UNITED STATES NAVY SKI JUMP EXPERIENCE AND FUTURE APPLICATIONS

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SUMMARY

The United States Navy has been evaluating the performance benefits of using a ski jump during takeoff. The significant gains available with the use of Vertical and Short Takeoff and Landing (V/STOL) aircraft operating from a ski jump have been documented many times in the past; however, the U.S. Navy has expanded this concept to include Conventional Takeoff and Landing (CTOL) aircraft. This paper will present the results of a recent shipboard evaluation of the AV-8B aboard the Spanish ski jump equipped ship PRINCIPE DE ASTURIAS, and a shore based flight test evaluation of CTOL aircraft operating from a ski jump ramp. The analytical tools developed during the CTOL phase of testing are used to project the benefits which could be realized by combining the steam powered catapult and a "mini" ski jump ramp compatible with today's aircraft carriers.

NOMENCLATURE

AOA	-	Angle of Attack
CG	-	Aircraft Center of Gravity
CRAT	-	Catapult/Ramp Assisted Takeoff
CTOL	-	Conventional Takeoff and Landing
MIL	-	Military Thrust
Max A/B	-	Maximum Afterburner Thrust
ROC	-	Rate of Climb
STO	-	Short Takeoff
SLW	-	Short Lift Wet
V	-	Ramp Exit Airspeed (KEAS)
V_e	-	Ramp Exit Speed (kt)
VTOL	-	Vertical Takeoff and Landing
V/STOL	-	Vertical and Short Takeoff and Landing
W	-	Aircraft Gross Weight (lb)
W_h	-	Hover Weight (lb)
W/W_h	-	Hover Weight Ratio
WOD	-	Wind Over Deck

AV-8B SKI JUMP

Introduction

Flight tests were conducted aboard PRINCIPE DE ASTURIAS, a Spanish ship designed for Harrier operations with a 12 degree ski jump ramp, December 1988 to define operating procedures and limitations and document performance gains over conventional flat deck short takeoffs (STO's). A total of 89 STO's were conducted. PRINCIPE DE ASTURIAS proved to be an excellent platform for Harrier operations. The flight test program clearly demonstrated the performance gains, reduced pilot workload, and improved safety inherent in a ski jump assisted shipboard takeoff. WOD requirements were approximately 30 kt less than flat deck requirements, resulting in significant fuel savings and flight operations having less impact on ship's heading and speed. Deck run requirements were approximately 350 ft (107 m) less than flat deck requirements, improving Harrier/helicopter interoperability. Maximum payload capability for a ski jump assisted launch is up to 53% greater than flat deck capability, allowing shipboard Harrier operations to the same takeoff gross weight as shore based. The heaviest Harrier to be launched from a ship to date was accomplished during the test program (31,000 lb). The ski jump launch always produced a positive rate of climb at ramp exit, the resulting altitude gain allowing aircrew more time to evaluate and react to an emergency situation. Pilot opinion is that the ski jump launch is the easiest and most comfortable way to takeoff in a Harrier.

Background

In the mid-1970's the British aerospace community identified the significant improvements in takeoff performance for vectored thrust aircraft obtained with the assistance of an upwardly inclined (ski jump) ramp and, as a result, incorporated ramps on existing Royal Navy carriers. In 1977, the Spanish Navy began construction of the first ship designed from the keel up to support Harrier operations. The basic ship design was modeled after the U.S. Navy sea control ship promoted by Admiral Zumwalt in the mid-1970's. A 12 degree ski jump ramp was incorporated to improve takeoff performance. Based on previous shore based ski jump testing and simulation efforts, a 12 degree ramp was found optimum for maximizing takeoff performance while maintaining aircraft structural loads within limits. The ramp profile is the same as that of HMS HERMES of the Royal Navy. Construction began in 1977 at the El Ferrol shipyard of Empresa Bazan Nacional. The ship was commissioned PRINCIPE DE ASTURIAS and delivered to the Spanish Navy 30 May 1988. Shortly thereafter, the Spanish Navy made an agreement with Naval Air Systems Command for Naval Air Test Center to conduct flight tests and engineering analysis required to publish an operating bulletin for AV-8B operations from the ship. Flight test objectives were to define operating procedures and limitations and document performance gains over conventional flat deck STO's.

Test Assets

Ship

PRINCIPE DE ASTURIAS can accommodate up to 36 aircraft consisting of both Harriers and helicopters. The flight deck is approximately 575 ft (175 m) long by 95 ft (29.0 m) wide. The ski jump ramp coordinates are presented in table 1. The maximum STO deck run length is 550 ft (168 m). The ship is stabilized in roll with four stabilizers. The ship has six VTOL spots. The flight deck including flight deck markings is illustrated in figure 1. A profile of the ship is presented in figure 2. The ship is equipped with SPN-35 radar for ground controlled approach, Harrier Approach Path Indicator (HAPI) and Deck Approach Projector Sight (DAPS) for glide slope information, and Hover Position Indicator (HPI) for height control. The ship has a 7,500 nautical mile range at 20 kt ship speed. The ship has a maximum speed of approximately 25 kt.

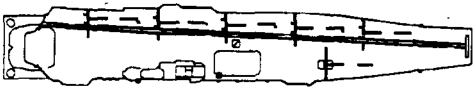


Figure 1
PRINCIPE DE ASTURIAS Flight Deck

Table 1
Ski Jump Ramp Coordinates

Distance Along Ramp ft	(m)	Ramp Height ft	(m)
0.0	(0.0)	0.00	(0.00)
11.5	(3.5)	0.20	(0.06)
21.3	(6.5)	0.50	(0.15)
31.2	(9.5)	0.88	(0.27)
41.0	(12.5)	1.36	(0.41)
50.9	(15.5)	2.00	(0.61)
60.7	(18.5)	2.74	(0.84)
70.5	(21.5)	3.66	(1.12)
80.4	(24.5)	4.69	(1.43)
90.2	(27.5)	5.89	(1.80)
100.1	(30.5)	7.23	(2.20)
111.6	(34.0)	9.02	(2.75)
121.4	(37.0)	10.69	(3.26)
131.2	(40.0)	12.56	(3.83)
141.1	(43.0)	14.55	(4.43)
151.6	(46.2)	14.94	(4.55)

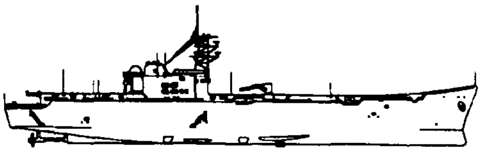


Figure 2
PRINCIPE DE ASTURIAS Profile

Test Aircraft

The AV-8B is a single place, single engine, tactical attack, vectored thrust, jet V/STOL aircraft built by McDonnell Aircraft Company (MCAIR). The aircraft has a shoulder mounted supercritical wing, four rotatable engine exhaust nozzles, and a lift improvement device system. The aircraft is powered by a Rolls Royce PEGASUS F-402-406A twin spool, axial flow, turbofan engine with an uninstalled sea level static short lift wet thrust rating of 21,500 lb (95,600 N). The primary flight controls consist of aerodynamic and reaction controls which are interlinked in all axes and hydraulically powered. The AV-8B is an excellent aircraft for ski jump takeoff due to its exceptional low-speed flying qualities. A three view drawing of the AV-8B is presented in figure 3.

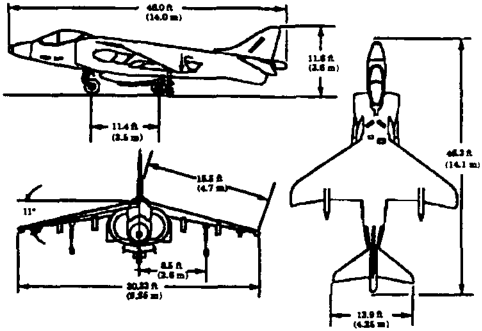


Figure 3
AV-8B Three View Drawing

Two aircraft were used for shipboard testing: a preproduction AV-8B which was instrumented for flying qualities and performance testing and nose and main landing gear strut positions, and a non-instrumented production AV-8B. Both aircraft were representative of production EAV-8B aircraft for the purpose of these tests.

Shipboard Tests

STO Launch Technique

A typical STO launch profile is illustrated in figure 4. Nozzles are positioned to 10 deg below fully aft for the deck run to reduce vibratory loads on the flaps and stabilator. The launch begins with application of full power with brake release as the tires begin to skid. The stick is guarded in the preset trim position throughout the deck run and nozzle rotation. As the aircraft exits the ramp, the pilot positions the nozzle lever to the preset STO stop. Ramp exit cues are both visual (nozzle rotation line) and physical (decrease in load factor as the aircraft leaves the ramp). After ramp exit, the pilot task is to maintain the aircraft pitch attitude achieved at ramp exit (approximately 18.5 deg) and monitor angle of attack (AOA). If AOA reaches 15 deg during the trajectory, the pilot decreases the aircraft pitch attitude as required to maintain AOA at or below 15 deg. Immediately after ramp exit, the velocity vector indicates a climb due to the upward velocity imparted by the ramp. This initial rate of climb is not a true indication of aircraft performance, and decreases to a minimum at an inflection point prior to the aircraft achieving a normal semi-jetborne climb. Prior to the inflection point, the aircraft normal acceleration is less than 1 g. The aircraft has a positive rate of climb due to the ramp induced vertical velocity, but rate of climb is decreasing due to insufficient lift. At the inflection point, the aircraft has accelerated to an airspeed at which aircraft normal acceleration is 1 g (lift=weight), and rate of climb is no longer decreasing. After the inflection point is reached, the aircraft begins a normal semi-jetborne climb (normal acceleration greater than 1 g), and rate of climb increases. At this point, the pilot gradually vectors the nozzles aft and accelerates to wingborne flight.

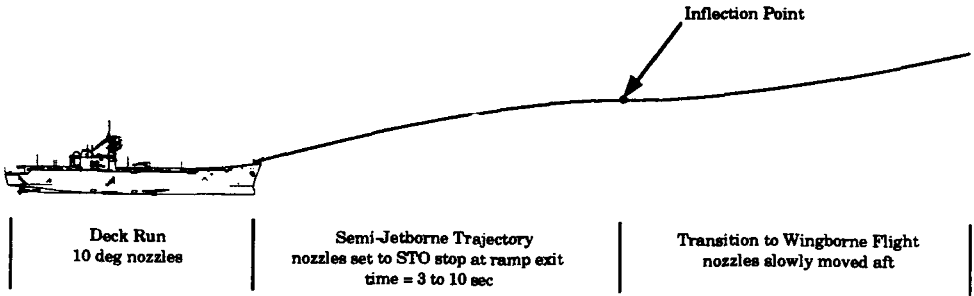


Figure 4
STO Launch Profile

STO Ramp Exit Speed

STO ramp exit speed must be accurately predicted to ensure ramp exit airspeed required is obtained and landing gear structural limits are not exceeded. Ramp exit speed is a function of aircraft hover weight ratio and deck run. Tests were conducted at deck runs from 200 to 550 ft (61 to 168 m). Actual Ramp exit speeds were obtained from infrared trips which were mounted at the end of the ramp. Ramp exit speed data was reduced to an exit speed parameter and plotted against deck run. The exit speed parameter is defined as $V^2(W/W_h)$ and its relationship to deck run is based on the dynamic relationship $V^2=2aS$ where "a" is the average acceleration and "S" is the deck run. STO ramp exit speed averaged one kt less than that of an identical flat deck launch due to the decelerating effects of the ramp. Ramp exit speed was predictable within 2.5 kt.

STO Landing Gear Structural Limits

During ski jump launch with no ship motion, loads are imparted on the landing gear due to aircraft gross weight, aerodynamic lift, vectored engine thrust, pitching moments, and inertial forces including centrifugal forces. Centrifugal forces are influenced by aircraft velocity and local ramp curvature. The primary dynamic response exhibited by the AV-8B during ski jump launch is in the aircraft heave mode. Dynamic response to aircraft pitch motion is small in comparison to heave.

STO maximum ramp exit speeds for landing gear structural limits were determined at gross weights of 26,000, 28,000, and 31,000 lb (11,793, 12,701, and 14,062 kg). Fatigue strength for 1,500 lifetime ski jump launches defined the limiting criteria for landing gear based on MCAIR analysis. Nose and main landing gear strut positions were instrumented and monitored real-time. Simulation data and previous ski jump testing indicated outrigger landing loads would not approach limiting criteria and were therefore not instrumented. Target ramp exit speed for the first launch at each gross weight was based on MCAIR simulation and was at least 10 kt below the predicted landing gear limit. The ramp exit speeds for successive launches were increased in increments of approximately three to five kt by increasing deck run until the limiting criteria were reached. A method suggested by MCAIR was used to account for ship motion. Load factor trends were incremented for sea state resulting in a shift in the aircraft gross weight vs maximum ramp exit velocity curve for given sea states. MCAIR correlated ship motion with sea state based on ship motion studies of similar type ships by David Taylor Ship Research and Development Center. Worst case phasing of ship's pitch, heave, and coriolis effects were used to determine load factor increments due to sea state. The coriolis effect is the additional normal acceleration of the aircraft due to its increased velocity normal to the deck while it travels away from the ship's pitch center. Analytical results were verified with test data and are presented in figure 5.

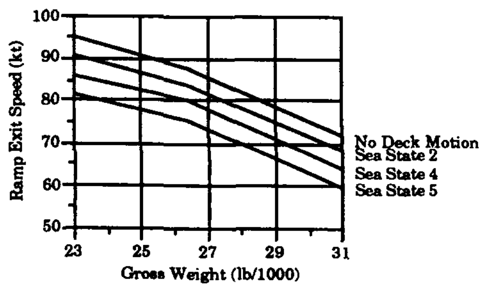


Figure 5
Landing Gear Structural Limits

STO Minimum Ramp Exit Airspeed

STO minimum ramp exit airspeed tests were conducted at hover weight ratios of 1.43, 1.52, and 1.60. The purpose of these tests was to define the minimum ramp exit airspeed required for a safe launch and to evaluate the sensitivity of reducing ramp exit airspeed when operating near the minimum. The minimum airspeed was approached by holding hover weight ratio constant while decreasing ramp exit airspeed for each successive launch. Ramp exit airspeed for the first launch at each hover weight ratio was based on MCAIR simulation and previous ski jump testing and targeted an airspeed approximately 15 kt above the predicted minimum. The ramp exit airspeeds for successive launches were reduced in decrements of approximately three to five kt by varying either deck run or WOD until the minimum ramp exit airspeed was reached. The limiting factor for ramp exit airspeed was zero rate of climb at the inflection point. Test results are presented in figure 6. Flying qualities at minimum ramp exit airspeeds were satisfactory. AOA was controllable with a maximum transient AOA of 17 deg. Lateral control was acceptable throughout the STO envelope. Longitudinal acceleration was acceptable for all launches, averaging two to four kt/sec for launches with rate of climb from 200 to 1,000 ft/min (61 to 305 m/min). The minimum longitudinal acceleration achieved during the test program was 1.5 kt/sec.

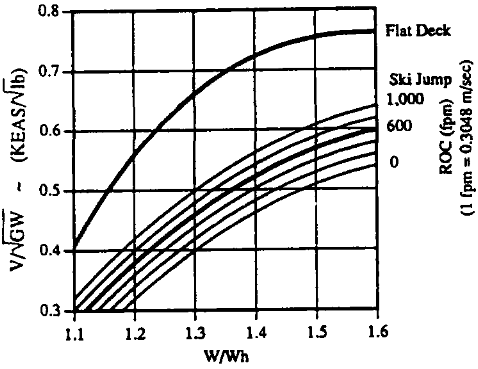


Figure 6
Takeoff Performance

Ski Jump/Flat Deck Comparison

Increased performance obtained from a ski jump assisted launch is realized through reduced WOD and/or deck run requirements and/or increased launch gross weight capability. The discussion in this section deals with the performance gains realized with the PRINCIPE DE ASTURIAS ramp. Performance gains obtained from different ramps will vary with ramp exit angle.

Ski jump launch WOD requirements are compared with flat deck requirements in figure 7. Required WOD for a ski jump assisted launch is approximately 30 kt less than a flat deck launch. Ski

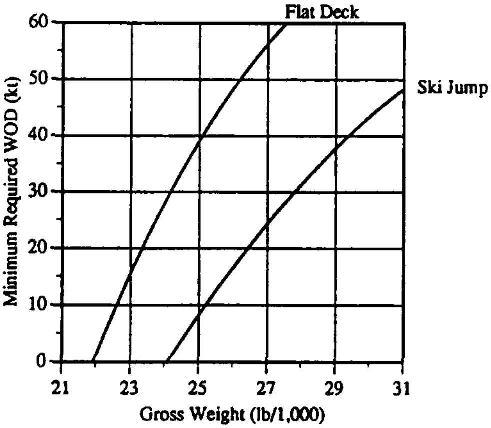


Figure 7
STO WOD Requirements
300 ft Deck Run
Standard Day, Nominal SLW Engine

jump launch operations are therefore not as dependent on natural winds for launch. As a result, normal launch operations do not dictate ship's heading, allowing the ship maneuvering flexibility and decreased operating area during flight operations. Reduced WOD requirements can be appreciated in fuel savings, as the ship can steam at the speed required for minimum steerage and not dictate ship's heading, allowing the ship maneuvering flexibility and decreased operating area during flight operations and still have the required WOD for normal launch operations. Reducing ship's speed from 25 to 7 kt decreases fuel consumption by approximately 80%.

Deck run requirements for ski jump launch are compared with flat deck requirements in figure 8. Instead of launching at lower WOD, ski jump launches can be conducted at the same WOD required for flat deck launches while reducing the deck run by approximately 350 ft (107 m). The result is improved interoperability between Harriers and helicopters. On flat deck ships, if a Harrier is to launch with a significant payload then the entire flight deck is often required for the deck run. This makes Harrier/helicopter interoperability extremely difficult. By reducing the required deck run with the assistance of a ski jump, Harriers can conduct takeoff and landing operations from the forward flight deck while helicopters operate concurrently and completely independently from the aft section. Vertical landing operations to the forward deck spots provide excellent visual cues due to the ramp height, offering significant improvement over vertical landing operations to forward deck spots on a flat deck ship. The ability to operate Harriers and helicopters at the same time from the same flight deck greatly enhances the efficiency of the amphibious assault force.

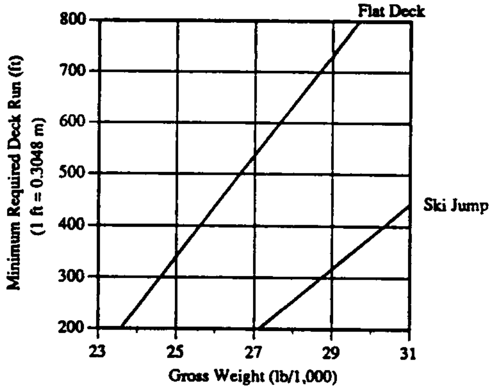


Figure 8
STO Deck Run Requirements
35 kt WOD
Standard Day, Nominal SLW Engine

Gross weight capability for a ski jump launch is compared with flat deck capability in figure 9. For a given WOD and deck run, an AV-8B can carry 3,000 to 5,900 lb more payload from a ski jump ship than from a flat deck ship. This equates to up to a 53% increase in takeoff payload capability. When operating from flat deck ships in tropical day conditions, AV-8B aircraft mission payload is limited by takeoff performance, which is not the case for operations from a ski jump ship. The efficiency of the close air support mission is therefore enhanced by a ski jump assisted launch by allowing more payload per sortie.

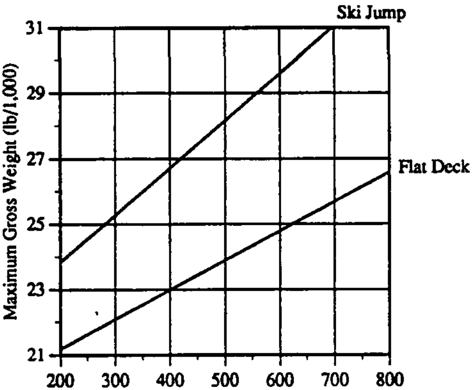


Figure 9
STO Gross Weight Capability
30 kt WOD
Tropical Day, Nominal SLW Engine

There are several safety enhancing characteristics inherent in a ski jump assisted launch. The tracking task during a ski jump launch is easier than during a flat deck launch because the tram lines are more prominent due to the height of the ramp. The ski jump launch produces no pitch-up tendencies at ramp exit and can be completely stick free for a few seconds after ramp exit. This reduces the tendency for pilot induced oscillations when attempting to capture a pitch attitude. The stick free characteristics inherent in a ski jump launch decrease pilot workload and allow more time for monitoring engine performance and critical launch parameters. The aircraft always has a positive rate of climb as it exits the ramp. The resulting additional altitude allows the aircrew more time to evaluate and react to emergency situations. The loss of an aircraft due to an emergency during a flat deck launch may be avoidable with the assistance of a ski jump. Pilot opinion is that the ski jump launch is the easiest and most comfortable way to takeoff in a Harrier.

<u>Summary</u>

PRINCIPE DE ASTURIAS proved to be an excellent platform for Harrier operations. The flight test program clearly demonstrated the performance gains, reduced pilot workload, and improved safety inherent in a ski jump assisted shipboard takeoff for Harrier aircraft when compared to that of a conventional flat deck. WOD requirements were approximately 30 kt less than flat deck requirements. Reduction in WOD requirements means significant fuel savings and flight operations having less impact on ship's heading. Deck run requirements were approximately 350 ft (107 m) less than flat deck requirements. Reduction in required deck run improves the Harrier/helicopter interoperability, allowing Harriers to use the forward half of the flight deck and helicopters the aft portion. Maximum payload capability for a ski jump assisted launch is up to 53% greater than flat deck capabilities, allowing 3,000 to 5,900 lb more payload. The heaviest Harrier to be launched from a ship to date was accomplished during the test program (31,000 lb). Increased payload capability allows shipboard Harrier operations to the same takeoff gross weight as shore based. A ski jump launch always produces a positive rate of climb at ramp exit. The resulting altitude gain allows the aircrew more time to evaluate and react to emergency situations. The loss of an aircraft due to an emergency during a flat deck launch may be avoidable with the assistance of a ski jump. Pilot opinion is that the ski jump launch is the easiest and most comfortable way to takeoff in a Harrier.

<u>CONVENTIONAL TAKEOFF AND LANDING (CTOL) AIRPLANE SKI JUMP EVALUATION</u>

<u>Background</u>

The U. S. Navy has also evaluated ski jump takeoff as an alternative to shipboard catapult launch for conventional airplanes. The Naval Air Test Center conducted a ski jump takeoff test using a T-2C, an F-14A, and an F/A-18A operating from a variable geometry ski jump ramp to:

a) Evaluate the feasibility of the concept.

b) Define the operating limitations.

c) Document performance gains.

d) Verify and update aerodynamic and structural ski jump simulations.

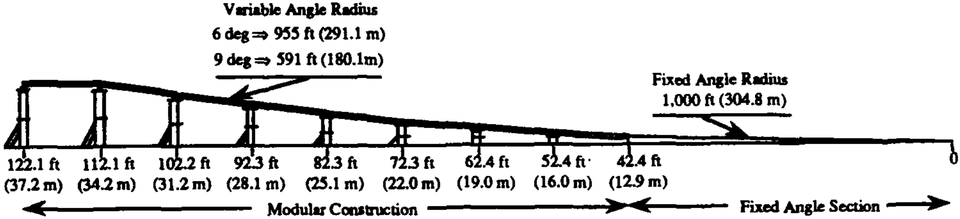
e) Propose airplane and ramp design considerations.

This section of this paper discusses the test program conducted with the F/A-18A airplane. Test results obtained with the T-2C and F-14A airplanes can be obtained from references 1 and 2. A more detailed discussion of the F/A-18A ski jump test program is presented in references 3 and 4.

<u>Test Equipment</u>

<u>Ski Jump Ramp</u>

The ski jump ramp, which was constructed at the Naval Air Test Center, was 60 ft (18.3 m) wide and 112.1 ft (34.2 m) or 122.1 ft (37.2 m) long, depending on the ramp angle. It was of modular steel construction of which the first 42 ft (12.8 m) was a fixed angle ramp with the remainder constructed of 10 x 30 ft (3.0 x 9.1 m) steel modules secured to steel pedestals. The heights of the steel pedestals was varied to give the desired ramp curvature. Figure 10 gives presents the general ramp arrangement and specific heights for the two ramp geometries. Leading into the ramp was a 60 ft (18.3 m) wide x 2,000 ft (609.6 m) long runway consisting of AM-2 matting. Centerline marking was two tram lines 2.5 ft (0.8 m) either side of the centerline. A modified holdback/release system was developed permitting stabilized thrust prior to the takeoff acceleration run. This system could be positioned anywhere along the runway to provide the desired ramp speed.



9 Degree Ramp Depicted

Distance Along Ramp ft (m)	Ramp Height ft (m) 6 deg	Ramp Height ft (m) 9 deg	Distance Along Ramp ft (m)	Ramp Height ft (m) 6 deg	Ramp Height ft (m) 9 deg
0	0	0	82.3 (25.1)	3.88 (1.18)	4.40 (1.34)
42.4 (12.9)	1.16 (0.35)	1.16 (0.35)	92.3 (28.1)	4.81 (1.47)	5.62 (1.71)
52.4 (16.0)	1.68 (0.51)	1.71 (0.52)	102.2 (31.2)	5.85 (1.78)	7.02 (2.14)
62.4 (19.0)	2.30 (0.70)	2.44 (0.74)	112.1 (34.2)	5.85 (1.78)	8.58 (2.62)
72.3 (22.0)	3.03 (0.92)	3.33 (1.01)	122.1 (37.2)	---	8.58 (2.62)

Figure 10
Ski Jump General Arrangement

__Test Airplane__

The F/A-18A airplane is a single-place, midwing, high performance, twin-engine strike fighter powered by two General Electric F404-GE-400 engines with an uninstalled thrust of 16,000 lb (71,171 N) each. The F/A-18 incorporates a digital fly-by-wire flight control system. The test airplane was aerodynamically and structurally representative of production airplanes. No modifications were made to the test airplane for the conduct of the tests. The following special flight test instrumentation installations were available:

a) Magnetic tape and telemetry system to record/transmit all required parameters.

b) Flight test instrumentation controls in the cockpit.

c) Ballast was installed to simulate the weight and CG of production equipment not installed in the airplane.

d) Radome mounted angle of sideslip vane which was displayed on the Head Up Display (HUD).

e) Retro-reflectors near the tip of each vertical tail to provide LASER tracking spatial data.

f) Landing gear instrumentation to obtain shock strut deflections and structural loads.

All build-up ground and flight tests and ski jump launch operations were conducted in the normal takeoff configuration. Table 2 details the test conditions. Two airplane gross weights were chosen to vary the thrust/weight ratio. External stores comprised two inert wingtip mounted AIM-9 (Sidewinder) and two inert nacelle mounted AIM-7 (Sparrow) missiles.

Table 2
Configuration Summary
F/A-18A Airplane

Takeoff Configuration	Gross Weight lb (kg)	Field Takeoff Airspeed KEAS	Thrust/Weight
Half Flaps (30 deg)	32,800 (14,878)	146	0.52 MIL 0.76 Max A/B
	37,000 (16,783)	154	0.46 MIL 0.67 Max A/B

__Manned Simulation__

Extensive simulation effort was expended prior to the first ski jump takeoff. Simulation included both an aerodynamic and a landing gear loads model. The simulations not only were used to predict performance gains and structural loads, but enabled the test team to develop a build-down procedure during actual ski jump operations. Also, airplane single engine failure response characteristics and minimum safe ejection airspeeds in the event of an engine failure were established.

Early in the simulation effort, it was determined that additional performance gains could be realized by a "man in the loop" pitch attitude capture technique. Earlier simulation and all the ski jump takeoff tests with the T-2C and F-14A had been using the "stick free" technique. With these two airplanes, longitudinal trim was set to achieve the desired flyaway AOA. However, current F/A-18 flight control logic is such that a trim AOA is based on the initial stabilator trim position prior to the takeoff run. This AOA /trim schedule is shown in figure 11. Initial simulation runs at the higher ramp exit airspeeds permitted initial trim settings providing stick free flyaways at 12 deg AOA. However, as the ramp exit airspeed was reduced, the initial trim position had to be reduced to keep peak AOA's within limit (17 deg AOA true) during the initial rotation phase following ramp exit. This resulted in trim AOA's during the flyaway somewhat below any optimum for use during a ski jump takeoff. A pilot pitch capture technique was investigated which resulted in a significant decrease in the takeoff airspeed of approximately 15 kt below the stick free results. The technique was to allow the pitch attitude to increase during the initial rotation following ramp exit and peak at approximately 18 deg, at which time nose down pitch rate was generated as the flight control system attempted to acquire the commanded trim AOA. As the pitch attitude decreased to 15 deg the pilot commanded aft stick to maintain 15 deg pitch attitude. A target capture pitch attitude of 15 deg was chosen as the HUD pitch ladder is incremented every 5 deg and at zero rate of climb, a 2 deg AOA margin below the limit AOA was provided. During the flight test program, both the stick free and pitch capture techniques were evaluated.

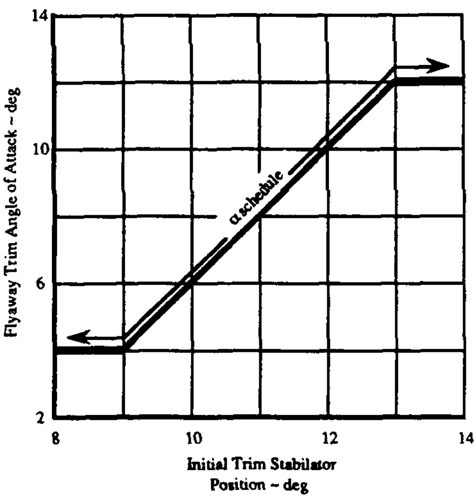


Figure 11
Trim Angle of Attack vs
Initial Stabilator Trim Position

<u>Single Engine Airspeed Considerations</u>

The reduced takeoff airspeeds attainable with ski jump operations are significantly below minimum controllability airspeeds in the event of a single engine failure. Simulation results allowed the test team to determine single engine airspeed boundaries and develop/employ aircrew procedures in event of an engine failure. Predicted F/A-18A minimum ski jump takeoff airspeeds were as much as 40 kt below dynamic singe engine control airspeeds. Ski jump operations in this region mandated ejection should an engine failure occur at or shortly after ski jump ramp exit. F/A-18 safe ejection boundaries were established during simulation. With but one exception (32,800 lb with Max A/B on the 6 deg ramp), safe ejection airspeeds occurred at ramp exit airspeeds below the predicted two engine minimum takeoff airspeeds. For this one condition, testing was conducted only down to the safe ejection airspeed. For all tests, ejection was mandatory below 120 kt.

<u>Build-up Test Operations</u>

Prior to initial ski jump takeoffs, extensive build-up ground tests were performed. These included:

a) Acceleration performance: Following thrust stand calibration, normal field takeoff tests were performed to equate ground roll and speed to airplane gross weight and thrust setting. The results provided ground roll requirements to provide the desired ramp speeds.

b) Abort capability: The abort capability and pilot procedures were defined during simulated aborted takeoffs with the additional requirement of the pilot taxiing around the ski jump ramp (ramp simulated in position). During the takeoff ground roll at the desired groundspeed, the pilot retarded one engine to idle. After 1 sec, to simulate reaction time, the pilot retarded the other engine to idle and made aggressive lateral/directional inputs to the right on the runway. From these tests an abort location and speed could be determined. These data were provided to the pilot for each test event.

c) Single engine-committed to takeoff: Once past the abort capable point, the airplane is committed to ramp takeoff. A single engine failure is the most critical from a standpoint of keeping the airplane within the 60 ft (18.3 m) width of the ski jump runway and ramp. As with the abort capability testing, engine failure during takeoff ground roll was simulated; however, the pilot task was to maintain runway centerline. The maximum lateral deviation recorded was 6 ft when using Max A/B. If an engine failure had occurred past the abort capable point, the airplane was controllable within the width of the runway and ramp.

<u>Test Results</u>

<u>General</u>

A total of 91 ski jump takeoffs were obtained with the F/A-18A operating from both the 6 and 9 deg ramps. Significant reductions in takeoff ground roll up to 66% with corresponding takeoff airspeed reductions of 64 kt were achieved. With the proper longitudinal trim set prior to the takeoff, a "hands off" takeoff during rotation and flyaway following ski jump ramp exit was possible. However, additional performance gains were obtained using the pilot pitch attitude capture technique described earlier.

Performance Gains

As the ski jump takeoff exit airspeed was decreased, the minimum rate of climb during the flyaway slowly decreased. The minimum rate of climb as a function of ramp exit airspeed for the 9 deg ramp is shown in figure 12. The minimum ski jump takeoff airspeed tested was dictated by zero rate of climb during takeoff. The minimum takeoff airspeeds achieved during tests are presented in table 3.

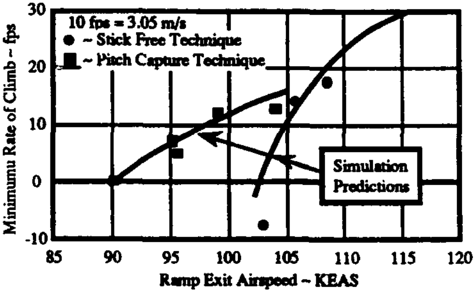


Figure 12
Minimum Rate of Climb during
Ski Jump Takeoff
9 Degree Ski Jump
F/A-18A Airplane
37,000 lb (16,783 kg) ~ Max A/B

Table 3
Ski Jump Minimum Takeoff Airspeeds

Thrust	Gross Weight lb (kg)	Minimum Takeoff Airspeed KEAS		Minimum Ground Roll ft (m)	
		6 deg ramp	9 deg ramp	6 deg ramp	9 deg ramp
MIL	32,800 (14,878)	102	98	1,075 (328)	850 (259)
	37,000 (16,783)	110	106	1,400 (427)	1,250 (381)
Max A/B	32,800 (14,878)	100	82	640 (195)	385 (117)
	37,000 (16,783)	99	90	700 (213)	575 (175)

NOTE: Minimum airspeed criteria: Proximity to zero rate of climb for all test points except 32,800 lb (14,878 kg) with Max A/B on 6 deg ramp which was limited by operation within safe ejection boundaries.

With the reduction in the ski jump takeoff airspeed was a corresponding reduction in the takeoff ground roll. F/A-18A ski jump reduction in takeoff distance for takeoff ground roll is presented in figure 13. The reduction is distance is related to the airplanes flight manual performance data for the test day conditions. The maximum reduction in takeoff ground roll relates to the minimum takeoff airspeed, whether dictated by zero rate of climb or single engine safe ejection boundaries. For any takeoff where minimum ground roll is required and the takeoff trajectory is not critical, the lowest airspeed is necessary. Reductions in takeoff distances are summarized in table 4.

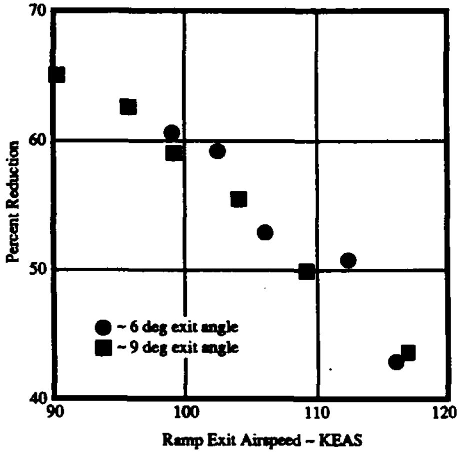


Figure 13
F/A-18A Reduction in Takeoff Distance
during Ski Jump Takeoff
37,000 lb (16,783 kg) ~ Max A/B

Table 4
Comparison of Reduction in Takeoff Distance
F/A-18A Ski Jump

Thrust	Gross Weight (lb)	% Reduction in Takeoff Ground Roll	
		6 Deg Ramp	9 Deg Ramp
MIL	32,800 (14,878)	51	51
	37,000 (16,783)	51	55
Max A/B	32,800 (14,878)	49	62
	37,000 (16,783)	61	66

Ground Handling and Flying Qualities

The ski jump takeoff commenced when the modified hold-back/release was activated. In both MIL and Max A/B thrust takeoffs, the initial acceleration was smooth with only a slight tendency towards pilot "head-jerk" at release. Although acceleration was more rapid in Max A/B, especially at the lower gross weight, the pilot had sufficient time to make pre-abort checks of engine performance. The airplane was not readily disturbed in its directional track by irregularities in the AM-2 matting; any small deviations were easily controlled ± 2.5 ft (± 0.8 m) of runway centerline. No significant longitudinal airplane response (pitch oscillation, nosewheel bounce, etc.) was encountered after holdback release. Nosewheel lightening was experienced prior to going onto the ramp; however, it was not objectionable and did not affect directional control. The abort capability point within ± 50 ft (15.2 m) was recognized by the pilot visually and reinforced by scanning the INS display for the predetermined ground speed for abort. Once beyond the abort point and committed to takeoff, the pilot was able to monitor engine performance and maintain centerline tracking. An increase in normal acceleration of 2 to 4 g characterized the entry onto the ramp, with more onset rate perceived on the 6 deg ramp than the 9 deg ramp. Using the 6 deg ramp, a rapid and abrupt g-onset was encountered, feeling to the pilot as though the airplane had rolled over a small obstacle. Entry onto the 9 deg ramp was smooth with predictable g-onset building rapidly and without the "thump" associated with the 6 deg ramp. Duration of elevated g on the ramp was short, lasting 1/2 to 3/4 sec. The dynamic landing gear interface with the ramp allowed for predictable and satisfactory flying qualities upon ramp exit.

The inclination of the ramp established the initial pitch attitude off the ramp. Longitudinal trim settings, accurate to within ± 0.5 deg, produced comfortable, initial positive pitch rates of 6-8 deg/sec. The trim setting was adjusted to obtain a peak pitch attitude of 18 ± 2 deg at less than the AOA limit of 17 deg. Pitch rates damped to zero or slightly positive during stick free takeoffs or were arrested to zero by pilot flight control input during pitch capture takeoffs. The airplane flew an arc with normal acceleration beginning at 0.25 g and increasing to 1 g over a 4 to 5 sec time frame. The 15 deg pitch capture was easily accomplished within ± 0.5 deg using longitudinal stick inputs of less than 2 inches (5 cm) and usually required only one stick input. No tendencies for longitudinal PIO were experienced during the pitch capture. The AOA peaked shortly after the peak pitch attitude and peaked a second time when the pilot captured 15 deg of pitch then smoothly decreased as the airplane accelerated.

Lateral control throughout the ski jump test program was excellent, even with a crosswind component. After departing the end of the runway, the airplane would yaw smoothly into the relative wind and little or no control input was required to maintain wings level attitude.

The F/A-18A digital flight control system eliminated any adverse flying qualities following takeoff from the ramp. The HUD information is sufficiently accurate for VMC and IFR conditions and would provide more than adequate information for night operations. The accurate and repeatable longitudinal trim system enhanced predictability for the ski jump takeoffs. All these factors made the F/A-18A ski jump takeoff, stick free or pilot-in-the-loop, easier than a field takeoff.

Structural Loads

Significant structural loads are imposed on an airplane during ski jump ramp transit. The stringent structural design requirements of US Navy carrier based airplanes provided the necessary strength for ski jump operations. The principle area of concern was landing gear loads. The desire to conduct initial ski jump takeoffs close to normal field takeoff airspeeds posed a dilemma in that the maximum loads were incurred during the first ski jump takeoffs. In general, main gear loads showed good agreement with simulation predictions; however, higher nose gear loads were obtained. A significant random variation in nose gear loads was experienced due to nose gear dynamics encountered prior to the start of the ramp. These nose gear dynamics were attributable to the unloading of the nose gear during the acceleration run and the uneven surface of the AM-2 matting runway. Most notable to the pilot during ramp transit is the incremental normal acceleration. Peak incremental accelerations measured at the airplane CG are shown in figure 14. Accelerations experienced by the pilot were higher.

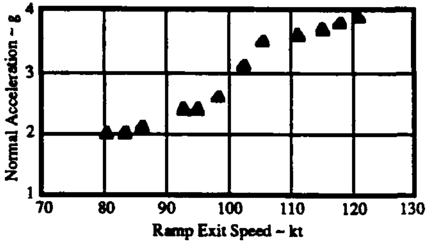


Figure 14
Maximum Normal Acceleration
During Ramp Transit
9 deg Exit Angle

A circular radius of curvature ramp, as tested, is not the optimum curvature profile for a ski jump ramp. Figure 15 depicts F/A-18A nose and main landing gear loads along the curvature of the ramp. High nose gear loads were encountered only during a small portion of the ramp. Ideally, landing gear loading should be equally distributed throughout ramp transit. This would permit attaining the desired ramp exit angle, ramp angle being the dominant factor in performance gains, using a minimum ramp size and still keeping the loads within limits. Simulation is the perfect tool to evaluate different ski jump ramp profiles to optimize nose and main landing gear loads.

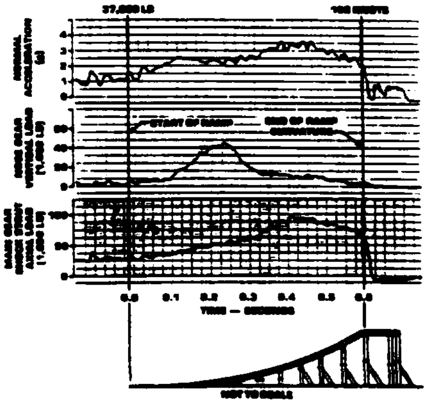


Figure 15
F/A-18A Nose and Main Landing Gear
Loading During Ramp Transit

Summary of CTOL Airplane Ski Jump Testing

Ski jump takeoff operations with current conventional fixed wing airplanes are possible. The significant performance gains, as exemplified by a 66% reduction in takeoff ground roll clearly demonstrates the potential of the ski jump concept. From a ground handling and flying qualities standpoint, a ski jump takeoff is an easier maneuver than a normal field takeoff. Longitudinal trim can be set to permit a stick free takeoff; however, additional performance gains were realized by the pilot using a pitch capture technique. Structural loads during ramp transit were well within the design limits of the test airplane.

CATAPULT/RAMP ASSISTED TAKEOFF

Introduction

The beneficial use of ramp assisted (Ski Jump) takeoff has been proven operationally by the British Navy, US Marine Corps and, most recently, by the Spanish Navy for AV-8B Harrier V/STOL aircraft. The US Navy test program described earlier in this paper demonstrated the feasibility of using Ski Jump to greatly reduce land-based takeoff distance requirements for CTOL aircraft as well. The analytical tools developed and validated during the US Navy CTOL program have been used to investigate potential benefits which might be derived from the use of Ski Jump for shipboard CTOL aircraft launch operations. A cross-section of operational US Navy carrier-based aircraft (F/A-18A, E-2C, A-6E, EA-6B, S-3A, F-14A) have been analyzed in conjunction with a modified mini-ramp geometry and steam catapult combination (Catapult/Ramp Assisted Takeoff (CRAT)). Aircraft performance, flying qualities, structural dynamics and piloting requirements were considered in determining possible required WOD reduction or allowable aircraft takeoff gross weight increase. Analytical results are presented which show potential reduction in WOD of from 5 to 35 kt for operational aircraft gross weights while keeping (1) maximum landing gear loads well below design limits and (2) minimum endspeeds above minimum aircraft control speed. A flight test program is planned to validate these results. The potential impact on aircraft carrier operations and possible operational problem areas are also discussed.

CRAT Concept and Ground Rules

The ski jump concept uses a ramp to rotate the aircraft flight path from horizontal to a positive climb angle at forward speeds less than those which are normally required to rotate the aircraft aerodynamically. The "early" rotation and lift-off provides an initial ROC and altitude margin which allows the aircraft to accelerate to flight speed while in a partially ballistic trajectory. A reduction in takeoff distance is achieved primarily as a result of lift-off speeds which may be considerably less than the stall speed of the aircraft.

CRAT uses the same concept as CTOL Ski Jump but replaces the free ground roll acceleration with a steam catapult assisted acceleration and the large ramp is replaced with a much smaller ramp due to deck space limitations. The lift-off speed reduction is applied to a reduction in catapult endspeed requirement for launch. In this case, takeoff distance is not reduced as it was in the previous CTOL Ski Jump effort but benefit is derived from:

1) Reduced WOD required for launch;

2) Increased takeoff gross weight at the conventionally required endspeed;

(3) Some combination of 1) and 2).

For ease of analysis and initial flight test validation, the geometry of the "fixed" portion of the ramp used in the previous CTOL Ski Jump test program was used for analytical evaluation and will be used in flight test. The geometry is presented in figure 16 and represents the first 42.4 ft (12.9 m) of the ramp shown in figure 10. It has a reference radius of curvature of 1,000 ft (305 m), a departure angle of approximately 2.1 degrees and a maximum height above the flat deck of 13.875 in (35 cm).

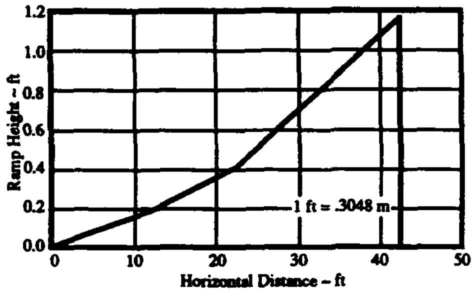


Figure 16
Mini-Ramp [42 ft (12.8 m)] Geometry

During a CRAT launch, the aircraft is assumed to leave the catapult (tow bar release) and immediately transition onto the ramp. Initial aircraft attitude, velocity, landing gear stroke, etc. are determined by the catapult stroke dynamics. Any stored energy in the landing gear due to strut compression during the catapult stroke will be released while the aircraft is on the ramp and resulting rotation is additive to that induced by the ramp. For the following analysis, each aircraft was assumed to enter onto the ramp with nominal end-of-catapult landing gear compression and aircraft pitch attitude (see table 5). Catapult endspeed was parametrically varied to evaluate performance benefits.

Table 5
Nominal Aircraft End-of-Catapult Conditions

Aircraft	Landing Gear Compression % Compressed		Pitch Attitude
	Nose	Main	deg
F/A-18A	80.7	75.0	-0.18
E-2C	0.0	83.5	1.35
A-6E	100.0	95.7	2.44
EA-6B	77.5	93.5	5.37
S-3A	96.0	84.5	1.10
F-14A	97.2	87.2	-2.13

"Minimum" Criteria Definition

The minimum launch airspeed for conventional aircraft catapult launch within the US Navy is defined as the minimum equivalent airspeed at the end of the catapult stroke for which the aircraft can safely fly away. Specifically, the minimum launch speed is set by a combination of related criteria which are described in reference 5 and are summarized here. The minimum launch airspeed is the highest of the following:

1) Stall Speed - The stall speed of the aircraft in the takeoff configuration or the speed at which stall warning first occurs if the warning does not significantly intensify as stall is approached.

2) Minimum Satisfactory Flying Qualities Speed -The speed below which the high AOA flying qualities of the configuration (e.g., damping, control response, etc.) become unsatisfactory.

3) Minimum Level Acceleration Speed - The speed at which sufficient thrust excess is available to provide at least 1 to 1.5 kt/sec of longitudinal acceleration.

4) Minimum Engine Inoperative Speed - The minimum airspeed for which there is sufficient lateral/directional control to counter an engine failure immediately following the catapult power stroke or for which single engine maximum rate of climb is attainable.

5) Minimum Rotation/Sink-off-the-Bow Speed - The speed below which aircraft pitch rotation is not sufficiently rapid or dynamic pressure is not great enough to provide enough lift (vertical acceleration) to arrest sink and establish level or climbing flight within some maximum acceptable amount of altitude loss; past experience indicates that this acceptable sink-off-the-bow is 15 to 20 ft (4.6 to 6.1 m).

The minimum conventional catapult end airspeed is typically defined by a combination of more than one of the preceding criteria over the takeoff gross weight range of a given aircraft. The operational minimum catapult end airspeed is set 15 kts higher than the previously defined minimum to allow for the negative effect of atmospheric disturbances, deck motion and non-optimum pilot technique, and to diminish (if not entirely remove) the probability of any sink-off-the-bow during normal launches.

Current practice for shipboard (AV-8A/B) ski jump operations is to define minimum launch speed such that the rate of climb during the flyaway does not become negative and available longitudinal acceleration does not become less than 1.5 kt/sec. Additionally, the obvious criterion that flying qualities must remain satisfactory down to the launch speed is also enforced. These criteria (zero minimum rate of climb, 1.5 kt/sec minimum acceleration and satisfactory flying qualities) were also used successfully to safely establish the minimum ramp endspeed for the CTOL Ski Jump program described earlier in this paper

Criteria for minimum endspeed for CRAT launches are not so clearly defined. Consider the possible flyaway trajectories of figure 17. When a ramp of any inclination is used to impart noseup rotation and rate of climb to a launching aircraft, the flyaway trajectory may be categorized into one of three classes. At higher speeds, comparable to conventional (flat deck) launch endspeeds, the trajectory exhibits positive rate of climb throughout (see trajectory 1 on the figure). As endspeed is decreased, the minimum rate of climb during the flyaway decreases until trajectory 2 is achieved with the rate of climb decreasing to zero but never becoming negative. This is equivalent to the minimum definition used for the previous CTOL programs. Finally, as endspeed is further decreased, the minimum rate of climb becomes increasingly negative and there is some minimum altitude (or maximum sink) achieved before rate of climb begins to increase (trajectory 3).

The likely candidate criteria for setting minimum endspeed are either 1) zero minimum rate of climb or 2) maximum allowable altitude loss. . Zero minimum rate of climb has been proven for existing ski jump operations (both V/STOL and CTOL) and has the added benefit of always providing the pilot with a reassuring positive rate of climb. Maximum allowable altitude loss, on the other hand, is most like the current criteria for setting minimum endspeed for conventional catapult launch. Piloted flight simulation and perhaps even flight test is required to adequately choose one criterion or some compromise of the two (e.g., maximum rate of sink). Of course, conventional catapult launch criteria 2), 3), and 4) from above must still be satisfied. The analytical results which follow include potential performance improvements for both zero minimum rate of climb and maximum allowable altitude loss trajectories.

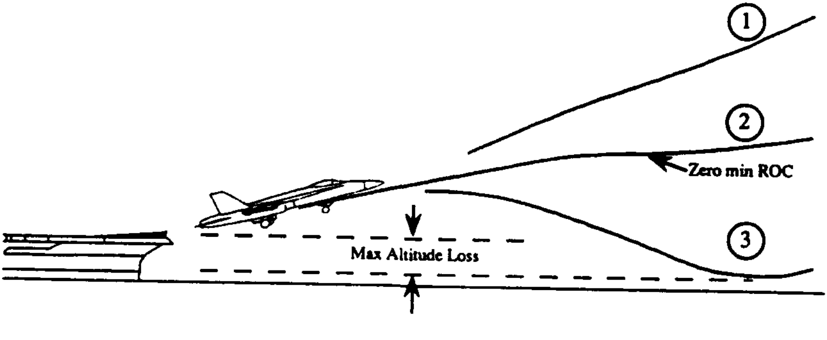


Figure 17
Possible CRAT Flyaway Trajectories

Analytical Results

The three degree of freedom (longitudinal, vertical and pitch dynamics) digital simulation model which was developed and validated during the CTOL Ski Jump program was used to analyze CRAT trajectories for a representative group of operational Navy aircraft. Table 6 list the aircraft configurations which were analyzed, including gross weights, thrust levels and flap settings. The models for each aircraft included nonlinear aerodynamic and thrust characteristics, nonlinear landing gear strut load and damping characteristics, and complete control system dynamics (see reference 6).

The analysis proceeded as follows. First, a conventional flat deck launch was simulated for each configuration at the minimum catapult endspeed and maximum altitude loss between 10 and 20 ft (3.1 and 6.1 m) was noted. These trajectories were used as a reference for comparison with the predicted CRAT launches. The ramp geometry of figure 16 was then simulated at the end of the catapult and the launch trajectories were recomputed for successively decreasing catapult endspeeds starting with the flat deck minimum and decreasing in 2-3 kt increments. Minimum rate of climb and altitude at zero rate of climb were recorded until the maximum altitude loss equalled or exceeded that for the flat deck launch. In all cases, nominal end of catapult conditions (landing gear strut compression, aircraft pitch attitude and CG height above deck) were assumed. Typical results are shown in figure 18 for the 46,000 lb (20,866 kg) F/A-18A with Max A/B Thrust. In this case, the flat deck minimum endspeed is 149 kt and the altitude loss at this speed is approximately 16 ft (4.9 m). With the ramp simulated, 16 feet of altitude loss occurs at an end speed of 129 kt providing a reduction in required catapult end airspeed of 20 kt. If the minimum were to be defined by zero minimum rate of climb instead of altitude loss, the minimum endspeed would be 137 kt providing a 12 kt reduction. Absolute minimum end airspeeds for all of the simulated configurations for flat deck launches with 15 to 20 ft (4.6 to 6.1 m) of sink and CRAT launches with comparable sink and zero minimum rate of climb are tabulated in table 7. Endspeed reduction potential for each of the minimum criteria (sink or zero rate of climb) is compared in figure 19. The results of table 7 and figure 19 indicate that minimum catapult end airspeed (and therefore required WOD) can be reduced by anywhere from 5.5 to 34.0 kt depending on the aircraft/configuration. If zero minimum rate of climb is used as a criterion, minimum endspeed reduction is decreased by a third to a half in most cases.

Table 6
Nominal Aircraft Configurations

Aircraft	Gross Weight lb (kg)	Thrust Setting
F/A-18A	46,000 (20,866) 46,000 (20,866) 52,000 (23,587) 52,000 (23,587)	MIL Max A/B MIL Max A/B
E-2C	53,000 (24,041) 53,000 (24,041)	MIL(1) MIL (2)
A-6E	46,000 (20,866) 58,600 (26,581)	MIL MIL(3)
EA-6B	50,000 (22,680) 58,600 (26,581)	MIL MIL
S-3A	44,000 (19,958) 52,500 (23,814)	MIL MIL
F-14A	59,000 (26,762) 59,000 (26,762) 69,800 (31,661)	MIL Max A/B Max A/B

Notes: 1. 10 degree flap setting
2. 20 degree flap setting
3. With loaded Multiple Bomb Racks

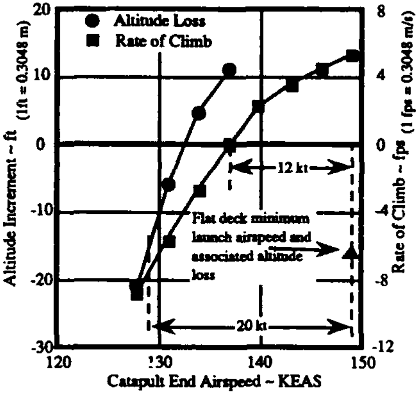


Figure 18
Altitude Loss and Minimum Rate of Climb vs. Endspeed
CRAT Launch of 46,000 lb (20,862 kg) F/A-18A with Max A/B

Table 7
CRAT Endspeed Summary

Aircraft	Configuration	Minimum Flat Deck Airspeed	Minimum Ramp Airspeed KEAS				Minimum Control Airspeed
			Altitude Loss		Zero Minimum ROC		
	Wt ~ Thrust lb (kg)	KEAS	Absolute KEAS	Δ kt	Absolute KEAS	Δ kt	KEAS
F/A-18A	46,000 (20,862) ~ MIL	152.0	138.5	-13.5	144.0	-8.0	120.0
	46,000 (20,862) ~ Max A/B	149.0	129.0	-20.0	137.0	-12.0	130.0
	52,000 (23,583) ~ MIL	164.0	150.5	-13.5	155.5	-8.5	120.0
	52,000 (23,583) ~ Max A/B	161.0	141.5	-19.5	150.0	-11.0	130.0
E-2C	53,000 (24,036) 10 deg flap	122.0	115.0	-7.0	122.0	0.0	97.0
	53,000 (24,036) 20 deg flap	108.0	102.5	-5.5	108.0	0.0	97.0
A-6E	46,000 (20,862)	115.0	105.5	-9.5	110.5	-4.5	* 105.0
	58,600 (26,576)	144.0	134.5	-9.5	138.5	-5.5	* 120.0
EA-6B	50,000 (22,676)	119.0	110.0	-9.0	114.0	-5.0	* 107.0
	58,600 (26,576)	129.0	119.0	-10.0	122.0	-7.0	* 120.0
S-3A	44,000 (19,955)	104.0	93.0	-11.0	102.0	-2.0	88.0
	52,500 (23,810)	115.0	106.0	-9.0	110.0	-5.0	88.0
F-14A	59,000 (26,757) ~ MIL	122.0	99.0	-23.0	111.0	-11.0	+ 88.0
	59,000 (26,757) ~ Max A/B	122.0	92.0	-30.0	105.0	-17.0	+ 103.0
	69,800 (31,655) ~ Max A/B	135.0	101.0	-34.0	112.0	-23.0	+ 103.0

* - 2 engine stall speed
\+ - Mid-Compression Bypass open, locked rotor, 10 deg sideslip

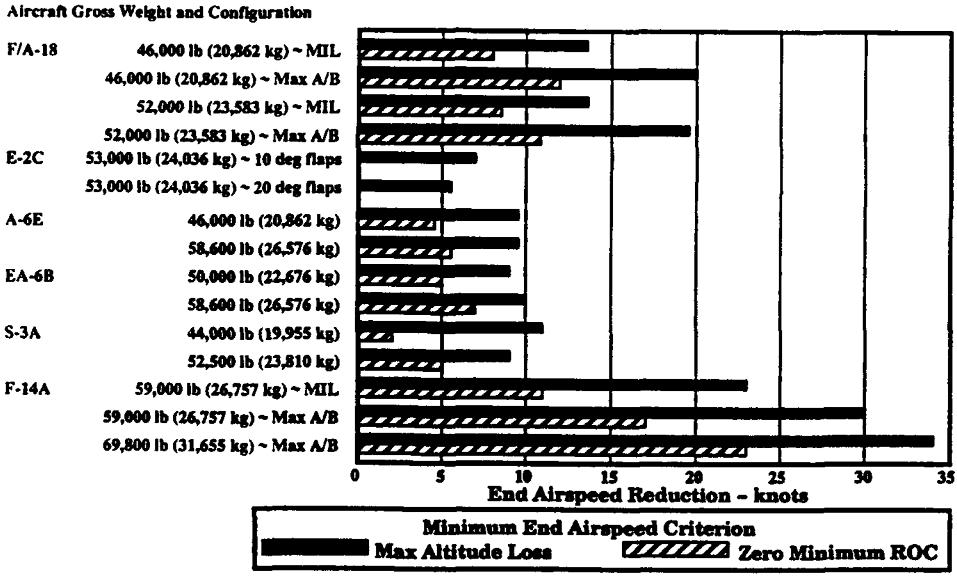


Figure 19
CRAT Endspeed Reduction Potential

The last column of table 7 indicates the minimum control speed for each of the configurations. This speed is determined from engine out control capability or aerodynamic stall speed of each configuration, whichever is most critical. The table shows that the minimum end airspeed with the ramp and using the altitude loss criterion is significantly below the minimum control speed for only the F-14A Max A/B cases. Therefore, the wind over deck reduction potential for these case may be limited by minimum control speed restrictions. If the zero minimum rate of climb criterion is used, all of the predicted endspeeds are greater than the corresponding minimum control speed. Table 8 summarizes the predicted maximum nose and main gear reaction loads and limit loads for each configuration for all speeds up to the current flat deck minimum launch speeds. In all cases the predicted loads are well below the limit loads.

Table 8
CRAT Landing Gear Load Summary

Aircraft	Configuration Wt ~ Thrust lb (kg)	Landing Gear Reaction Load ~ 1,000 lb (kN)			
		Nose		Main	
		Maximum	Limit	Maximum	Limit
F/A-18A	46,000 (20,862) ~ MIL	53.2 (236.6)	80.0 (355.9)	48.3 (214.9)	77.0 (342.5)
	46,000 (20,862) ~ Max A/B	50.6 (225.1)	⇓	46.4 (206.4)	⇓
	52,000 (23,583) ~ MIL	66.7 (296.7)	⇓	61.9 (275.3)	⇓
	52,000 (23,583) ~ Max A/B	64.5 (286.9)	⇓	59.6 (265.1)	⇓
E-2C	53,000 (24,036) 10 deg flap	19.4 (86.3)	81.0 (360.3)	65.8 (292.7)	109.0 (484.9)
	53,000 (24,036) 20 deg flap	14.4 (64.1)	⇓	46.4 (206.4)	⇓
A-6E	46,000 (20,862)	41.9 (186.4)	64.0 (284.7)	38.4 (170.8)	88.0 (391.4)
	58,600 (26,576)	47.9 (213.1)	⇓	54.3 (241.5)	⇓
EA-6B	50,000 (22,676)	35.6 (158.4)	132.0 (587.12)	67.8 (301.6)	137.0 (609.4)
	58,600 (26,576)	41.7 (185.5)	⇓	70.4 (313.2)	⇓
S-3A	44,000 (19,955)	36.5 (162.4)	80.0 (355.9)	29.0 (129.0)	105.0 (467.1)
	52,500 (23,810)	38.3 (170.4)	⇓	36.2 (161.0)	⇓
F-14A	59,000 (26,757) ~ MIL	58.8 (261.6)	70.0 (311.4)	41.0 (182.4)	100.0 (444.8)
	59,000 (26,757) ~ Max A/B	58.8 (261.6)	⇓	42.2 (187.7)	⇓
	69,800 (31,655) ~ Max A/B	65.1 (289.6)	⇓	52.5 (233.5)	⇓

Operational Considerations

While the preceding simulation results indicate the strong potential for reducing WOD requirements for catapult launch from an aerodynamic performance viewpoint operational factors must still be considered. For example, is there sufficient usable space in front of existing catapult installations to accommodate a ramp of the required length? Should ramps be positioned in front of all catapults or just the bow catapults? If ramps are positioned in front of the waist catapults, what is the effect on bolter performance/characteristics and safety? Should operational launch speed be based on the minimum altitude criterion plus 15 kt excess, the zero minimum rate of climb criterion or some other criterion? These questions, as well as I'm sure others, must be answered before CRAT becomes an operational reality.

Plans

The current US Navy plan is to conduct pilot-in-the-loop simulation evaluation of F/A-18 shipboard CRAT performance and handling characteristics. This simulation would also investigate failure procedures (engine and other system failures) and piloting techniques prior to any flight test. Following successful simulation, a technology demonstration flight test program is planned using the existing 42 ft (12.8 m) mini ramp and the Naval Air Test Center TC-7 steam catapult installation. If the flight test successfully validates the CRAT concept, the simulation tools will be updated, if required, and CRAT compatibility with all US Navy carrier-based aircraft will be verified. Shipboard operational compatibility questions will be answered and, ultimately, a shipboard test program will be conducted.

Summary

In summary, non-real time simulation has indicated the potential to reduce WOD requirements for current US Navy carrier-based aircraft by as much as 35 kts using a combined catapult/ramp assisted launch. Maximum landing gear reaction loads remain well within acceptable limits and minimum airspeeds experienced are above the minimum aircraft control speeds. Based on the non-real time simulation, pilot-in-the-loop simulation followed by land-based demonstration flight test is planned to validate the concept. If the demonstration is successful, ramp shape, size, placement and construction will be optimized and the feasibility of carrier-based flight test will be investigated.

RELEASE

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