DTNSRDC-83/020

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

SHORT TAKEOFF PERFORMANCE USING A GRAVITY ASSIST SKI JUMP

by

Roger J. Furey

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

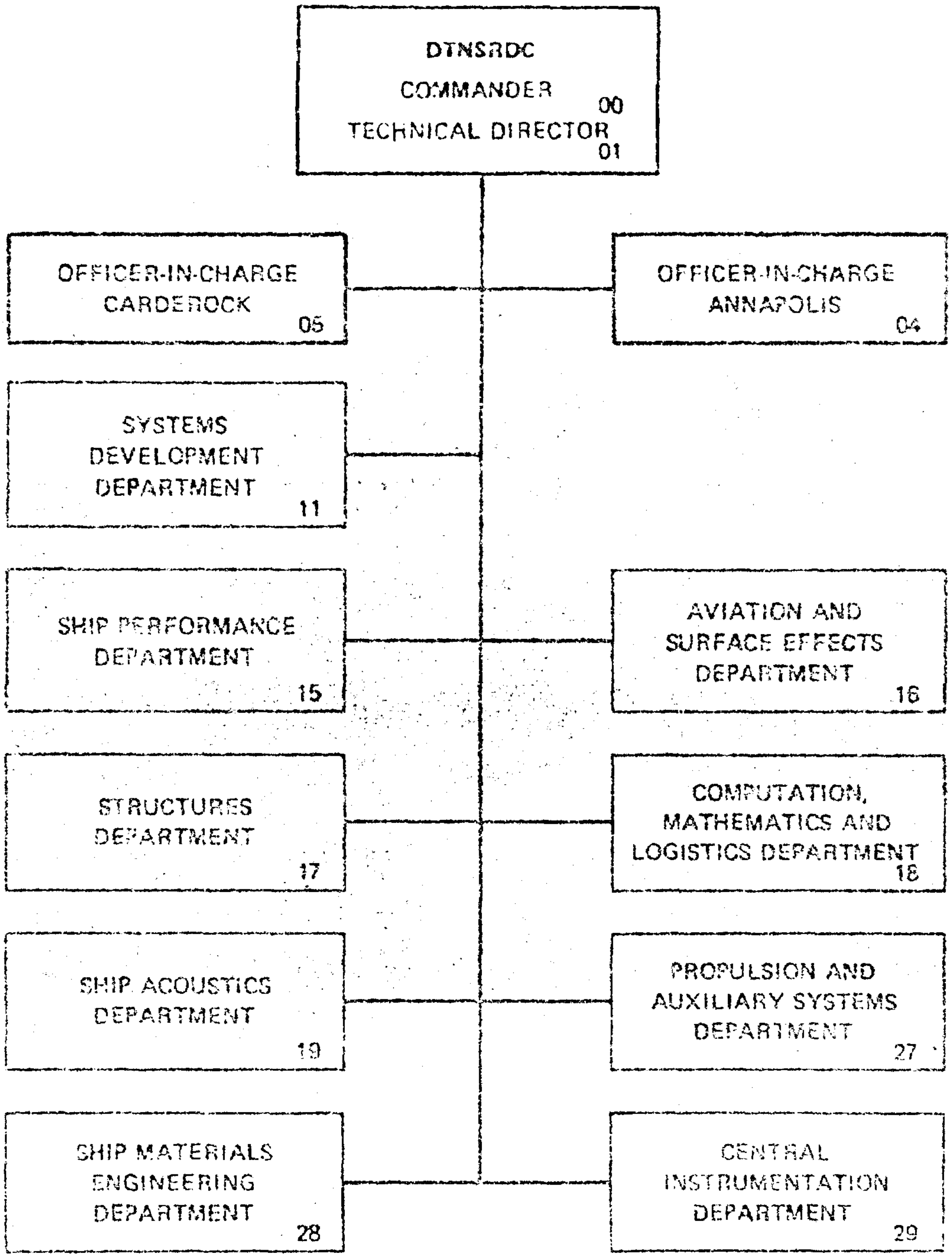
AVIATION AND SURFACE EFFECTS DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

March 1983

DTNSRDC-83/020

SHORT TAKEOFF PERFORMANCE USING A GRAVITY ASSIST SKI JUMP

MAJOR DTNSRDC ORGANIZATIONAL COMPONENTS



REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DTNSRDC-83/020	2. GOVT ACCESSION NO. AD-A126 456	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SHORT TAKEOFF PERFORMANCE USING A GRAVITY ASSIST SKI JUMP		5. TYPE OF REPORT & PERIOD COVERED Final
		6. PERFORMING ORG. REPORT NUMBER Aero Report 1281
7. AUTHOR(s) Roger J. Furey		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship Research and Development Center Bethesda, Maryland 20084		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (See reverse side)
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Systems Command AIR 311D Washington, D.C. 20361		12. REPORT DATE March 1983
		13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS(If different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

DTIC
ELECTE
APR 6 1983
S D
A

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

STOL
Ski Jump
Minimum Takeoff Roll
Performance Optimization

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A modified or gravity assist ski jump is developed, through an application of the calculus of variations, to provide for the shortest takeoff roll for a thrust vector control type vertical or short takeoff and landing (V/STOL) aircraft that will maintain a better-than-minimum required rate of climb. As a means of comparison between the resulting modified and a conventional ski jump, the equations of motion are programed to model the

(Continued on reverse side)

(Block 10)

Program Element 6224111
Task Area WF41 421000
Work Unit 1660-821

(Block 20 continued)

takeoff performance using a ski jump. The results of this model are found to compare well with Naval Air Test Center ski jump test results of the AV-8A aircraft. A comparison of the standard and gravity assist ski jump shows a reduction of 30 percent in required ground roll and 20 percent in distance to a 50-ft altitude, while maintaining a better-than-minimum required rate of climb, with the modified ramp. A simple modified ramp, using a pair of standard multiple girder bridging (MGB) ramps, is shown to provide similar improvements in takeoff performance.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

NOTATION

Symbol	Definition	Units
$\mathcal{R}$	Aspect ratio	
C_L	Lift coefficient	
C_{L_α}	Lift curve slope	
C_D	Drag coefficient	
C_{D_o}	Zero lift drag coefficient	
g	Gravity	ft/sec^2
K	Induced drag factor $C_L^2/\pi \mathcal{R} e$	
L	Lift	lb
ℓ	Ramp length	ft
q	Dynamic pressure	lb/ft^2
R/C	Rate of climb	ft/min
S	Wing reference area	ft^2
s	Arc length of ramp	ft
s_f	Length at end of ramp	ft
t	Time	sec
T	Thrust	lb
TOGW	Takeoff gross weight	lb
V	Velocity	ft/sec
V_f	Velocity at ramp exit	ft/sec
W	Weight	lb
W_{sto}	Weight for short takeoff	lb

Symbol	Definition	Units
W_H	Hover weight	
x	Horizontal coordinate	ft
y	Vertical coordinate	ft
Z	Local slope (dy/ds)	
α	Angle of attack	
γ	Angle of pitch	
δ	Angle of thrust deflection	
ζ	Square of velocity ratio	
λ	Lagrange multiplier	
μ	Friction coefficient	
ν	Constant multiplier	
ρ	Atmospheric density	
$(\dot{\ })$	$\frac{d}{ds}$ through Equation (24)	
	$\frac{d}{dt}$ Equations (25)-(28)	

ABSTRACT

A modified or gravity assist ski jump is developed, through an application of the calculus of variations, to provide for the shortest takeoff roll for a thrust vector control type vertical or short takeoff and landing (V/STOL) aircraft that will maintain a better than minimum required rate of climb. As a means of comparison between the resulting modified and a conventional ski jump, the equations of motion are programed to model the takeoff performance using a ski jump. The results of this model are found to compare well with Naval Air Test Center ski jump test results of the AV-8A aircraft. A comparison of the standard and gravity assist ski jump shows a reduction of 30 percent in required ground roll and 20 percent in distance to a 50-ft altitude, while maintaining a better-than-minimum required rate of climb, with the modified ramp. A simple modified ramp, using a pair of standard multiple girder bridging (MGB) ramps, is shown to provide similar improvements in takeoff performance.

ADMINISTRATIVE INFORMATION

The work reported was authorized by the Naval Air Systems Command (AIR 311) and was funded under Program Element 622411, Task Area WF41 421000, Work Unit 1660-821, STOL Aerodynamics.

INTRODUCTION

The ski jump concept was first proposed as a launching technique for thrust vectoring vertical or short takeoff and landing (V/STOL) type aircraft by Taylor[1*] in 1973. The history of the development of this idea, as outlined by Fozard,[2] shows the first flights to have occurred in July 1977 at the Royal Aircraft Establishment in Bedford, England. The initial test flights were flown, with an AV-8A, off a ramp with a 6 deg exit angle and progressed to a maximum ramp angle of 20 deg in early 1979. The takeoff technique showed great promise for shipboard application where it was demonstrated that liftoff velocities were as much as 30 knots lower than were feasible with a flat deck takeoff for aircraft with the same takeoff gross weight (TOGW). With the introduction of the AV-8A into the United States Marine Corps (USMC), interest in the ski jump launch technique resulted in flight tests being

---

*A complete listing of references is given on page 25.

conducted at the Naval Air Test Center (NATC) at Patuxent River, Maryland. These flight tests further demonstrated the performance and/or payload benefits that could be obtained.[3]

While the performance benefits to be gained through the use of the ski jump have been demonstrated, it seems reasonable that, as in the case of an actual skier, as assist from gravity in the initial downhill run prior to the ramp entry would provide for greater initial acceleration and thereby further performance gains. The current report is an effort to determine what the ski jump shape should be in order to provide for a maximum payload with the shortest takeoff roll. The payoff would include smaller ships platforms from which such aircraft could operate.

The approach will be to apply the calculus of variations to the equations of motion defining the takeoff maneuver, in order to determine what this optimum ski jump shape should be. An additional takeoff routine will be developed and evaluated by simulating the ski jump takeoffs carried out at NATC and presented in Reference 3. The same takeoff conditions will then be applied using the mathematically determined optimum ski jump shape in order to determine any advantages made possible through its use.

MATHEMATICAL FORMULATION

The derivation of the optimum ski jump will be set up and obtained as a Mayer's problem in the calculus of variations. The coordinate system is the usual x and y system of Figure 1 with, for convenience of formulation, the arc length, s, taken as the independent variable. The state equations defining the takeoff roll and the geometry of the ski jump are as follows:

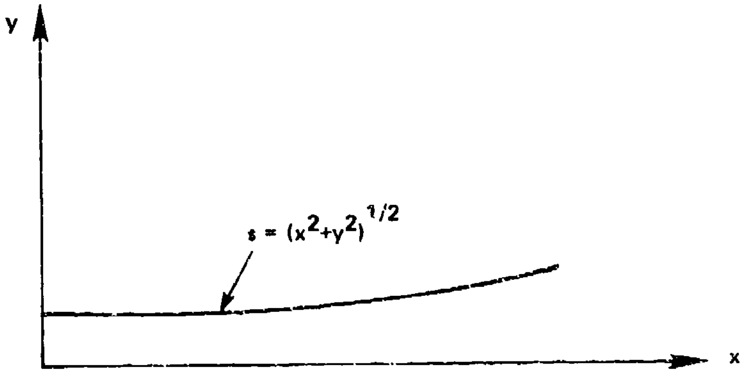


Figure 1 - Coordinate System

$$\dot{\zeta} = \frac{2g}{V_f^2}\left\{\frac{T}{W}\cos(\alpha+\delta)-Z-K_1\left[C_{D_o}+KC_{L_\alpha}^2\alpha^2\right]\zeta\right.$$

$$\left.-\mu\left(\left[1-Z^2\right]^{1/2}-K_1C_{L_\alpha}\alpha\zeta-\frac{T}{W}\sin(\alpha+\delta)\right)\right\} \tag{1}$$

$$\dot{x} = \left(1-Z^2\right)^{1/2} \tag{2}$$

$$\dot{y} = Z \tag{3}$$

where

$$\zeta = \left(\frac{V}{V_f}\right)^2, \quad K_1 = \frac{PV_f^2}{2(W/s)} \text{ and } Z = \frac{dy}{ds}$$

In this form the equations have the state variables ζ, x, y and the control variables Z, α, δ. In order to apply the calculus of variations, this system will be simplified by first assuming the angle of attack range to be small and to be described by a step function, i.e., $\alpha = \alpha_R\delta\ (\zeta-0.5)$. The angle of attack will then go from zero to some small predetermined angle at rotation:

$$\alpha = \alpha_R\delta\ (\zeta-0.5)\begin{cases}\alpha = 0 \text{ at } \zeta < 0.5\\ \alpha = \alpha_R \text{ at } \zeta \geq 0.5\end{cases}$$

The small angle assumption also provides for $\cos\alpha = 1$, $\sin\alpha = \alpha$ and $\alpha^2 = 0$. Experience with the ski jump has shown that the most beneficial way of using thrust vector control (TVC) is to deflect the thrust vectoring nozzles from the horizontal to some predetermined setting as the aircraft exits the ramp. This procedure will be assumed here, and thrust deflection will not be a parameter in developing the ramp shape (i.e., δ=0). The ramp enables the aircraft to accelerate to a controllable flying speed and orients it at a favorable climbing attitude in the shortest distance. Equations (1)-(3) then reduce to

$$\dot{\zeta} = \left(\frac{2g}{V_f{}^2}\right)\left\{\left(\frac{T}{W}\right) - Z - K_1 C_{D_o}\zeta - \mu\left(\left[1-Z^2\right]^{1/2} - K_1 C_{L_\alpha}\alpha\zeta - \left(\frac{T}{W}\right)\alpha\right)\right\} \qquad (4)$$

$$\dot{x} = (1-Z^2)^{1/2} \qquad (5)$$

$$\dot{y} = Z \qquad (6)$$

In the calculus of variations formulation we have, then, the variables ζ, x, y, Z and the independent variable s. The initial and final conditions are stated as

$$\zeta(0) = x(0) = y(0) = \alpha(0) = 0 \text{ and } Z(0) = Z_o \qquad (7)$$

$$y(s_f) = 0,\ \zeta(s_f) = 1,\ \alpha(s_f) = \alpha_R \qquad (8)$$

The quantity to be minimized is $x(s_f)$, the horizontal distance for the takeoff roll. Setting up as a Mayer problem in the calculus of variations,[4] the governing equations, Equations (4)-(6), and the initial and final conditions, Equations (7) and (8), provide

$$F = \lambda_\zeta\left(\dot{\zeta} - \left(\frac{2g}{V_1^2}\right)\left\{\left(\frac{T}{W}\right) - Z - K_1 C_{D_o}\zeta - \mu\left[\left(1-Z^2\right)^{1/2} - K_1 C_{L_\alpha}\alpha\zeta - \left(\frac{T}{W}\right)\alpha\right]\right\}\right)$$

$$+ \lambda_x\left[\dot{x} - \left(1-Z^2\right)^{1/2}\right] + \lambda_y(\dot{y}-Z) + \lambda_\alpha\{\alpha - \alpha_R\delta(\zeta-0.5)\} \qquad (9)$$

$$J = x_f \qquad (10)$$

$$H = x_f + \nu_1 x_o + \nu_2 y_o + \nu_3 \zeta_o + \nu_4 \alpha_o + \nu_5 y_f + \nu_6(\zeta_f - 1) + \nu_7(\alpha_f - \alpha_R) \tag{11}$$

where λ_ζ, λ_x, λ_y are Lagrange multipliers and ν_1, ν_2 ... ν_7 are constant multipliers. Applying Euler's equation

$$\frac{d}{dt}\left(\frac{\partial F}{\partial \dot{x}_i}\right) = \frac{\partial F}{\partial x_i}$$

to Equation (9) provides

$$\dot{\lambda}_\zeta = \left(\frac{2g}{V_f^{\,2}}\right)\left(K_1 C_{D_o} - \mu K_1 C_{L_\alpha} \alpha\right) \lambda_\zeta \tag{12}$$

$$\dot{\lambda}_x = C \tag{13}$$

$$\dot{\lambda}_y = 0 \tag{14}$$

$$0 = \lambda_\zeta \left\{\left(\frac{2g}{V_f^{\,2}}\right)\left[1 - \frac{\mu Z}{\left(1-z^2\right)^{1/2}}\right]\right\} + \lambda_x \frac{Z}{\left(1-Z^2\right)^{1/2}} - \lambda_y \tag{15}$$

$$0 = \lambda_\alpha - \lambda_\zeta \left(\frac{2g}{V_f^{\,2}}\right) \mu \left(K_1 C_{L_\alpha} \zeta + \frac{T}{W}\right) \tag{16}$$

Equation (11) and the transversality conditions provide

$$\lambda_x = -1 \tag{17}$$

$$\dot{x}_o + \lambda_y \dot{y}_o + \lambda_{\zeta_o} \dot{\zeta}_o = 0 \tag{18}$$

$$\lambda_y \dot{y}_f + \lambda_{\zeta_f} \dot{\zeta}_f + \dot{x}_f = 0 \tag{19}$$

Equation (12) can be written as

$$\dot{\lambda}_\zeta - C_2\lambda_\zeta = 0$$

$$C_2 = \left(\frac{2g}{V_f^{\,2}}\right) K_1 \left(C_{D_o} - \mu C_{L_\alpha} \alpha\right)$$

with the solution

$$\lambda_\zeta = \lambda_{\zeta_o} e^{C_2 s} \tag{20}$$

Substituting Equation (20) into Equation (15)

$$\lambda_{\zeta_o} e^{C_2 s} \left\{\left(\frac{2g}{V_f^{\,2}}\right) \left[1 - \frac{\mu Z}{\left(1-Z^2\right)^{1/2}}\right]\right\} - \frac{Z}{\left(1-Z^2\right)^{1/2}} - \lambda_y = 0$$

which reduces to

$$\frac{Z}{\left(1-Z^2\right)^{1/2}} = \frac{\dot{y}}{\dot{x}} = \frac{dy}{dx} = \frac{-\lambda_y + \lambda_{\zeta_o}\left(\frac{2g}{V_f^{\,2}}\right)e^{C_2 s}}{1 + \mu\lambda_{\zeta_o}\left(\frac{2g}{V_f^{\,2}}\right)e^{C_2 s}} \tag{21}$$

Assuming the initial slope of the ramp to be negative and requiring $y(s_f) \approx y(0)$, then at some point s_m between $s = 0$ and s_f, $(dy/dx)_{s=s_m} = 0$ and the constants λ_{ζ_o} and λ_y can be determined as

$$\lambda_y = \lambda_{\zeta_o} \left(\frac{2g}{V_f^{\,2}}\right) e^{C_2 s_m} \tag{22}$$

$$\lambda_{\zeta_o} = \frac{-\left(\frac{dy}{dx}\right)_o}{\left(\frac{2g}{V_f^2}\right)\left\{e^{C_2 s_m} - 1 + \mu\left(\frac{dy}{dx}\right)_o\right\}} \tag{23}$$

and

$$\frac{dy}{dx} = \frac{\lambda_{\zeta_o}\left(\frac{2g}{V_f^2}\right)\left(e^{C_2 s} - e^{C_2 s_m}\right)}{1 + \mu\lambda_{\zeta_o}\left(\frac{2g}{V_f^2}\right)e^{C_2 s}} \tag{24}$$

The shape of the ramp can be determined through Equations (23) and (24) and by assuming both an initial slope and the low point of the ramp.

Figure 2 is indicative of this ski jump ramp. The figure shows the ramp shape for a number of initial slopes and lengths and includes the trajectory of the AV-8A on leaving the ramp. It remains to establish a takeoff routine for the conventional ski jump and to establish its validity through comparison with flight test data.

SKI JUMP MODEL

The equations of motion governing the takeoff roll and climb out are, from Reference 6,

$$\dot{x} = V \cos \gamma \tag{25}$$

$$\dot{y} = V \sin \gamma \tag{26}$$

$$\dot{V} = g\left(\frac{T}{W}\cos \delta - \left(C_{D_o} + KC_L^2\right)\frac{q}{(W/S)} - \mu\left(1 - \frac{L}{W}\right) - \sin \gamma\right) \tag{27}$$

$$\dot{\gamma} = \frac{g}{V}\left(\frac{T}{W}\sin \delta + \frac{L}{W} - \cos \gamma\right) \tag{28}$$

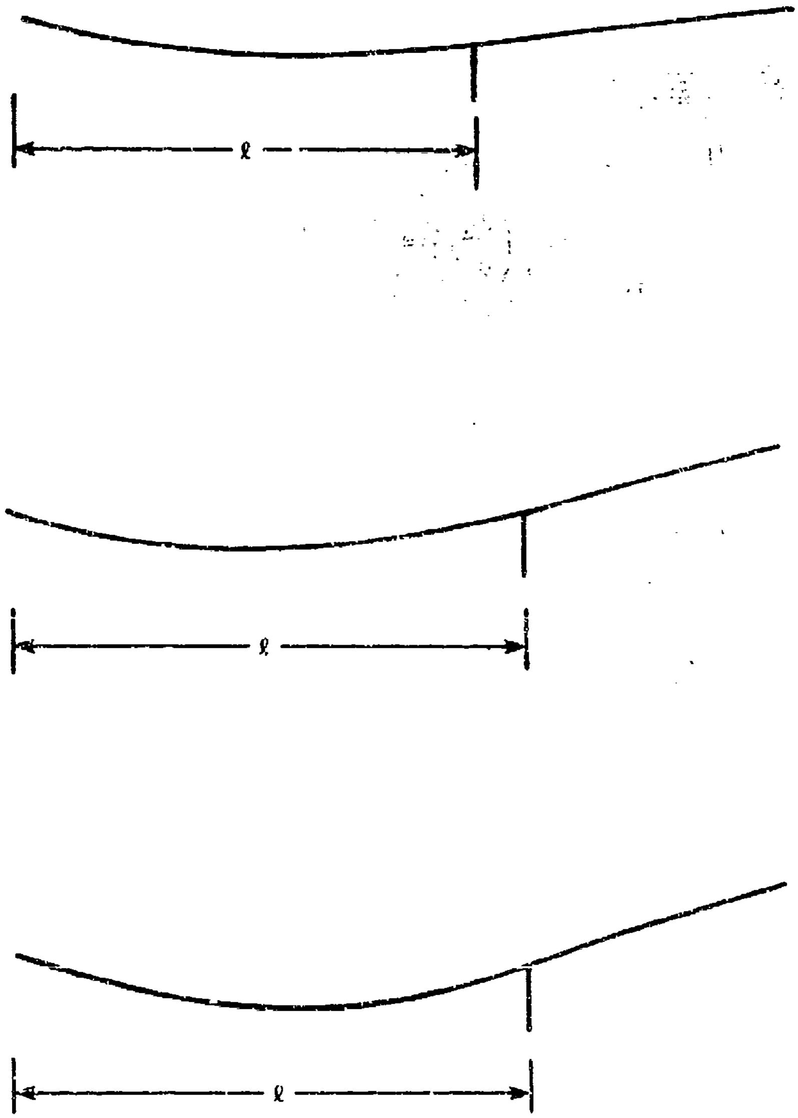


Figure 2 - Optimum ramp Shape for Given Initial Slope and Ramp Length, ℓ

The ski jump used in the NATC test series has the shape of a fourth order power law, i.e.,

$$Y = A + Bx + Cx^2 + Dx^3 + Ex^4 \tag{29}$$

The ramp is 135-ft long with an exit angle of 12 deg at 14.8 ft above the starting point. Equations (25)-(28) together with Equation (29) were programed on the Apple II computer. This ski jump math model was then used to simulate the test data of Reference 3. The test methods used during the NATC evaluations included precomputing the ground roll distance as a function of gross weight, hover weight ratio, and desired end speed. The method for doing this is outlined in Reference 3. The aircraft used was the two seat T/AV-8 which is identical with the AV-8A in aerodynamic characteristics. Over 60 takeoffs were conducted in this series with the takeoff gross weight (TOGW) ranging from 17,176 lb to 21,491 lb. The 12-deg ski jump ramp was found to decrease the distance to 50 ft above ground level (AGL) by approximately 70 percent with respect to NATOP's predictions for a 21,500 lb aircraft and a conventional short takeoff (STO).

A comparison of some of the NATC test results and the computer results are shown in Table 1. The ramp exit velocity is seen to be consistently higher, by a few knots in the computer predictions, than the test results. The exit velocity in the NATC data is ground speed and, therefore, neglects the headwind component which is accounted for in the computer results. With this taken into account, the correlation is good. The comparison between minimum rate of climb and distance to 50-ft AGL is also quite good except in the case of the 18,374 lb TOGW. In this case, the NATC data were obtained with a 5-knot tail wind which may account for the difference in minimum rate of climb.

Having established a reasonable validity in the computer model of the ski jump, the model will now be used to compare the performance of the standard and modified ski jumps. The path for the takeoff roll is, in the case of the modified ski jump, described by Equation (24).

RESULTS

Figures 3 through 6 show the profile of the takeoff roll and early airborne trajectory for the standard and modified ski jump samples. Figure 3 shows the

TABLE 1 - COMPARISON OF NATC AV-8A SKI JUMP TEST RESULTS WITH COMPUTER PREDICTIONS

STOGW (lb)	$\frac{W_{STO}}{W_H}$	T (lb)	Ground Roll Prior to Ramp Entry	Total Ground Roll	α_{AVG} (deg)	V at Ramp Exit (knots)		Min R/C (ft/min)		Dist. to 50-ft Alt. (ft)	
						NATC	Computed	NATC	Computed	NATC	Computed
17,776	1.07	16,613	102	232	9	63.7	66.1	954	1123	529	451
18,374	1.13	16,260	152	282	12.5	65.9	71	252	1146	649	502
18,604	1.12	16,610	149	279	11.5	65	70	960	1135	529	501
19,004	1.15	16,525	155	285	17	64.7	70.6	744	617	397	568
19,304	1.16	16,641	162	292	15.5	62.6	71	156	1051	566	521

Figure 3 - Ski Jump Takeoff Profiles


TAKEOFF ROLL PRIOR TO RAMP
ENTRY 102 FT

AV-8A SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=17776 LB
ROT DIST=130 FT
LIFTOFF DIST=232 FT
VEL AT LIFTOFF=111.49 FPS
66.01 KNOTS
DIST TO 50 FT ALT.=455 FT
VEL AT 50 FT ALT.=165.45 FPS
82.03 KNOTS
MIN R/C=1011 FPM AT DIST OF 657 FT

Figure 3a - TOGW = 17,776 Pounds


TAKEOFF ROLL PRIOR TO RAMP
ENTRY 152 FT

AV-8A SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=18374 LB
ROT DIST=130 FT
LIFTOFF DIST=282 FT
VEL AT LIFTOFF=119.82 FPS
70.95 KNOTS
DIST TO 50 FT ALT.=516 FT
VEL AT 50 FT ALT.=225.63 FPS
85.97 KNOTS
MIN R/C=532 FPM AT DIST OF 1076 FT

Figure 3b - TOGW = 18,374 Pounds

Figure 3 (Continued)

```
TAKEOFF ROLL PRIOR TO RAMP
ENTRY 149 FT
                              AV-8A SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
                              TOGW=18604 LB
                              ROT DIST=130 FT
                              LIFTOFF DIST=279 FT
                              VEL AT LIFTOFF=119.46 FPS
                              70.73 KNOTS
                              DIST TO 50 FT ALT.=523 FT
                              VEL AT 50 FT ALT.=212.72 FPS
                              86.91 KNOTS
                              MIN R/C=340 FPM AT DIST OF 1179 FT
```

Figure 3c - TOGW = 18,604 Pounds

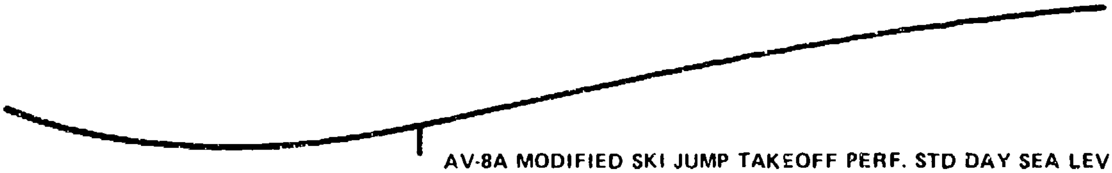
```
TAKEOFF ROLL PRIOR TO RAMP
ENTRY 162 FT
                              AV-8A SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
                              TOGW=19304 LB
                              ROT DIST=130 FT
                              LIFTOFF DIST=292 FT
                              VEL AT LIFTOFF=120.59 FPS
                              71.40 KNOTS
                              DIST TO 50 FT ALT.=521 FT
                              VEL AT 50 FT ALT.=219.09 FPS
                              85.26 KNOTS
                              MIN R/C=718 FPM AT DIST OF 960 FT
```

Figure 3d - TOGW = 19,304 Pounds

Figure 4 - Modified Ski Jump Takeoff Profiles for Ramp Length = 200 Feet

```
AV-8A MODIFIED SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=17776 LB
GROUND ROLL=201 FT
VEL AT LIFTOFF=111.39 FPS 65.95 KNOTS
RAMP ANGLE=15 DEG
DIST TO 50 FT ALT.=482 FT
VEL AT 50 FT ALT.=141.69 FPS
83.89 KNOTS
MIN R/C=1477 FPM AT 655 FT
```

Figure 4a - TOGW = 17,776 Pounds



```
AV-8A MODIFIED SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=18604 LB
GROUND ROLL=201 FT
VEL AT LIFTOFF=108.87 FPS 64.46 KNOTS
RAMP ANGLE=15 DEG
DIST TO 50 FT ALT.=540 FT
VEL AT 50 FT ALT.=146.10 FPS
86.51 KNOTS
MIN R/C=430 FPM AT 1194 FT
```

Figure 4b - TOGW = 18,604 Pounds

Figure 4 (Continued)

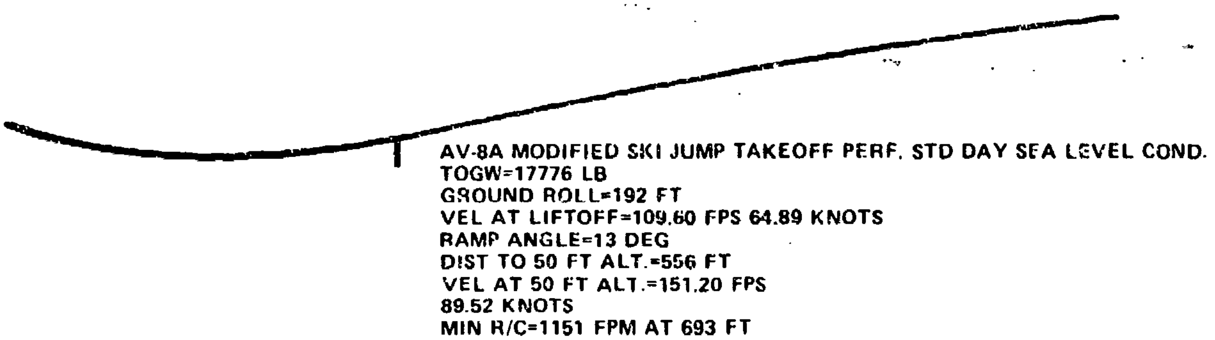
```
AV-8A MODIFIED SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=19004 LB
GROUND ROLL=200 FT
VEL AT LIFTOFF=107.35  FPS 63.56 KNOTS
RAMP ANGLE=15 DEG
DIST TO 50 FT ALT.=528 FT
VEL AT 50 FT ALT.=141.45 FPS
83.75 KNOTS
MIN R/C=907 FPM AT 861 FT
```

Figure 4c - TOGW = 19,004 Pounds

```
AV-8A MODIFIED SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=19304 LB
GROUND ROLL=202 FT
VEL AT LIFTOFF=107.21 FPS 63.47 KNOTS
RAMP ANGLE=15 DEG
DIST TO 50 FT ALT.=529 FT
VEL AT 50 FT ALT.=141.21 FPS
83.61 KNOTS
MIN R/C=654 FPM AT 999 FT
```

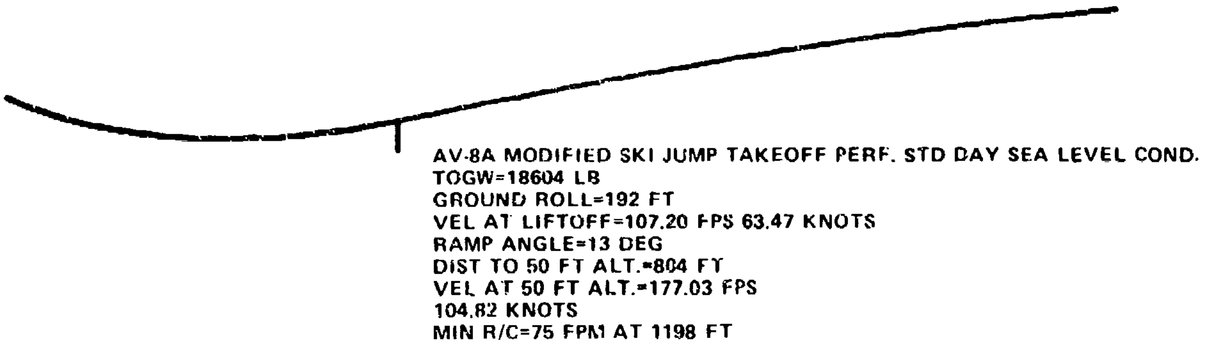
Figure 4d - TOGW = 19,304 Pounds

Figure 5 - Modified Ski Jump Takeoff Profiles for Ramp Length = 190 Feet



```
AV-8A MODIFIED SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=17776 LB
GROUND ROLL=192 FT
VEL AT LIFTOFF=109.60 FPS 64.89 KNOTS
RAMP ANGLE=13 DEG
DIST TO 50 FT ALT.=556 FT
VEL AT 50 FT ALT.=151.20 FPS
89.52 KNOTS
MIN R/C=1151 FPM AT 693 FT
```

Figure 5a - TOGW = 17,776 Pounds



```
AV-8A MODIFIED SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=18604 LB
GROUND ROLL=192 FT
VEL AT LIFTOFF=107.20 FPS 63.47 KNOTS
RAMP ANGLE=13 DEG
DIST TO 50 FT ALT.=804 FT
VEL AT 50 FT ALT.=177.03 FPS
104.82 KNOTS
MIN R/C=75 FPM AT 1198 FT
```

Figure 5b - TOGW = 18,604 Pounds

Figure 5 (Continued)

```
AV-8A MODIFIED SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=18604 LB
GROUND ROLL=201 FT
VEL AT LIFTOFF=108.87 FPS 64.43 KNOTS
RAMP ANGLE=15 DEG
DIST TO 50 FT ALT.=513 FT
VEL AT 50 FT ALT.=142.08 FPS
84.12 KNOTS
MIN R/C=977 FPM AT 896 FT
```

Figure 5c - TOGW = 18,604 Pounds

```
AV-8A MODIFIED SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=19004 LB
GROUND ROLL=191 FT
VEL AT LIFTOFF=105.75 FPS 62.61 KNOTS
RAMP ANGLE=13 DEG
DIST TO 50 FT ALT.=678 FT
VEL AT 50 FT ALT.=159.25 FPS
94.29 KNOTS
MIN R/C=594 FPM AT 865 FT
```

Figure 5d - TOGW = 19,004 Pounds

AV-8A SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=19304 LB
ROT DIST=130 FT
LIFTOFF DIST=200 FT
VEL AT LIFTOFF=98.34 FPS
58.23 KNOTS
MIN R/C=—391 FPM AT DIST OF 1049 FT

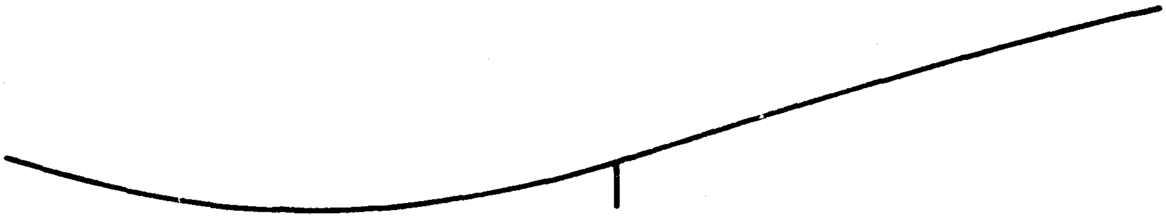
Figure 6 - Ski Jump Takeoff Profile with Limited Takeoff Roll

conventional ski jump and indicates the takeoff roll prior to ramp entry that is required for the various takeoff weights. The liftoff velocity at the end of the ramp, the distance from start of roll to a 50-ft altitude, and the minimum rate of climb (out to a distance of 1200 ft from start of roll) are also shown for each case. The takeoff procedure for both the standard and modified ski jumps provides for rotating the nozzles to 40 deg and flying at a predetermined angle of attack on exiting the ramp. The conventional ski jump shows that the distance-to-ramp exit varies from 232 ft at a TOGW of 17,776 lb to 292 ft at 19,304 lb. All cases maintain better than the recommended minimum rate of climb of 400 ft/min.[3] Figure 4 shows the same range of TOGW while operating from a modified ski jump 200 ft in length. All cases show the aircraft to reach the 50-ft altitude level at approximately the same distance from brake release as their standard ski jump counterparts, while maintaining considerably more than the recommended minimum rate of climb. It should be noted that the 50-ft altitude is being measured from the start of the ramp which is some 20 ft above the ramp's low point. The aircraft is, in fact, some 70 ft above the low point of its takeoff roll at the indicated 50-ft altitude.

The modified ramp has provided the means to achieve similar or better takeoff performance with 30 to 90 ft less takeoff roll. Figure 5 illustrates the results of the same TOGW range while operating from a 190 ft modified ramp. While the distance to a 50-ft altitude is increased, the aircraft maintains better than the recommended minimum rate of climb except for the case of the 18,604 lb example of Figure 5b. In this case, the average angle of attack the aircraft maintained on leaving the ramp was 11 deg. The case was repeated while maintaining 14 deg on leaving the ramp. The results, shown in Figure 5c, indicate a minimum rate of climb well above the required minimum and a decrease of 300 ft in the distance to a 50-ft altitude.

As a point of comparison, the 19,304 lb TOGW case was repeated using the standard ski jump with a takeoff roll of 200 ft, i.e., equivalent to the ground roll of the modified ramp. The results are given in Figure 6 and show that the aircraft reaches a negative rate of climb. Furthermore, the aircraft had not reached the 50-ft altitude during the calculated trajectory and was, in fact, losing altitude. The comparison is quite clear that a satisfactory takeoff is simply not achievable with the standard ski jump and a 200-ft ground roll, while takeoff is easily attained with the modified ski jump of 200-ft length.

The ramp geometry, as defined by Equation (24), requires that both the initial ramp slope and the low point of the ramp be specified. The initial slope in the examples of Figures 4 and 5 was taken to be 24 deg and provided for an increase in the initial acceleration of about 40 percent ($-\sin\gamma=0.4$ in Equation (27)). The low point of the ramp was taken at 60 percent of the total ramp length. The results in Figure 7 are obtained by maintaining the initial slope and reducing the distance to the ramp low point to 55 percent of the total ramp length. This action maintains the steepness of the original slope for a slightly longer stretch. The liftoff velocity is maintained, but the ramp exit angle and, thereby, the initial climb angle are steeper than shown in the example of Figure 4a. The rate of climb is increased by nearly 600 ft/min and the distance to a 50-ft altitude was reduced by 100 ft. As the problem now stands, the ramp shape is dependent upon the minimum controllable flight speed. For a TVC type aircraft (such as the AV-8A with a reaction control system (RCS) for longitudinal and lateral control), the minimum controllable flying speed only depends upon the thrust-to-weight ratio. On meeting only the minimum rate of climb requirements, the ramp length and distance to a 50-ft altitude are much reduced from that of the standard ski jump, as shown in Figure 8. A summary of ground roll distances and the distance to a 50-ft altitude for the



AV-8A MODIFIED SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=17776 LB
GROUND ROLL=202 FT
VEL AT LIFTOFF=109.85 FPS 65.04 KNOTS
RAMP ANGLE=19 DEG
DIST TO 50 FT ALT.=386 FT
VEL AT 50 FT ALT.=127.63 FPS
75.57 KNOTS
MIN R/C=2008 FPM

Figure 7 - Modified Ski Jump with Initial Downhill Slope Extended

various AV-8A takeoff weights, using the ramp of Figure 7, (which provides for a liftoff velocity of approximately 70 knots, equivalent to what is being achieved with the standard ski jump), is also shown in Figure 8. The significance of the modified ramp is clearly shown in the reduction of the takeoff roll and distance to a 50-ft altitude. In all cases, considerably more than the required minimum rate of climb has been maintained.

The benefit of the modified ramp is in the increased acceleration that can be achieved in the early part of the takeoff roll as a result of the initial downhill run.

A near-term validation of this notion could be carried out by using two MGB ramps of the type used in the NATC ski jump tests. By arranging the ground level sections end-to-end, a form of the modified ramp can be obtained. The resulting end-to-end 260-ft ramp and AV-8A trajectory are shown in Figure 9. The associated takeoff performance is shown in Table 2.

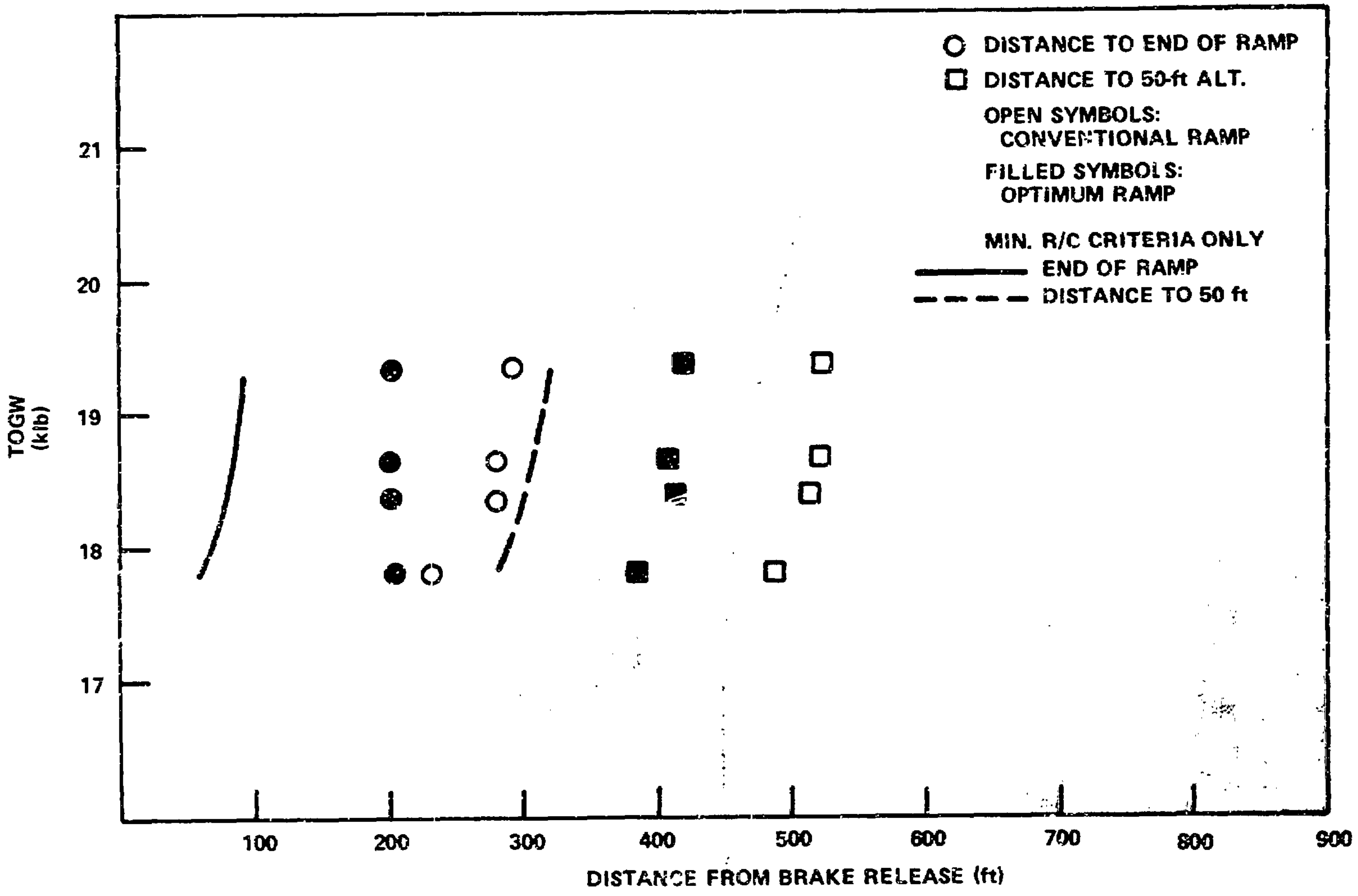


Figure 8 - AV-8A Takeoff with Standard and Modified Ramps

AV-8A SKI JUMP TAKEOFF PERF. STD DAY SEA LEVEL COND.
TOGW=18374 LB
ROT DIST=130 FT
LIFTOFF DIST=260 FT
VEL AT LIFTOFF=118.72 FPS
70.29 KNOTS
DIST TO 50 FT ALT.=482 FT
VEL AT 50 FT ALT.=165.20 FPS
84.58 KNOTS
MIN R/C=833 FPM AT DIST OF 700 FT

Figure 9 - Takeoff Profile for AV-8A with End-to-End MGB Ramps

TABLE 2 - COMPARISON OF TAKEOFF PERFORMANCE WITH END-TO-END MGB RAMP AND CONVENTIONAL RAMP

	End-to-End MGB Ramp			Conventional Ramp		
TOGW (lb)	18,374	18,604	19,304	18,374	18,604	19,304
Liftoff Distance (ft)	260	260	260	282	279	292
Ramp Exit Velocity (knots)	70.2	70.5	69.4	71	70	71
Distance to 50-ft Alt. (ft)	482	480	495	502	501	521
Min. R/C (ft-min)/Distance to Min. R/C (ft)	833/700	877/701	589/703	1,146/-	1,135/-	1,051/-

CONCLUSIONS

A modified or gravity assist ski jump ramp shape was generated through an application of the calculus of variations. The modified shape employs an initial down run which takes advantage of gravity to maximize acceleration and energy at the beginning of the takeoff.

The gravity assist ramp provided for considerable improvement in AV-8A takeoff performance over what could be achieved with the conventional ski jump. The ground roll was reduced by up to 30 percent and the distance required to climb to a 50-ft altitude was reduced by up to 20 percent while providing the same liftoff velocity and maintaining better than the recommended minimum rate of climb.

The purpose of this report has been to present results which are necessarily preliminary in the sense that a limited number of variables have been evaluated. Although such an arrangement of ski jump ramps may be physically challenging, the challenge is no greater than the single ski jump ramp first presented. Since the results show significant promise, it is recommended that: (1) a further analysis be conducted to evaluate these results, and (2) a conceptual design study be initiated to examine possible methods of implementing such a ski jump ramp.

REFERENCES

1. Taylor, D.R., "The Operation of Fixed-Wing V/STOL Aircraft From Confined Spaces," Thesis, University of Southhampton, England (1974).

2. Fozard, J.W., "Ski-Jump - A Great Leap for Tactical Airpower," AIAA/RAeS/CASI/AAAF Atlantic Aeronautical Conference, Williamsburg, Va. (Mar 1979).

3. Stromberg, R.M. Maj., T.E. Devereux, D.E. House, "Flying Qualities and Performance Evaluation of the T/AV-8A Aircraft/Medium Girder Bridge Ski Jump," NATC Report SA-24R-81 (May 1981).

4. Bliss, G.A., "Lectures on the Calculus of Variations," The University of Chicago Press (1961).

5. Lawden, D.F., "Interplanetary Rocket Trajectories," Advances in Aerospace Sciences, Vol. 1, pp. 1-53, Academic Press (1959).

INITIAL DISTRIBUTION

Copies		
1	CNO	
	1	OPNAV 508D/R.H. Thompson
2	ONR	
	1	Code 210/CAPT Howard
	1	Code 452/R. Whitehead
1	DIA/P. Scheurich	
2	NAVMAT	
	1	Code 071/O.J. Remson
	1	Code 05M/LCOL G.R. Gay
2	NAVAIRDEVCEN	
	1	Tech Library
	1	Code 6053/J. Clark
4	NAVAIR	
	1	AIR 311D/D. Kirkpatrick
	1	AIR 314B/R. Murray
	1	AIR 950D/Library
	1	AIR 5511B1/R. Turner
5	NAVSEA	
	1	1-50111/D. Ewing
	1	1-50151/K. Spaulding
	1	1-50151/M. Bebar
	1	1-50151/W. White
	1	1-05R/E. Botler
1	NWC	
	1	Tech Library
3	NAVAIRTESTCEN	
	1	SA8B/R. Traskos
	1	SA70B/A. Smith
	1	CT23/J. Hoeg
12	DTIC	
1	NASA/AMES Res Cen	
	1	M. Ardema

CENTER DISTRIBUTION

Copies	Code	Name
2	1606	Aerodynamics Collection
10	5211.1	Reports Distribution
1	522.1	Unclassified Lib (C) 1M
1	522.2	Unclassified Lib (A)
1	93	Patent Counsel