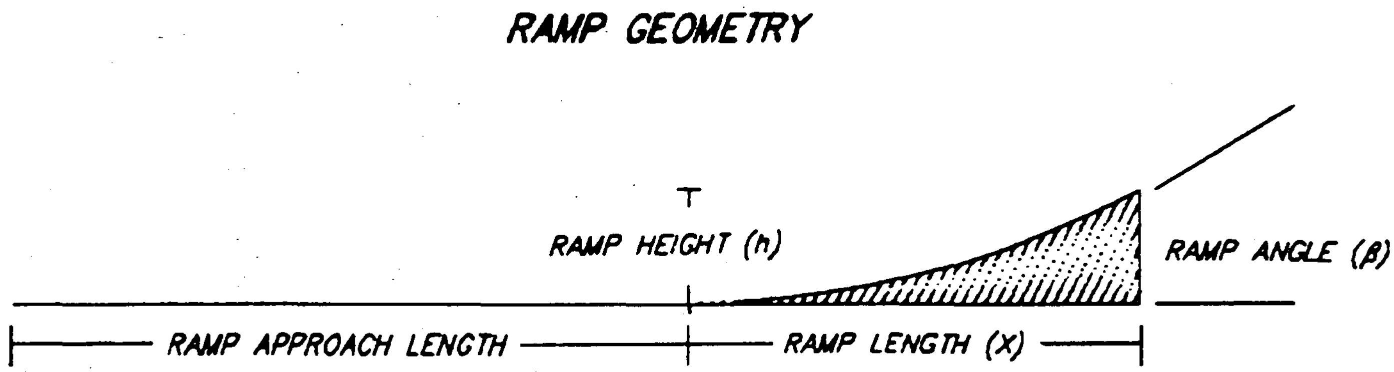
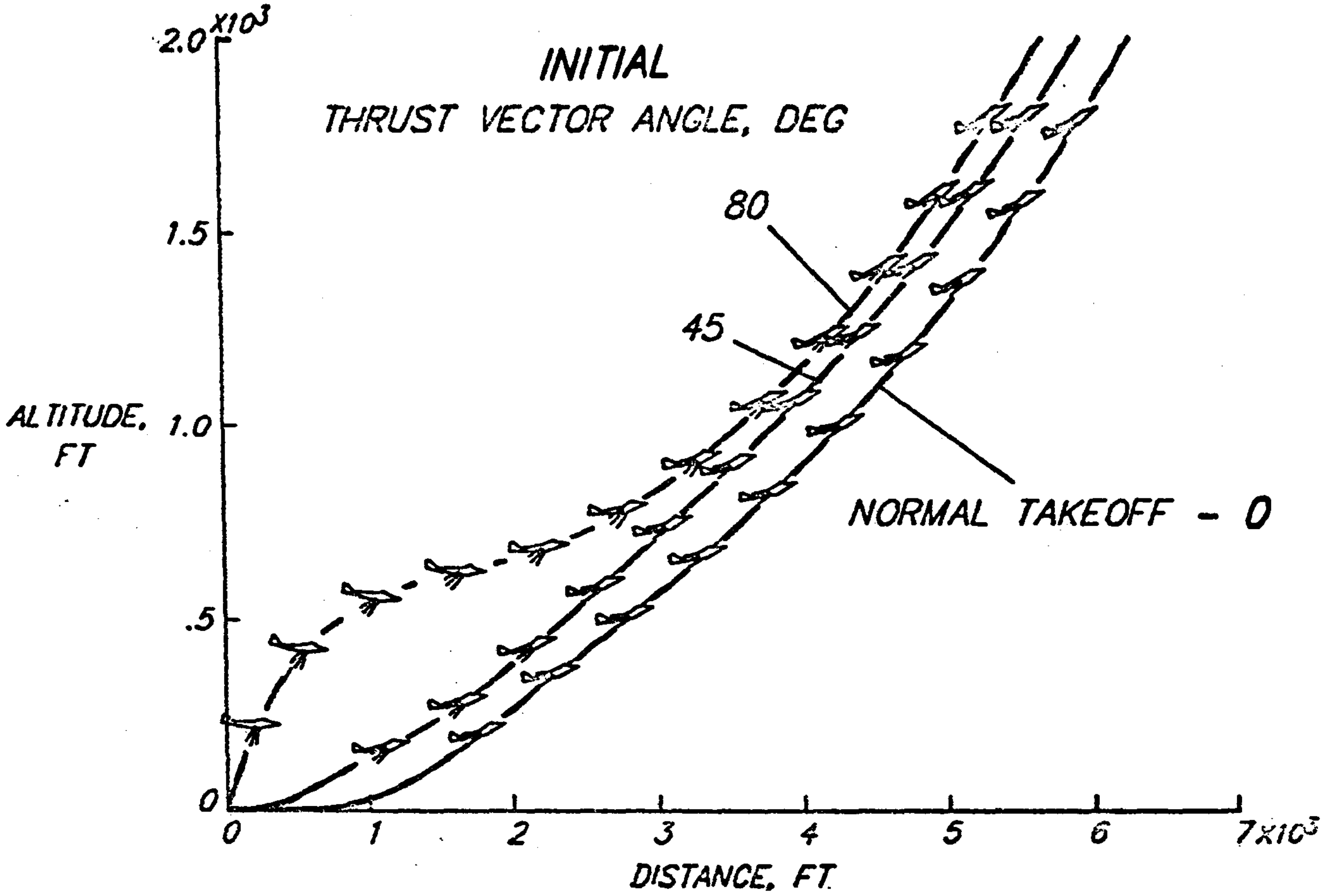
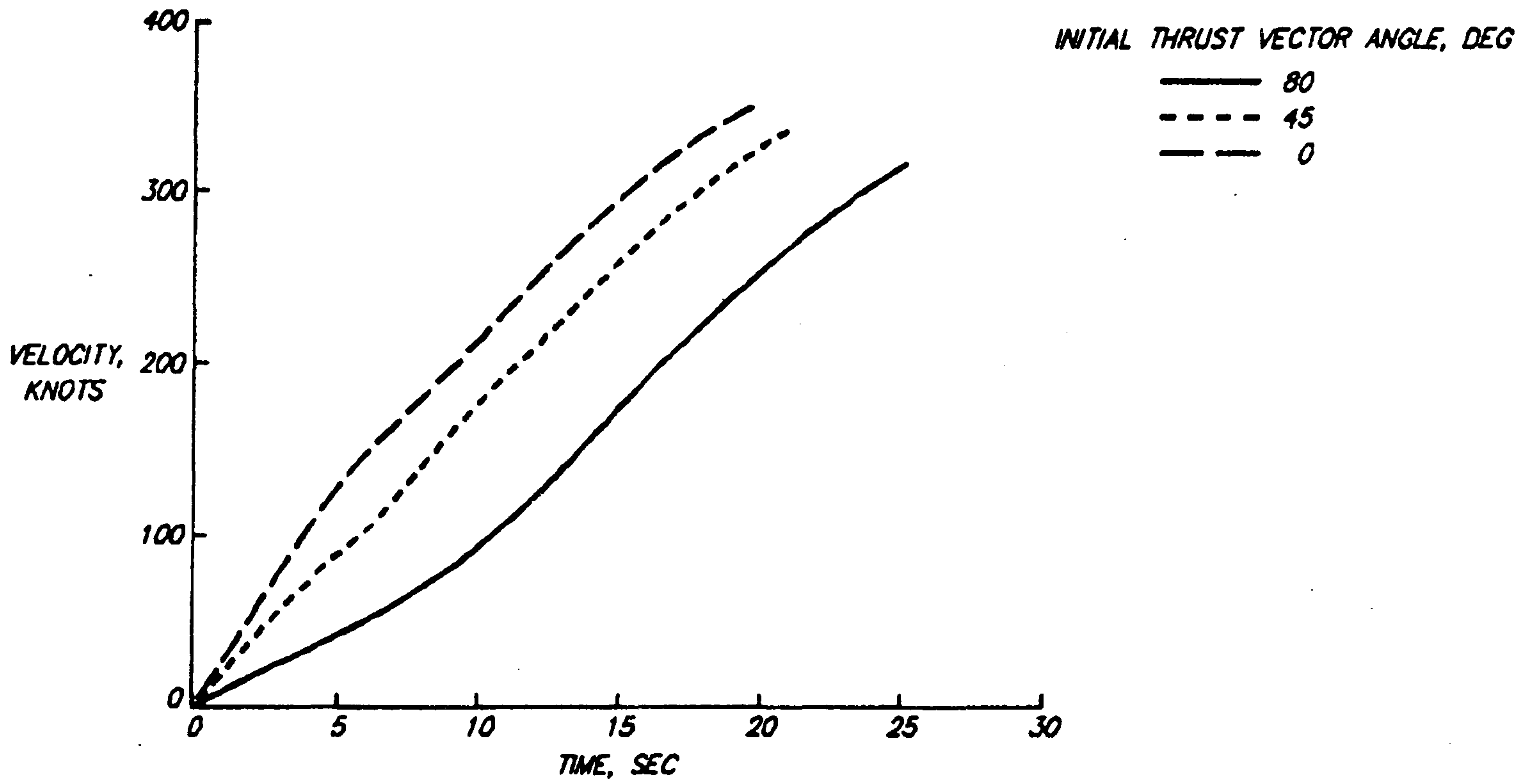


Figure 2.- Definition of the ramp geometry.



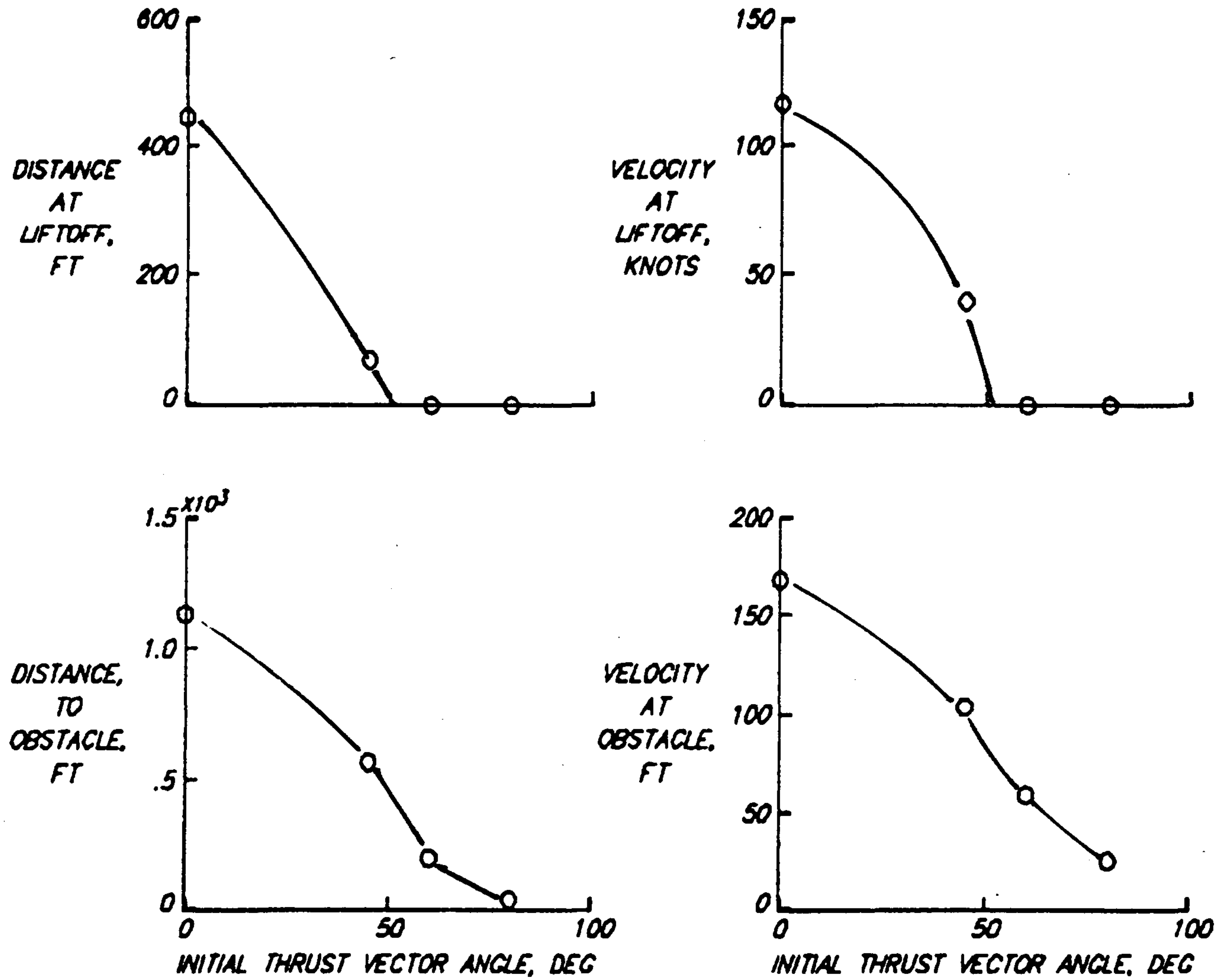
(a) Flight paths.

Figure 3.- The effect of initial thrust vector angle on takeoff for baseline configuration.



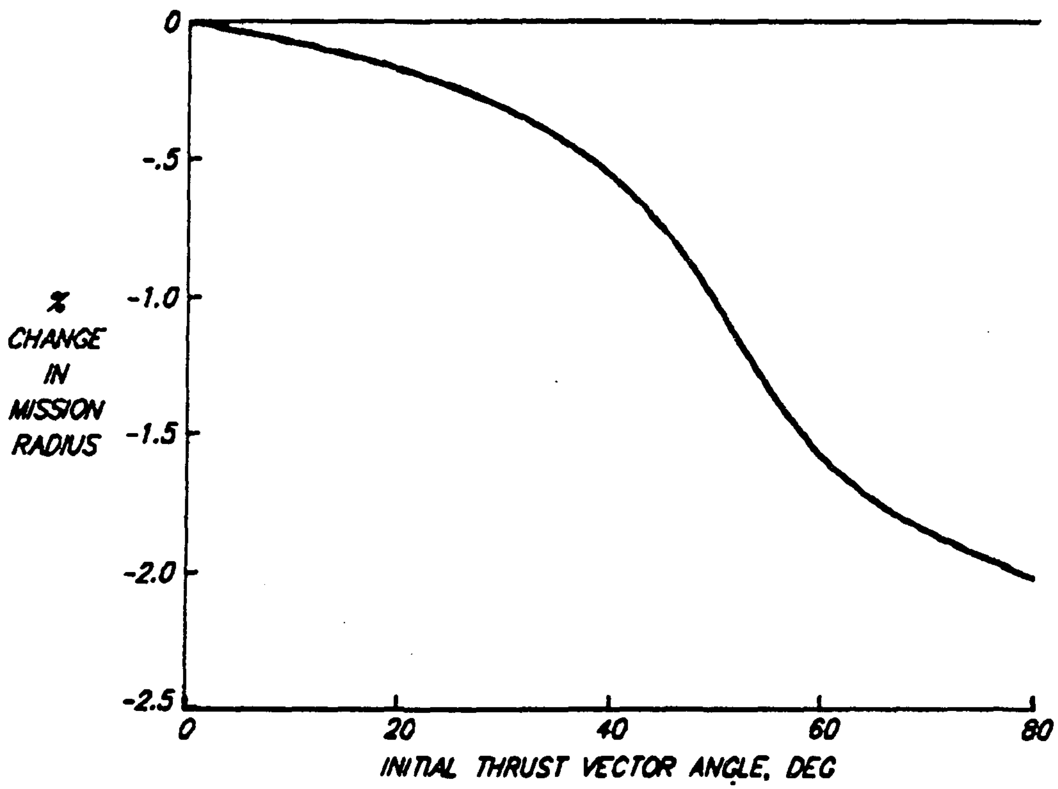
(b) Velocity profiles.

Figure 3.- Continued.



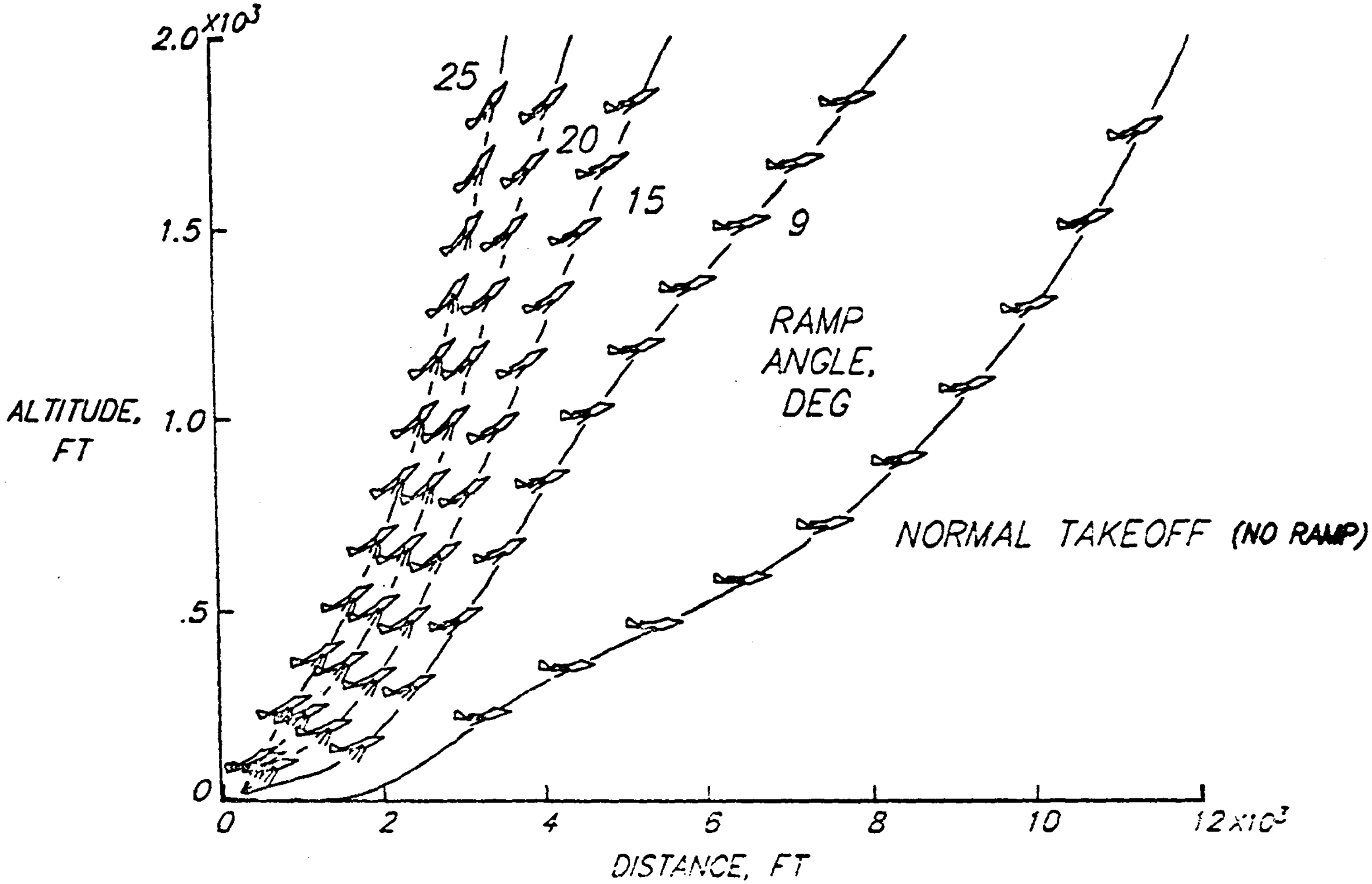
(c) Summary results.

Figure 3.- Continued.



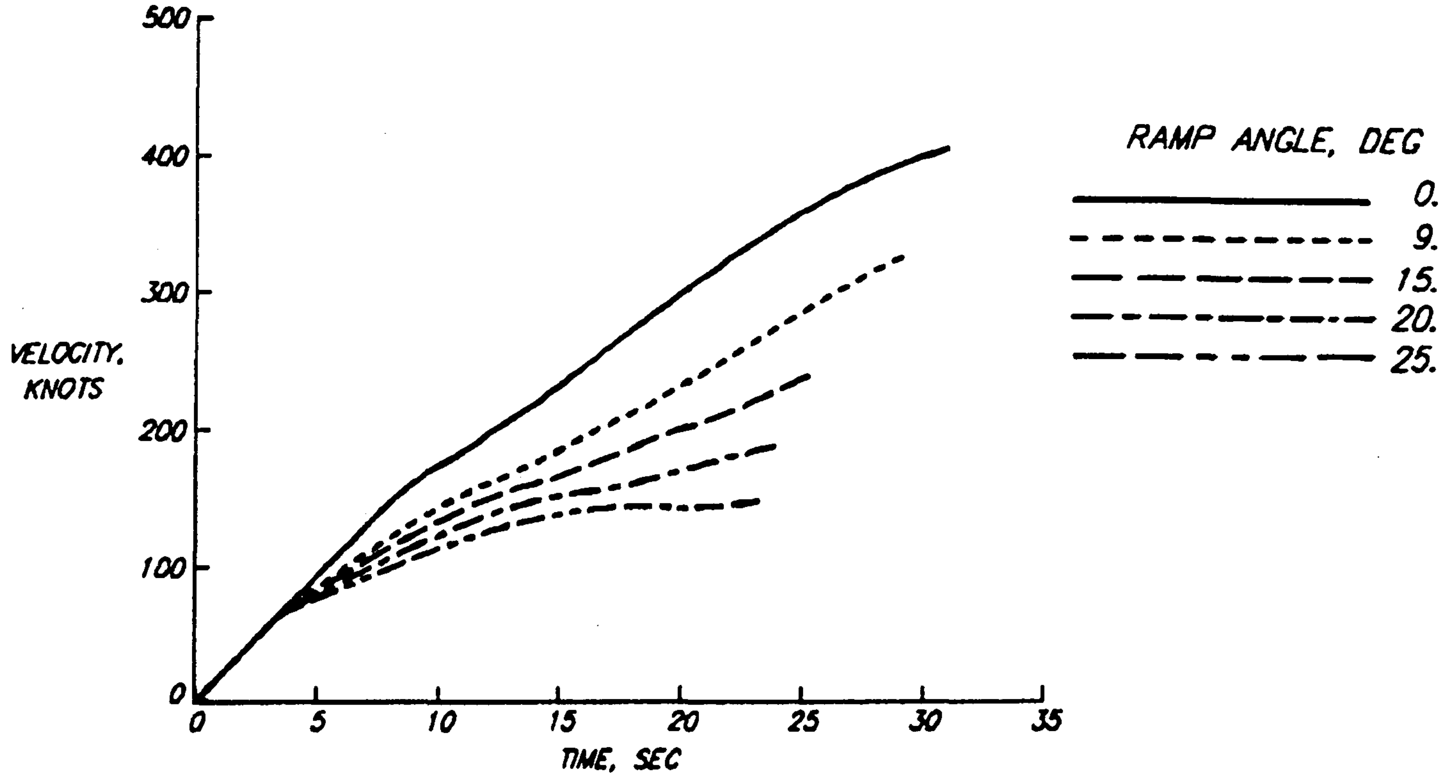
(d) Percent change in mission radius.

Figure 3.- Concluded.



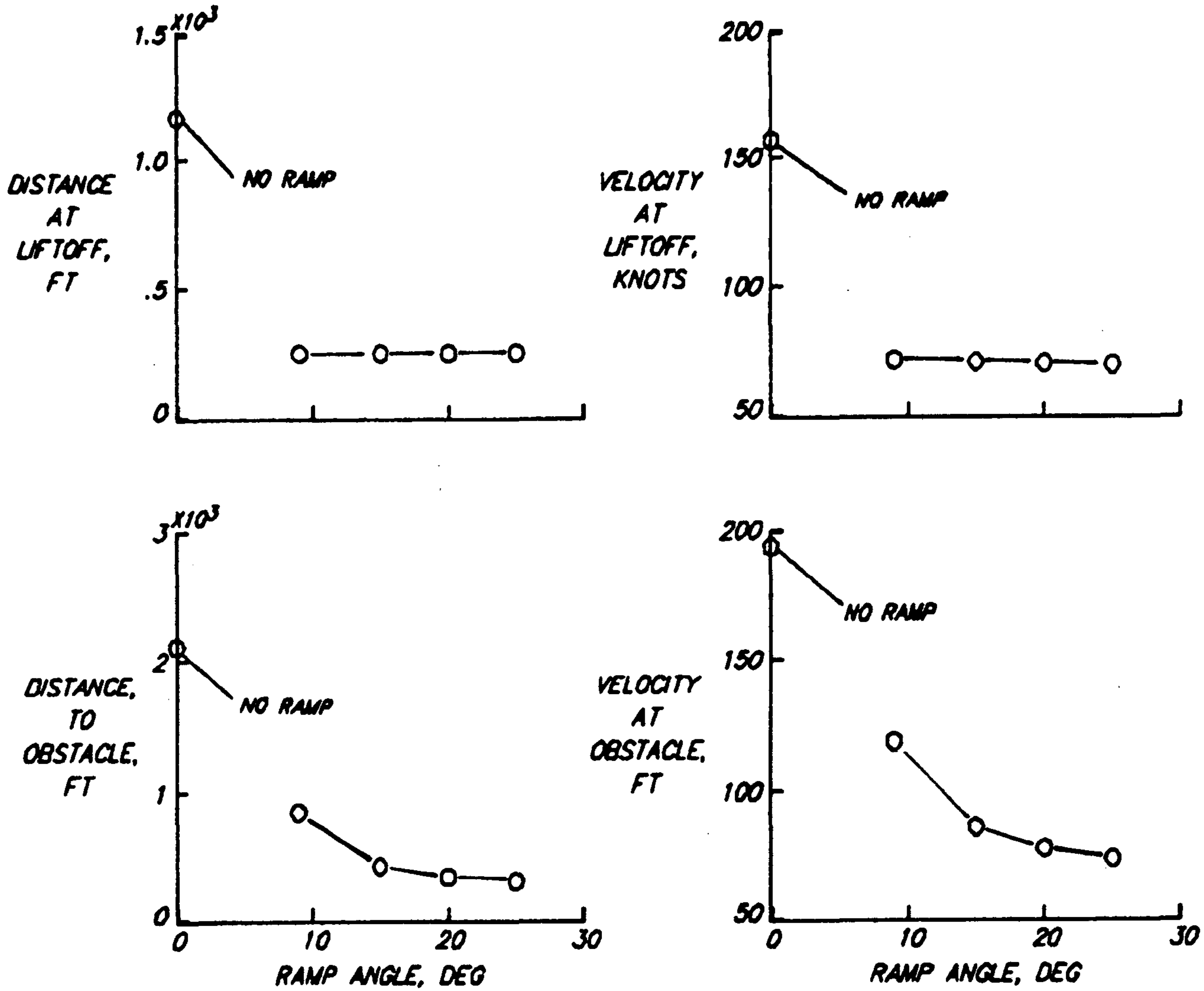
(a) Flight paths.

Figure 4.- The effect of ramp angle on ramp-assisted takeoff for overloaded configuration with T/W = 1.0.



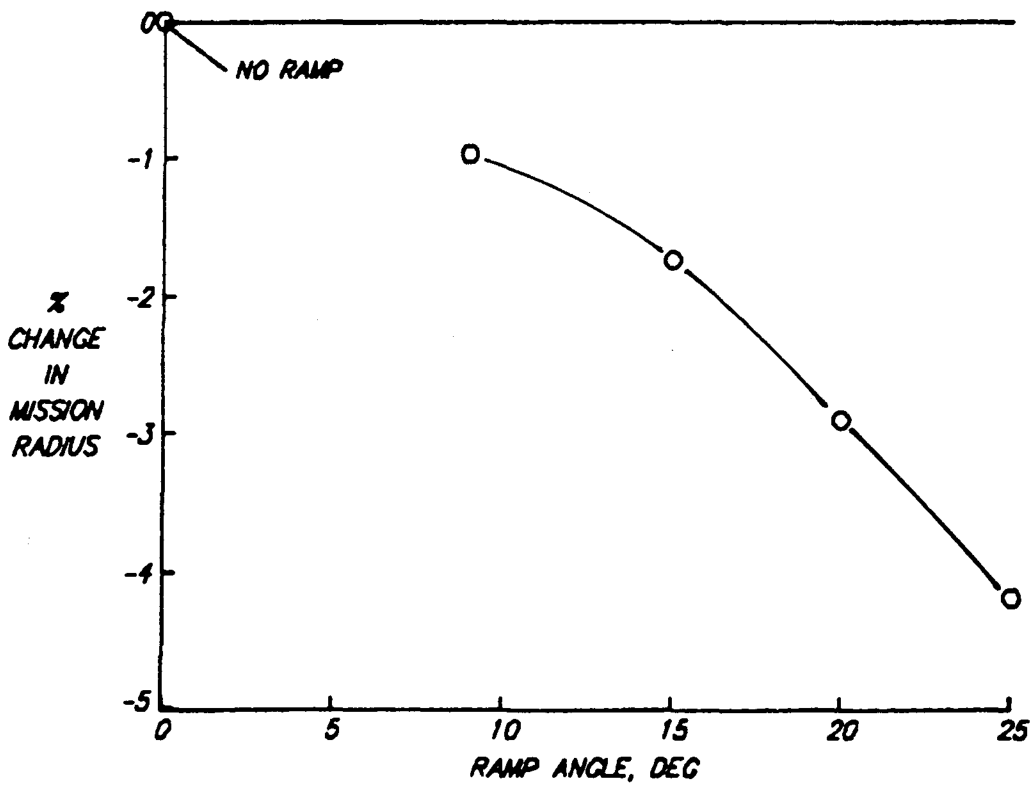
(b) Velocity profiles.

Figure 4.- Continued.



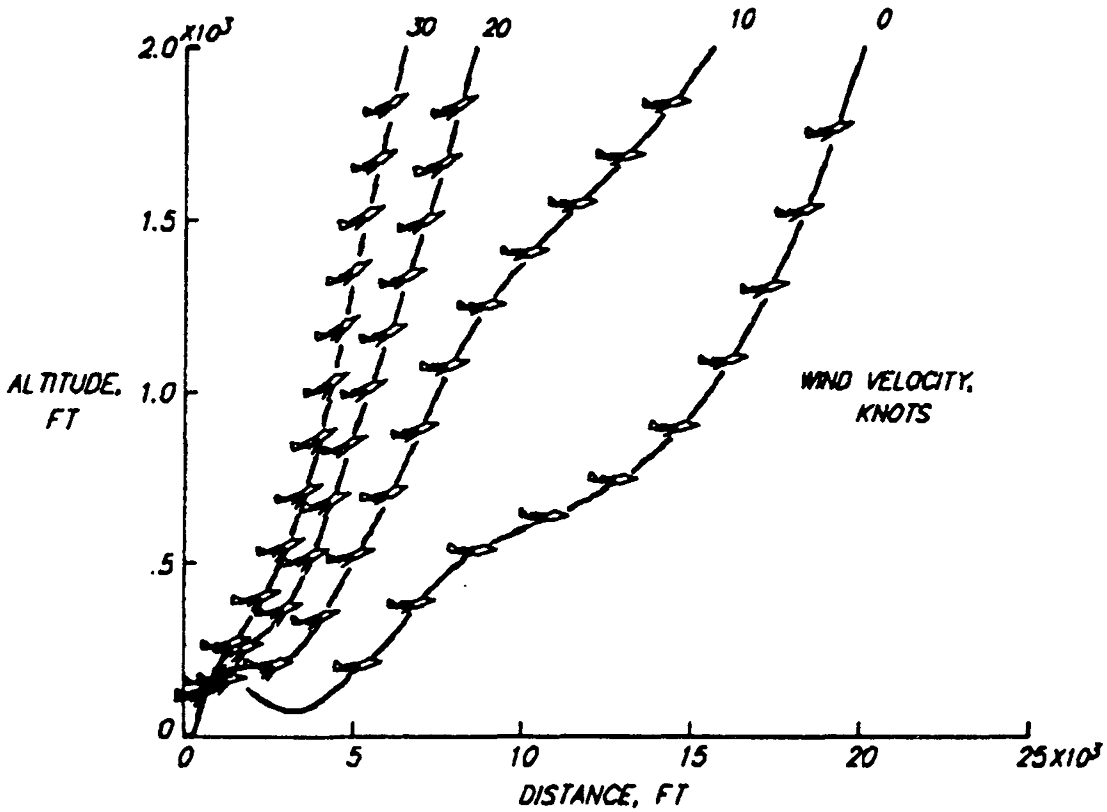
(c) Summary results.

Figure 4.- Continued.



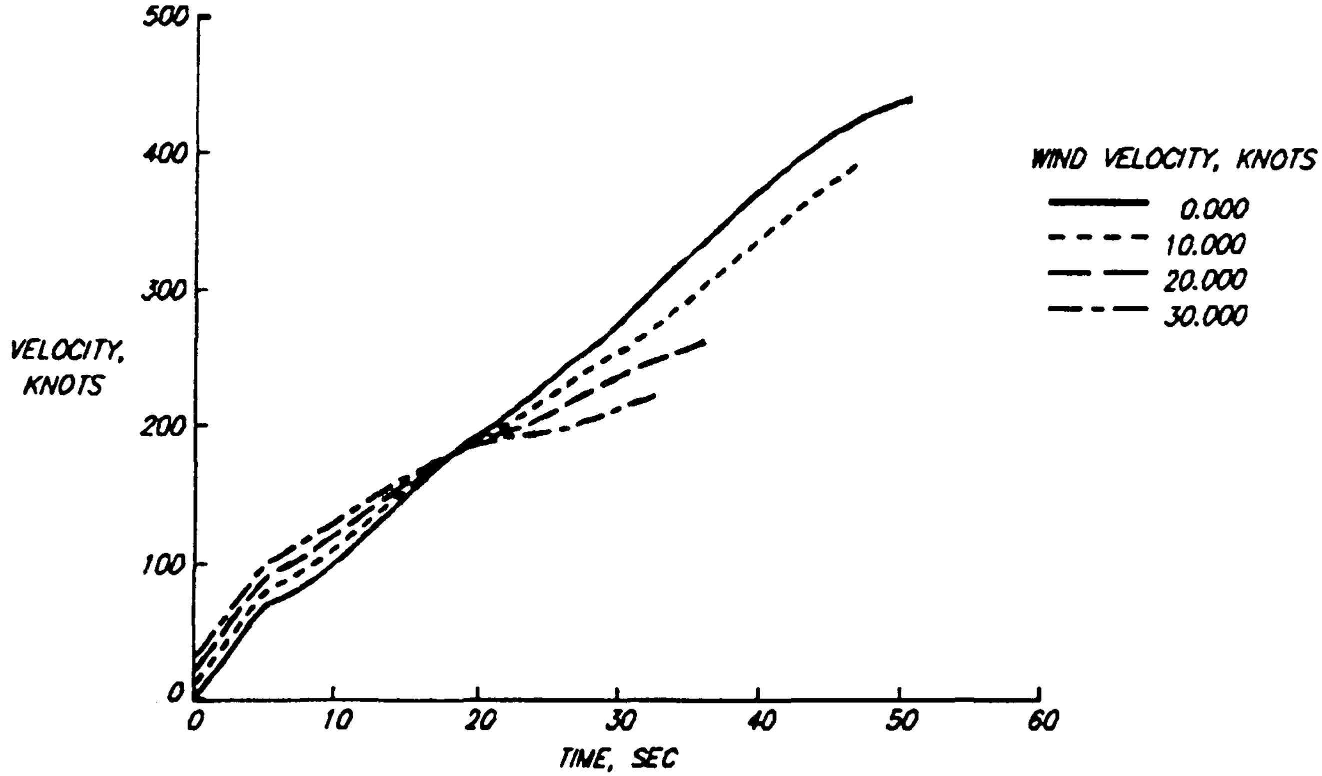
(d) Percent change in mission radius.

Figure 4.- Concluded.



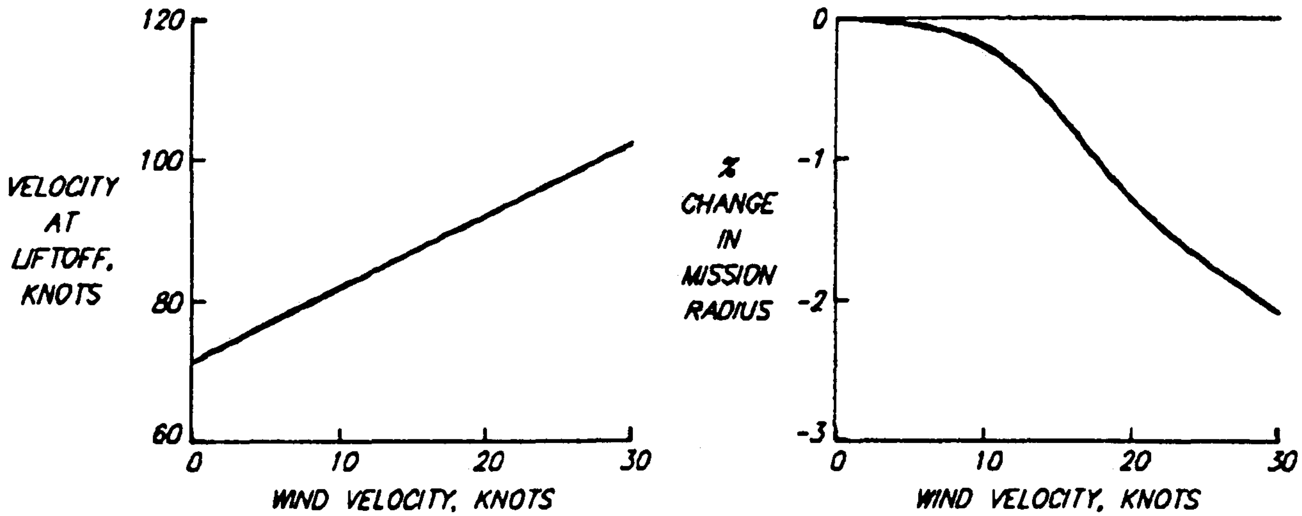
(a) Flight paths.

Figure 5.- The effect of head wind on ramp assisted takeoff for overloaded configuration with T/W = 0.75 (ramp angle = 35°).



(b) Velocity profiles.

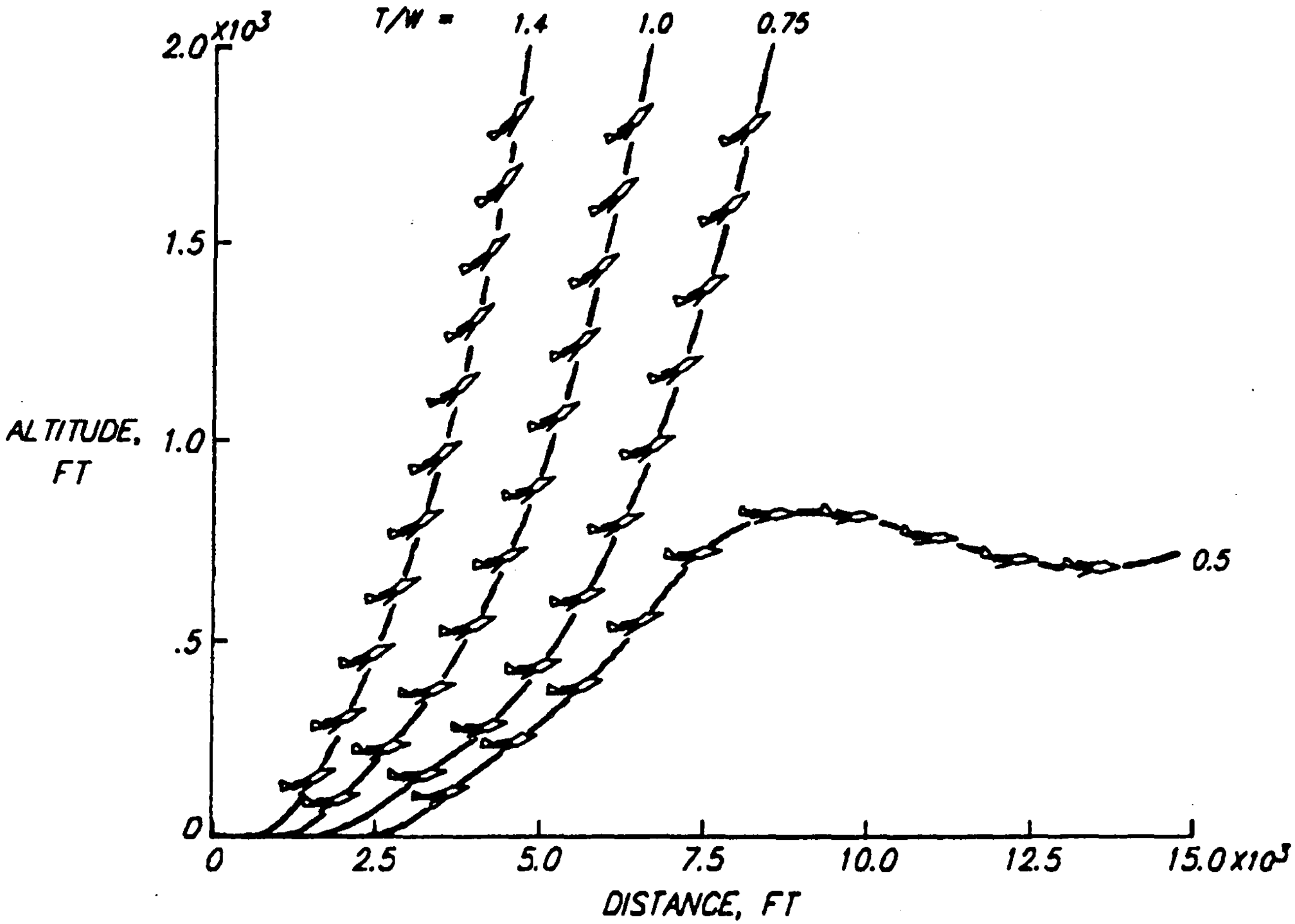
Figure 5.- Continued.



(c) Velocity at liftoff.

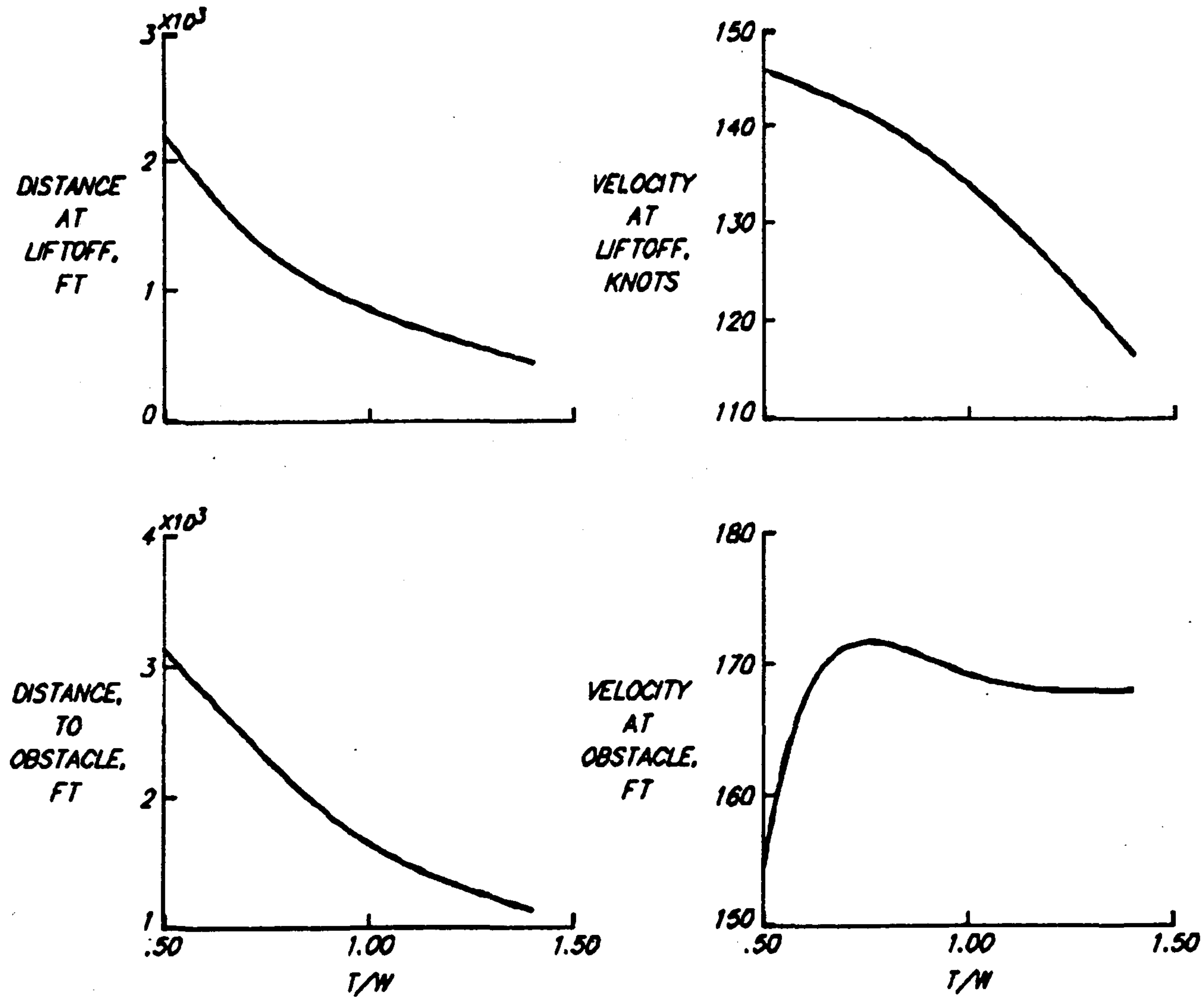
(d) Percent change in mission radius.

Figure 5.- Concluded.



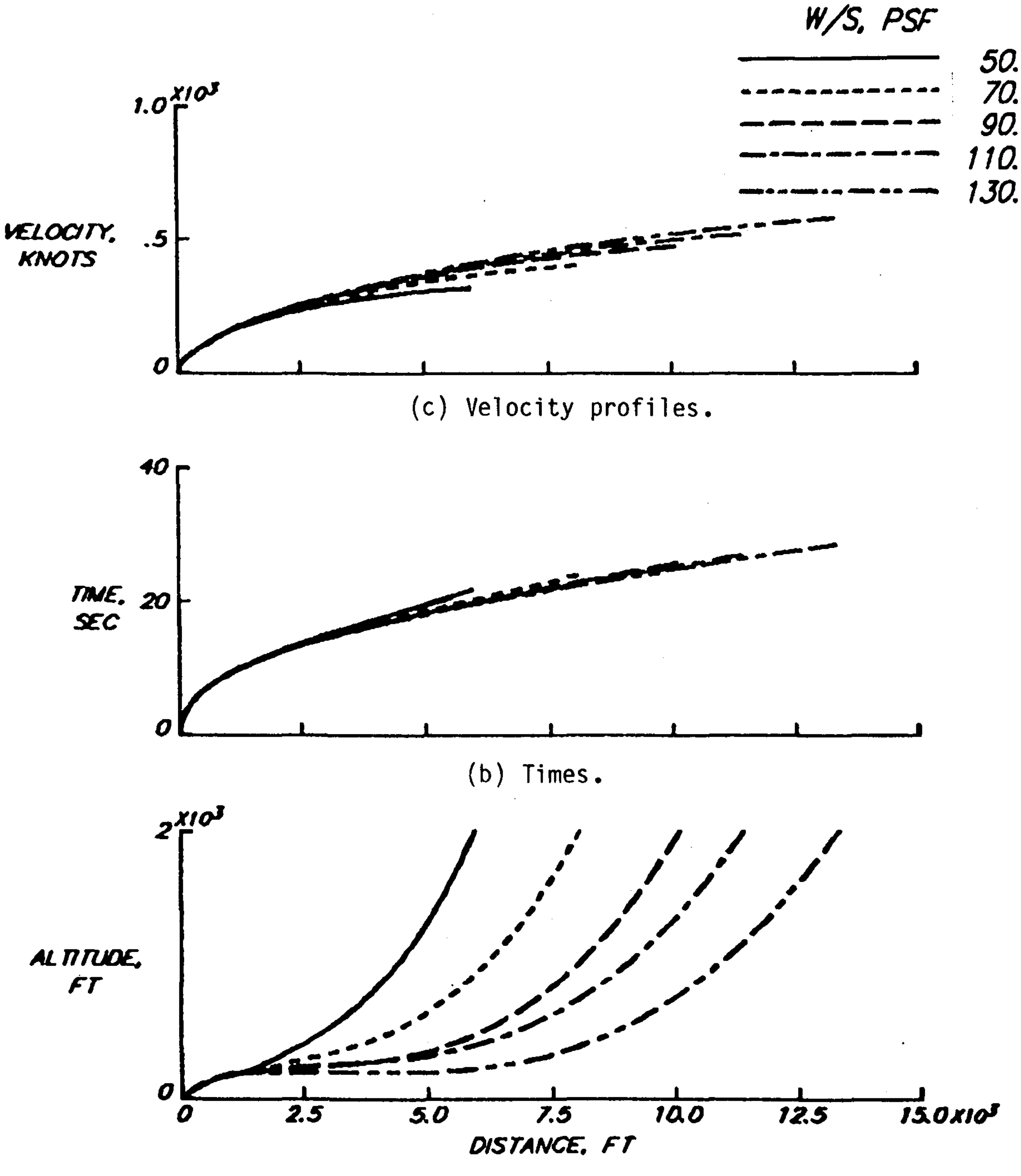
(a) Flight paths.

Figure 6.- The effect of T/W on normal takeoff for constant gross weight and W/S.



(b) Summary results.

Figure 6.- Concluded.

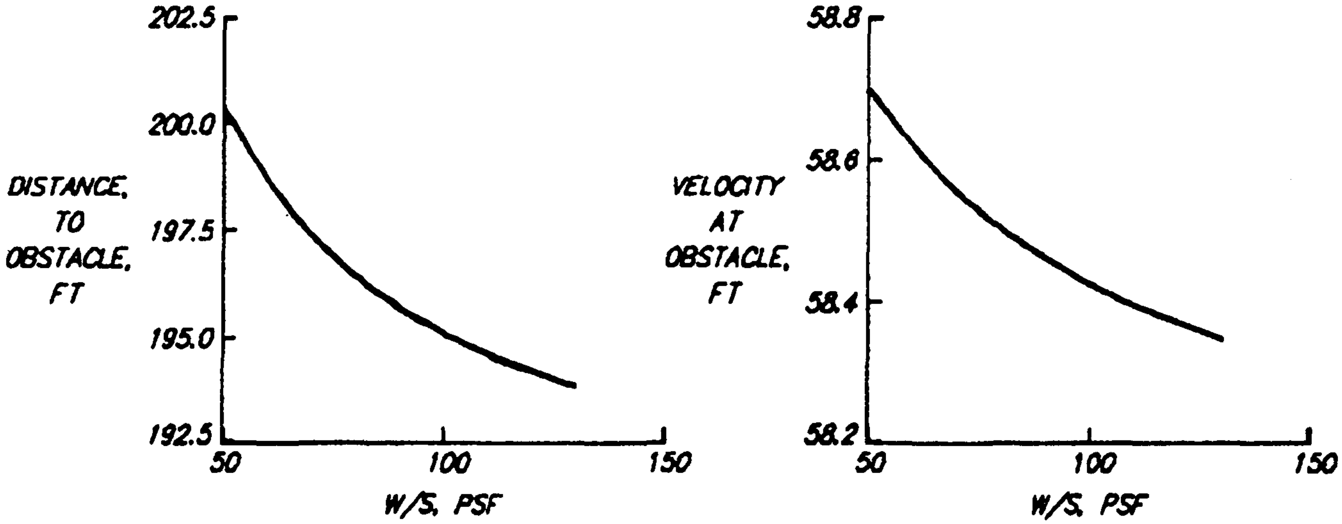


(c) Velocity profiles.

(b) Times.

(a) Flight paths.

Figure 7.- The effect of W/S on vertical takeoff for constant T/W and gross weight.



(d) Summary results.

Figure 7.- Concluded.

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15. Supplementary Notes

16. Abstract

A procedure that allows rapid preliminary evaluations of the vertical, short, and normal takeoff performance of supersonic cruise aircraft concepts has been developed into a numerical computer program. The program is used to determine the effects on takeoff performance of various parameters, such as thrust-weight ratio, wing loading, thrust vector angle, and flap setting. Ramp-assisted takeoffs for overloaded configurations typical of a ground-attack mission are included. The effects of wind on the takeoff performance are also considered.

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