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Ryberg, Eric S.

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While the implications of shipboard compatibility have long influenced the design of maritime-based aircraft, the Joint Strike Fighter (JSF) is unique in that the program is centered on the concurrent development of a family of highly common aircraft variants, two of which are to operate from distinctly different ship types. This procurement strategy poses a formidable challenge to the aircraft designer: How to design an air system that meets the unique needs of its multiple warfighter customers while preserving enough commonality to reap the benefits of the "family" approach to design, manufacture, and operational sustainment. This paper describes how the configurations of the United States Navy's aircraft carriers and amphibious assault ships, as well as the United Kingdom Royal Navy's INVINCIBLE-class of carriers, have influenced the basic configurations of the catapult launch / arrested landing (CV) and the short takeoff / vertical landing (STOVL) variants of the JSF. From these discussions, the designers of future air capable ships can better understand which characteristics of current ship designs impose the most significant constraints for the aircraft based aboard them, and where ship/air interface considerations should play.

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The Influence of Ship Configuration on the Design of the Joint Strike Fighter

Mr. Eric S. Ryberg

ABSTRACT

While the implications of shipboard compatibility have long influenced the design of maritime-based aircraft, the Joint Strike Fighter (JSF) is unique in that the program is centered on the concurrent development of a family of highly common aircraft variants, two of which are to operate from distinctly different ship types. This procurement strategy poses a formidable challenge to the aircraft designer: How to design an air system that meets the unique needs of its multiple warfighter customers while preserving enough commonality to reap the benefits of the "family" approach to design, manufacture, and operational sustainment. This paper describes how the configurations of the United States Navy's aircraft carriers and amphibious assault ships, as well as the United Kingdom Royal Navy's INVINCIBLE-class of carriers, have influenced the basic configurations of the catapult launch / arrested landing (CV) and the short takeoff / vertical landing (STOVL) variants of the JSF. From these discussions, the designers of future air capable ships can better understand which characteristics of current ship designs impose the most significant constraints for the aircraft based aboard them, and where ship/air interface considerations should play significant roles in ship design decisions.

INTRODUCTION

JSF Acquisition Strategy

The JSF program is a joint program among the U.S. Air Force (USAF), U.S. Navy (USN), and U.S. Marine Corps (USMC) with full partnership participation by the United Kingdom (UK). The JSF program objective is to develop and deploy a family of highly common and affordable strike fighter aircraft to meet the operational needs of the USAF, USN, USMC, UK, and US allies. This family of strike aircraft consists of three variants: Conventional Takeoff and Landing (CTOL), Aircraft Carrier Suitable (CV), and Short Takeoff and Vertical Landing (STOVL). The focus of the program is affordability—reducing the development, production, and total ownership costs of the JSF air system, while providing combat capability to meet the operational needs of the warfighters.[1]

Multi-service Operational Needs

USN OPERATIONAL NEEDS

For the USN, the CV variant of JSF will meet the need for a stealthy, multi-role strike fighter to complement the F/A-18E/F Super Hornet. It will be capable of conducting both offensive and defensive air-to-air and air-to-surface missions, operating independently or in conjunction with other assets organic to the aircraft carrier battle group. The CV variant will be designed for compatibility with NIMITZ-class aircraft carriers (CVN-68 through -77). The evolution of the USN's Next Generation Aircraft Carrier (CVNX) program will be integrated closely with that of JSF to maximize compatibility between the weapon systems.[2]

USMC OPERATIONAL NEEDS

The USMC needs a stealthy, multi-role, Short Takeoff Vertical Landing (STOVL) strike fighter to replace the AV-8B Harrier II and the F/A-18A/C/D Hornet. The aircraft will perform operations within the broad functions of offensive air support, anti-air warfare, aerial reconnaissance, electronic warfare, escort of assault support, and control of aircraft and missiles. The STOVL variant will be designed for compatibility with the TARAWA (LHA-1) and WASP (LHD-1) classes of amphibious assault ships as well as NIMITZ-class aircraft carriers. As with the future aircraft carrier CVNX, the evolution of the projected replacement for LHA, currently identified as LHA(R), will be closely tied to the development of JSF.[3]

UK OPERATIONAL NEEDS

The UK requires a Future Joint Combat Aircraft (FJCA) that will be a stealthy, multi-role aircraft to follow on from the Sea Harrier FA2, Harrier GR7, and Harrier T10 operated by the Royal Navy (RN) and Royal Air Force (RAF). The aircraft must be capable of sustained air interdiction, close air support, offensive and defensive counter air, suppression of enemy air defenses, combat search and rescue, reconnaissance, and anti-surface warfare missions.[4] While the STOVL JSF is to be evaluated for basic compatibility with INVINCIBLE-class (CVS) carriers, it is unlikely that the aircraft will ever be deployed aboard CVS for any extended periods. Instead, the UK Ministry of Defence (MoD) has initiated development of a future aircraft carrier (CVF) scheduled to enter service at or about the same time as its JSF. The CVF program is currently in its concept development phase, and the ship will be designed for compatibility with the shipboard JSF variant, CV or STOVL, that will be procured for use by the UK's joint air forces. The UK's selection of JSF variant is scheduled to occur during the first half of 2002.

JSF Program Schedule

The JSF System Development and Demonstration (SDD) phase schedule is depicted in Figure 1. In October 2001 the DoD Undersecretary for Acquisition, Technology, and Logistics (USD(AT&L)) granted authorization for the program to proceed into the SDD phase of acquisition. The SDD schedule accommodates the warfighters' needs for initial operational capabilities (IOC) of their respective variants in FY2010 for the USMC, FY2011 for the USAF, and FY2012 for the USN and UK. To illustrate JSF's relationships with future carrier development programs, figure 2 provides development schedules for CVNX and CVF.

Concurrent with the authorization for JSF to enter SDD, the USD(AT&L) selected between two proposed air system designs and development programs competing for the SDD contract. The Lockheed Martin Company was awarded an approximately $19B cost-plus-award-fee contract to define, develop, and validate the JSF weapon system family in preparation for a multi-year production effort

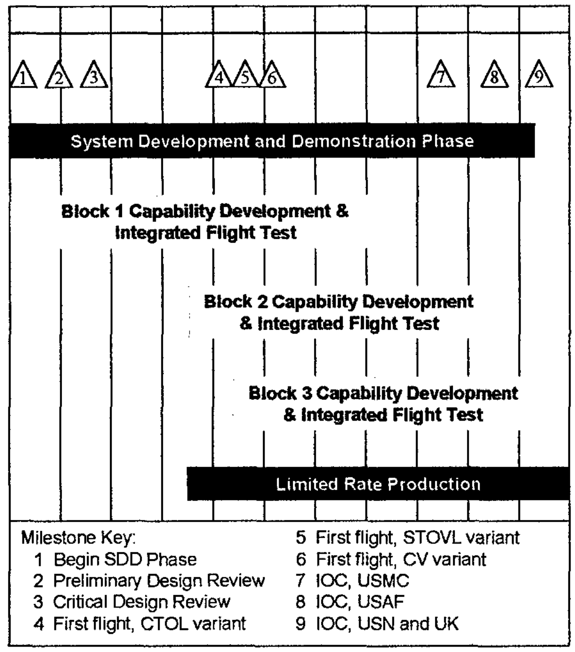

Figure 1. Joint Strike Fighter System Development and Demonstration

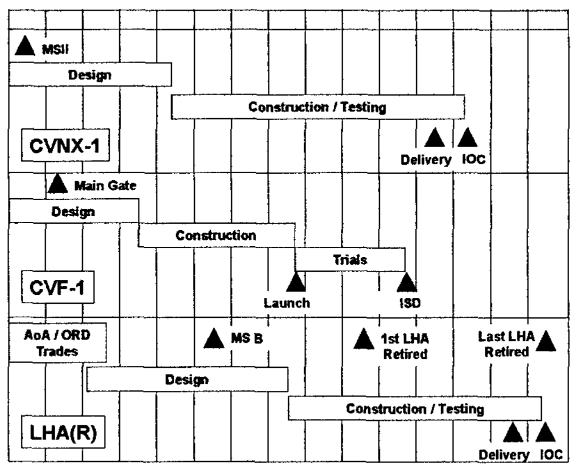

Figure 2: Ship Development Programs Concurrent with JSF

estimated to be worth in excess of $200B, dependent upon the level of international participation in the program. At these lofty amounts, JSF qualifies as DoD's largest ever acquisition program.

JSF Air Vehicle Description

Lockheed Martin's family of air vehicles, which will be known as F-35A, B, and C, is depicted in figure 3. The three variants all share a highly common structure that includes the same fuselage. All models of the design look

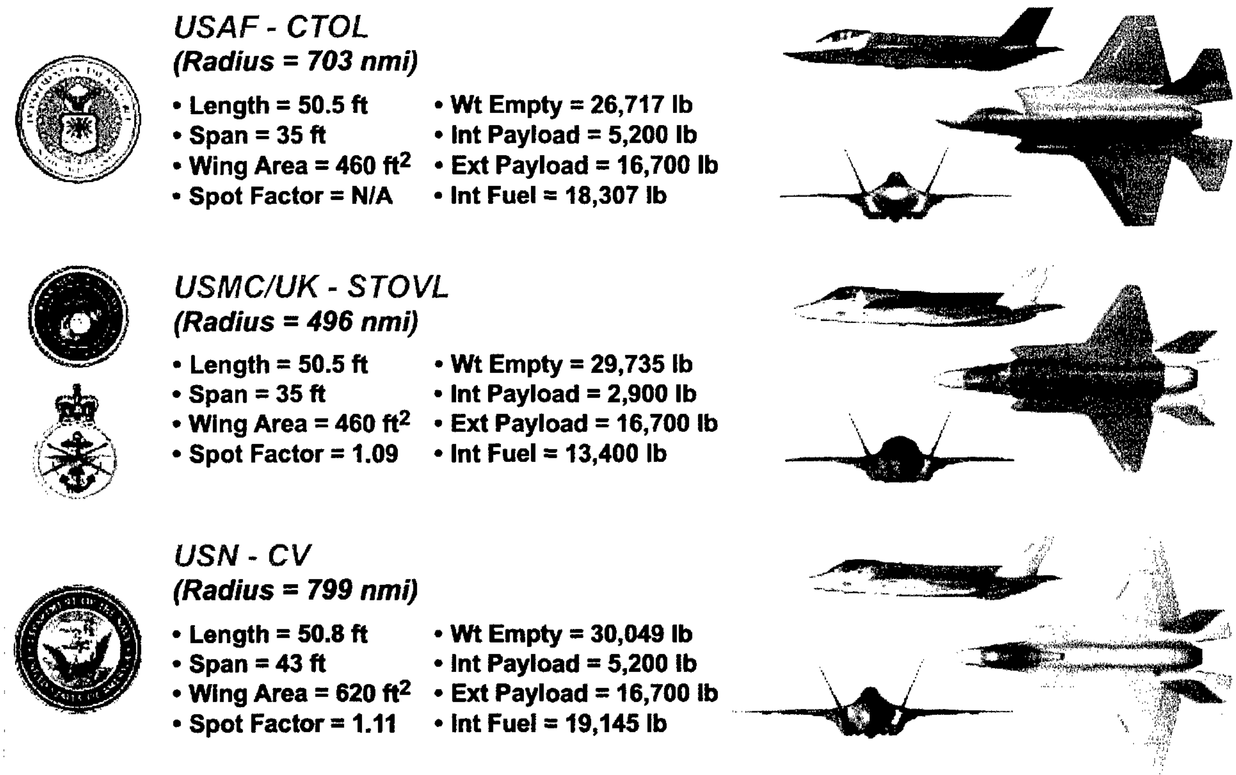

Figure 3: Description of the Joint Strike Fighter Family of Aircraft

essentially alike, with common structural geometries, identical wing sweeps, and similar tail shapes. They carry weapons in two parallel bays located in front of the main landing gear. Major portions of the fuselage contain common or closely related parts, referred to as cousin parts. The canopy, radar, ejection system, subsystems, and most of the avionics are common. All the aircraft are powered by a modification of the same core engine, the Pratt & Whitney F135.[5] During SDD, a competition will be held between P&W and General Electric, maker of the F120, for JSF's production engine.

Unique features of the CV variant include a wing with approximately 35% greater area than that on the other two variants, larger tail surfaces, and ailerons on the trailing edges of the wings. These features were added to improve the slow-speed performance and flying qualities required for carrier landings. Additionally, landing gear and other main structural components have been strengthened to withstand shipboard launch and recovery. A launch bar and arresting hook are incorporated to allow catapult takeoff and arrested landings.

The STOVL variant achieves its vertical capability through the incorporation of a non-combusting, shaft-driven lift fan and a three-bearing swivel nozzle. To operate in the vertical mode, a clutch engages the lift fan's drive shaft mounted at the front face of the engine, spinning the fan to generate downward thrust. The lift fan serves as the forward of two lift posts. The aft lift post is created by the operation of the three-bearing swivel nozzle, which can direct the exhaust of the main engine in any direction from fully aft to just slightly forward of vertical. Pitch control in the hover mode is achieved by modulating the thrust between the two lift posts. Roll control is achieved by exhausting engine bypass air through roll ducts mounted in each wing. The three bearing swivel nozzle also provides yaw control in that it can be splayed left or right of vertical to create the desired yawing moment.

JSF Ship Basing Platforms

The sea-going JSF variants will deploy on types of ships that vary widely in terms of size, shape, accommodations, and missions. A summary of the characteristics of these ships is shown in Table 1.

	CVN-68	LHA	LHD	CVS
Overall Length (ft)	1,092	820	844	680
Flight Deck Width (ft)	251(1)	118	118	117
Landing Area Length (ft)	786	820	820	550
Landing Area Width (ft)	125	50(2)	57	44
Displacement, (t) (3)	97,000	39,400	40,500	20,600
Speed (kt)	30+	24	22+	30
Launch and Recovery Equipment	Cat / Arresting Gear	None	None	12 deg Ramp

Notes:
(1) At widest point adjacent to end of catapult #4.
(2) Minimum width at the bow.
(3) Fully-loaded

Table 1. Comparison of JSF Shipboard Basing Platforms

SHIP SUITABILITY DESIGN CONSIDERATIONS

Consideration for the shipboard environment, ship interface requirements, and the users' at-sea concepts of operations is critical to the successful design of a ship-based air system. The factors that influence shipboard compatibility are quite numerous, and their impacts are often underestimated and/or misunderstood by those not completely familiar with carrier-based aviation. This next section of the paper discusses the most pertinent ship suitability design drivers to have influenced the design of JSF.

Geometric Compatibility

Probably the most intuitively obvious factor to influence the design of a ship-based aircraft is geometric compatibility. Simply stated, the airplane must be of an acceptable size and shape to fit within the constrained operating spaces aboard ship.

MAXIMUM DENSITY SPOT FACTOR

Maximum Density Spot Factor, commonly referred to as just "Spot Factor", is an empirical calculation that provides an indicator of the amount of flight or hangar deck space required to base a given aircraft aboard ship. Spot Factor is not just dependent on the pure size of a vehicle, but it is also highly affected by the aircraft's planform, and whether its shape allows multiple aircraft to be grouped easily in tight spaces. An aircraft's spot factor is calculated in accordance with a set of rules provided by the Naval Air Warfare Center Aircraft Division in Lakehurst, NJ and is expressed in terms of a ratio relative to the F/A-18C Hornet.[6]

The JSF Operational Requirements Document (ORD) established a design threshold for the Spot Factor of the CV variant, in that it could be no greater than 1.24. Early in the JSF design process, it became evident that the Spot Factor requirement would not constrain the size and shape of the aircraft. In fact, it's likely that the CV variant would satisfy the ORD Spot Factor threshold even without the capability to fold its wings. As will be discussed, however, other considerations have shown that such a mechanism is a worthwhile addition to the CV design, despite the added weight, complexity, and cost.

OPERATIONAL SPOTTING

Maximum Density Spot Factor is purely an academic exercise to quantify an aircraft's size and shape. An operational spotting analysis helps to determine how Aircraft Handling Officers could most efficiently operate a ship's complement of aircraft. Efficiency is typically quantified through use of metrics such as sortie generation rate and aircraft turnaround time. The positions where aircraft can be parked pre-launch, post-recovery, and for maintenance or servicing greatly affect these metrics. Obviously, the flight deck layout is a major determinant in deck efficiency, as are the configurations of the aircraft that make up the airwing.

Through the conduct of spotting analyses, it was determined that a folding wing afforded the JSF CV variant increased flexibility in its deck handling, enough so to offset the impact of incorporating the folding mechanisms. The CV variant's folded wingspan approximates that of an F/A-18C, the aircraft it will eventually replace in the carrier airwing. This similarity should allow Handling Officers aboard CVNs to position JSF very much like they position F/A-18C today.

Unlike the CV variant, the JSF STOVL variant did not have a spot factor requirement levied upon it. Instead, the ORD specified a spotting requirement in operational terms. The USMC operators required that it be possible to park a total of six STOVL variants aft of the island on an LHA or LHD, such that none fouls the landing area and that any one of them can be moved without first moving any other. This requirement constrains the STOVL variant's wingspan to be no more than 35 ft.

OTHER GEOMETRIC CONSTRAINTS

Aside from the amount of flight deck space needed to accommodate an aircraft, there are several additional constraints that affect its geometry. Aircraft are stored in hangar bays with constrained overhead clearances. The ceiling height must allow the conduct of all maintenance and support actions, including such tasks as the removal and replacement of the canopy and ejection seat. Additionally, compatibility with deck elevators may constrain an aircraft's length, width, or both. Safe launch and recovery operations require sufficient separation from any deck obstacle, a criterion that often dictates the shape of an aircraft and the location of its wing pylons. Table 2 summarizes for each pertinent ship class the constraints imposed by the elevators and hangar dimensions. Figure 5 presents the composite envelope formed by the superposition of the deck obstructions that surround the four catapults on CVN-68 class ships.

	CVN-68[1]	LHA[2]	LHD[1]	CVS[3]
Hangar Ceiling Height (ft)[4]	25	20	20	20
Hangar Width (ft)	108	80	80	39
Elevator Length (ft)	70 - 85	Aft: 60 Port: 50	50	55
Elevator Width (ft)	52	Aft: 35 Port: 34	44	32

Notes:
(1) CVN-68 and LHD are equipped with deck edge elevators that allow the extremities of an aircraft to extend beyond the elevator dimensions on the forward, aft, and/or outboard sides.
(2) LHA has two elevators of different sizes: a deck-edge elevator on the port side and an aft elevator open only at the stern.
(3) Both CVS elevators are positioned mid-deck, leaving no flexibility to extend beyond the elevator edges
(4) Nominal height and width. Because of ceiling and wall-mounted obstructions, specific areas of the hangar may have more or less clearance.

Table 2. Hangar Deck and Aircraft Elevator Dimensional Constraints

IMPACTS OF GEOMETRIC CONSTRAINTS

While all of these dimensional constraints have been considered in the design of the JSF family, only in isolated cases has a ship constraint dictated the size of the airplane. The basic size of the variants is as large as can be supported by the allowable STOVL performance level attainable with the government-furnished engine and the contractor-determined STOVL lift mechanisms. For the sake of commonality, the other two variants are of the same basic size as the STOVL variant, with differences incorporated where necessary to meet the unique requirements of each service customer. In general, this size airplane is easily accommodated aboard the CVN-68 class, since the size of the CV variant approximates that of aircraft currently deployed. In designing the STOVL variant for operations aboard LHD class, it too, is of a size that readily fits within existing spaces, despite it being considerably larger than the AV-8B it will replace. However, basing the STOVL variant on LHA and CVS classes would require some modification to the aircraft to ensure complete size compatibility with all constraints (e. g., flight deck elevators). Since JSF will be based on these older ship types for a small fraction of the aircraft's overall service life, requirements officers and acquisition officials have been careful not to compromise aircraft performance over a 40 year span, in exchange for full compatibility with

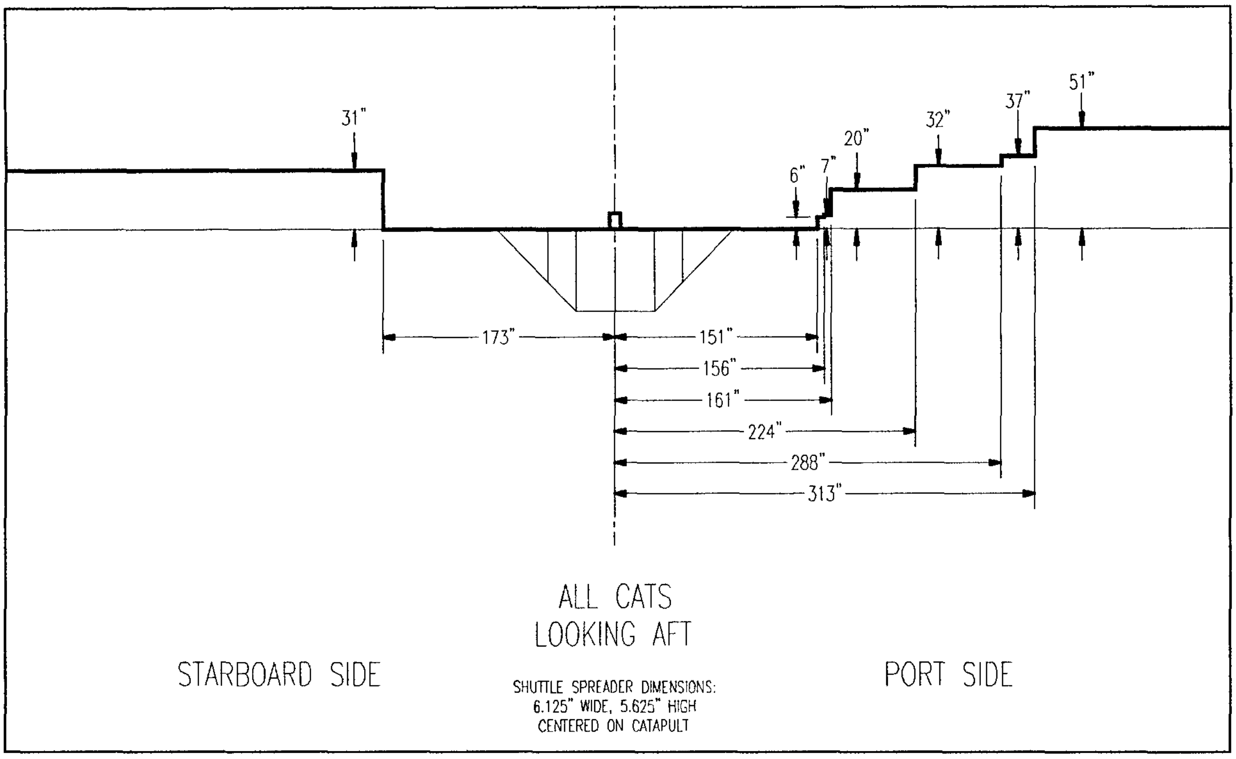

Figure 4: Composite Catapult Clearance Envelope, CVN-68 Class

ships that will be out of service within five years of the aircraft's introduction to the Fleet.

Structural Design Considerations

It is well known that the rigors of shipboard launch and recovery operations inflict ground loads upon an airframe that are typically much greater than those experienced during land-based operations. This is especially true when launch and recovery are assisted with catapults and arresting gear. The ship configuration plays a major role in the magnitude of these ground loads, not just because of the type of aircraft launch and recovery equipment installed aboard the ship, but also because the ship layout significantly affects dispersions in touchdown conditions.

AIRCRAFT LAUNCH AND RECOVERY

The JSF aircraft have been sized to take full advantage of the aircraft launch and recovery equipment available on the ships of interest. For example, the CV variant is designed to withstand the tow loads imposed by the C-13 Mod 1 and Mod 2 catapults, as well as the deceleration loads of the Mk-7 Mod 3 arresting gear. If future launch and recovery systems offer substantially different loading profiles than those factored into the design, a substantial impact to launch performance (i.e., wind-over-deck requirements) and/or service life could result.

TAKEOFF RAMP COMPATIBILITY

Since the UK is a customer for JSF, the STOVL variant will be designed to be compatible with the 12 deg short takeoff (STO) ramp, or ski jump, found on the bows of INVINCIBLE class ships. An aircraft performing a ramp-assisted STO experiences an increased normal load factor, the result of centripetal acceleration applied as the aircraft traverses the curved ramp. While the benefit to aircraft takeoff performance is predominantly a function of the inclination angle at ramp exit, the load on the aircraft is a function of the ramp's radius of curvature, coupled with the geometry and dynamics of the aircraft landing gear.

In the design of JSF, structural analyses indicated that the loads predicted for a STO off INVINCIBLE's 12 deg ramp were less severe than other design conditions such as high sink rate landings and rolling over deck obstacles. Hence, the ramp takeoff does not act as a structural design driver. However, changes in ramp profile that lessen its radius of curvature, such as an increase in exit angle for a fixed-length ramp, or a decrease in the length of a ramp with the same exit angle, may cause the STO ramp takeoff to become the most severe ground load contributor. Future ships incorporating ramps should account not just for takeoff performance benefits added by the ramp, but also for the impact of added ground loads on any aircraft to use the ramp. Use of high fidelity aircraft simulations would allow the ramp profile to be "tuned" for a particular launch scenario, such that the ramp design maximizes aircraft performance gain while minimizing the impact of added ground loads.

LANDING LOADS

In recent years, the recognized industry practice for designing an aircraft structure adequately sized for ground loads has been based around a probabilistic, multivariate approach to landing conditions. As outlined in the Joint Service Specification Guide for Aircraft Structures, aircraft are categorized by type of vehicle (fixed wing, rotary wing, STOVL), operating location (shore base, ship, austere base), and runway condition. For each combination of vehicle type and operating venue, statistical samplings have determined the distributions of eight critical landing parameters: pitch attitude, roll attitude, roll rate, yaw attitude, off-center distance, approach speed, engaging speed, and sink rate. Safe design practice recommends the aircraft structure be fully capable of withstanding without damage all landings whose conditions are more probable than 1/1000. With the empirically derived probability functions for each of the eight parameters, multivariate envelopes are computed using the total probability of $P=1 \times 10^{-3}$ to define the extremes of the envelope. The designer uses these envelopes to define the critical landing conditions that drive the structural design of the aircraft. Multivariate envelopes are also used to ensure the aircraft maintains sufficient clearance between its structure and the ground, so that it will not be susceptible to frequent ground impingement of its wing, tail, control surfaces, or externally carried stores. An example of a two-dimensional envelope formed by sink rate and roll attitude is shown in figure 5.[7]

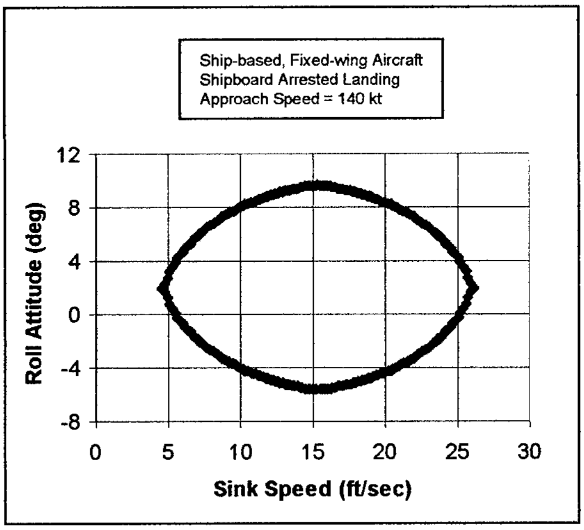

Figure 5. Example Multivariate Design Envelope

The success of this design approach clearly hinges upon the applicability of the legacy data used to generate the probability distributions. Changes in aircraft flying qualities, operational procedures, or ship configuration could significantly affect these distributions. For example, a narrower landing area leaves less room for the aircraft to deviate laterally, and may cause higher roll attitude and roll rate distributions, as the pilot task is made more difficult due to the increased precision required for landing within the safe zone. In this example, the strength of the airframe may be under-designed and ground impingement may become more frequent, as design criteria were based on probability distributions that are no longer valid. Any proposed ship configuration change that significantly alters the definition of the landing task should be evaluated for its effect on the dispersions of touchdown conditions.

Flying Qualities and Performance

Shipboard operations introduce a host of environmental factors not present ashore, and many of these factors have a significant impact on the required performance of the aircraft and its associated flying qualities.

CV VARIANT APPROACH SPEED

A safe carrier landing requires the aircraft to be capable of flying slowly enough to be recovered within the capacities of the arresting gear, while not imposing an unacceptably high requirement on the ship to generate wind-over-deck. This capability of a slow approach speed cannot come at the expense of unsatisfactory flying qualities. The aircraft must also possess good waveoff and bolter characteristics, for the times when an approach is aborted and when the arresting hook fails to engage the arresting wire. These requirements have caused the CV JSF to incorporate ailerons plus a wing and tail surfaces larger than those of the other two variants.

The Naval Air Systems Command currently defines carrier approach speed as the slowest speed that meets each of six criteria[8], but the design of JSF was driven predominantly by three: (1) the approach attitude of the aircraft must provide the pilot enough over-the-nose field-of-view to see his visual cues for landing; (2) the aircraft must be capable, without changing engine thrust, of effecting a change in flight trajectory that intersects a glidepath positioned 50 ft above and parallel to the aircraft's glidepath at the start of the maneuver, within 5 sec of control application; and (3) the aircraft must maintain desirable flying qualities throughout the maneuver. Each of these criteria will be described in more detail.

The over-the-nose field-of-view requirement is depicted in figure 6. The requirement specifies that as the pilot's eye intersects a 4 deg optical glideslope, with the aircraft in level flight 600 ft above sea level and 1-1/4 nm aft of the touchdown point, the pilot must be able to see the stern of the ship at the waterline. Upon solving this exercise in trigonometry, the requirement can be simplified to read that the aircraft's field-of-view must provide a "look down" angle greater than or equal to the aircraft's approach angle of attack (AOA) plus 4.8 deg. For example, an aircraft with an approach AOA of 10 deg must provide the pilot a field-of-view extending at least 14.8 deg below the fuselage reference line. The field-of-view requirement significantly impacts the design of the forward fuselage and canopy, which are key contributors to the aerodynamic characteristics of the aircraft, especially at high speeds.

This approach speed criterion is an excellent indicator of how ship geometry affects an aircraft characteristic completely unrelated to carrier launch and recovery, such as supersonic performance. In future aircraft, the over-the-nose field-of-view requirement will likely become less of a factor, as advanced capabilities should provide the pilot with a synthetic view of the landing area regardless of the attitude of the aircraft. For uninhabited vehicles operating automatically, this requirement is obviously not valid.

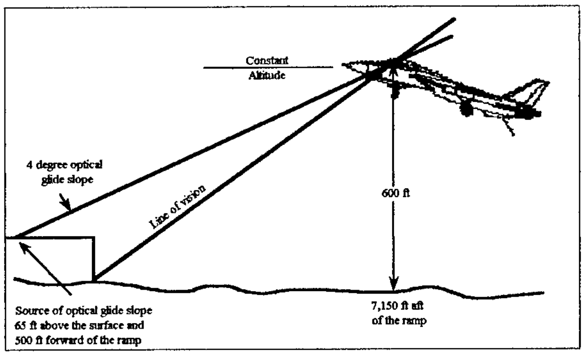

Figure 6. Over-the-nose Field-of-view Approach Speed Criterion

The glideslope transfer criterion is illustrated in Figure 7. This criterion, sometimes referred to as the "50 ft pop-up maneuver", was established during the time when jet aircraft first appeared on carrier flight decks. Its aim was to ensure that an aircraft's pitch control effector, typically just a proportional deflection of the elevator or an all-moving horizontal tail, provided enough authority to quickly alter flight path, as would be necessary in a waveoff, since the thrust response of the early jets was so sluggish that a rapid flight path change could not be achieved via a throttle input alone. Over time, the thrust response of jet engines has greatly improved, and aerodynamic controls have become much more sophisticated and often integrated with engine controls. Examples of these advances include direct lift control and automatic approach power compensator modes, both of which have been incorporated into the JSF CV variant. These modes allow the aircraft to easily accomplish the glideslope transfer, essentially rendering the criterion meaningless.

At the slow airspeed needed for approach, stability and control of an aircraft typically becomes more difficult, as aerodynamic control surfaces become less effective due to the reduced dynamic pressure. Shipboard environmental factors, such as deck motion and ship-induced airwake turbulence, further compound the challenge. Designers of the JSF have performed extensive analyses to ensure desirable flying qualities are maintained throughout the approach regime. Particularly demanding is the requirement to have enough roll control power to enable a large lineup correction during the late stages of the approach. Historically, the design metric used to quantify this attribute is the ability to command a 30 deg bank angle in no more than 1 sec. This roll control criterion was the primary impetus for incorporating ailerons to the CV variant. Similar metrics were used to size other control surfaces, which differ from those on the other two variants.

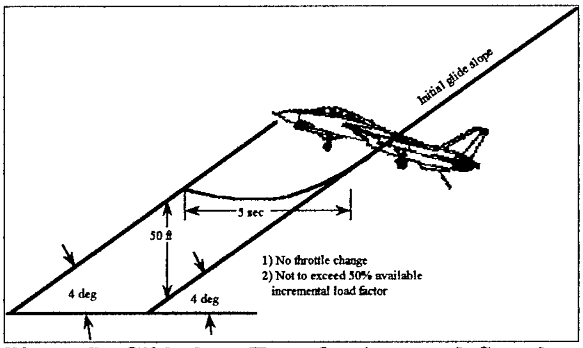

Figure 7. Glideslope Transfer Approach Speed Criterion

CV VARIANT WAVEOFF AND BOLTER PERFORMANCE

A waveoff is an aborted approach that occurs when the flight deck cannot be made ready in time to accept a landing aircraft or when conditions do not allow the approach to continue. Waveoff performance is quantified by the amount of altitude lost by the airplane from the time a waveoff is commanded until a positive rate of climb can be established. While waveoff performance must also be a consideration for land-based aircraft, it is much more critical for carrier operations because the rapid tempo of a recovery cycle make waveoffs more frequent. The need for good waveoff performance was the principal factor is sizing the desired thrust response characteristics of the JSF engine.

A bolter is an approach that was continued to touchdown, but the arresting hook was unable to engage the cross deck pendant, either because the aircraft landed beyond the landing area or because the dynamics of the landing caused the hook to skip over the wire(s). The bolter is, in essence, an unintentional touch-and-go landing. Bolter performance is measured by the amount of settle experienced by the airplane as it rolls off the edge of the flight deck. As it is for the waveoff, thrust response is a critical factor in bolter performance, in that the engine must quickly accelerate to the takeoff power setting. Yet bolter performance demands considerable pitch control power as well, because the airplane must also rotate about its main landing gear to quickly attain a flyaway attitude. Both of these events must occur prior to the aircraft leaving the flight deck, or else the aircraft would experience unacceptable settling. Bolter performance was a critical factor in sizing the tail surfaces of the CV variants. Here is another example of where ship geometry, specifically the length of the landing area, directly influenced the design of the aircraft.

STOVL VARIANT CONTROL MODES

A shipboard vertical landing is not considerably different from a vertical landing conducted ashore. While factors such as ship motion and airwake turbulence can affect pilot workload and touchdown dispersions, the vertical landing task is virtually the same regardless of location. One notable difference is the effect of the ship's translation through the water. By definition, a vertical landing conducted ashore guarantees that the aircraft will have no translational motion relative to the ground. In contrast, a vertical landing at sea requires the aircraft to match the speed of the ship, which will rarely be zero. The requirement to easily control the aircraft's relative closure with a moving ship platform has influenced the design of the control laws used in the STOVL flight regime.

Landing Gear Geometry

The shipboard environment has significant influence on the geometry of an aircraft's landing gear, much of which tends to drive the position of the landing gear in opposing directions. For example, a large landing gear footprint is desirable for stability during deck handling, thereby preventing a tendency to tipback or rollover. A large footprint also eases the positioning of critical maintenance and servicing points, so that they can be accessed when the aircraft is parked with its tail extending beyond the deck edge. However, a large footprint can complicate deck handling in that the aircraft requires more deck space for maneuvering, and a longer separation between nose and main gear requires more pitch control power to rotate the aircraft during field takeoffs and bolters. Gear height is also influenced by ship basing concerns. A shorter landing gear is more desirable for tipback and rollover stability and for maintainer accessibility, while taller landing gear aids in clearing deck obstacles and in avoiding ground impingements. For JSF, the designer has strived for the best balance between these opposing forces.

Other Ship Interface Considerations

This paper has focused primarily on the influences of the ship configuration on the fundamental characteristics of the JSF air vehicle. The issues discussed here are but a subset of the multitude of interface items that must be considered in introducing an air system to the shipboard environment or aboard a different ship type. These include the compatibility with maintenance and servicing facilities, common support equipment, and shipboard environmental factors, such as the corrosive nature of salt spray and the harsh electromagnetic environment caused by an array of shipboard emitters. Much work has been performed to ensure that the JSF will be compatible in these areas as well, but discussion of these items is outside the scope of this paper.

SHIP SUITABILITY DESIGN "PENALTY"

Because of the numerous factors that influence the design of a ship-based aircraft, many assume these considerations have significantly compromised the mission performance of the CV and STOVL variants. Correspondingly, it is assumed that the remaining CTOL variant carries appreciable "scar impacts" to maintain commonality with its sea-going siblings. However, the JSF design solution has been quite successful in minimizing the "penalty" of ship suitability. As was discussed earlier, the most notable evidence of the CV variant's carrier suitability requirement is its increased wing size and strengthened structural components. These features increase the weight and drag characteristics of the air vehicle, which in turn diminish slightly its maximum speed capability and acceleration performance. However, turn performance is actually improved, and the larger wing provides more fuel volume for a longer range and greater endurance. Similar impacts are seen in the STOVL variant, the result of the incorporation of a vertical lift capability. However, numerous trade studies and operational analyses have confirmed that these small performance impacts have negligible impacts on the mission effectiveness of the CV and STOVL variants. And, since commonality is achieved largely through the use of "cousin" components (those identical in shape, but scaled in size to meet variant-specific requirements), the CTOL variant carries virtually no scars as the result of the ship suitability of the other two variants. The JSF program has clearly shown that shipboard compatibility does not have to come at the expense of such critical attributes as lethality and survivability.

CONCLUSIONS

Ship compatibility can only be achieved through the use of a comprehensive, detailed process that identifies every critical interface issue, diligently monitors their status, and determines sensible resolutions for any areas of incompatibility. The Joint Strike Fighter Program has established such a process, and the designs of its family of aircraft have been influenced by the configurations of the ships on which the aircraft will be based. As was done with JSF, the designers of new ship-based air systems must engage themselves with the ship builder early in their design effort, to understand where ship characteristics will influence their aircraft design. Conversely, the designers of new air-capable ships must coordinate with air system designers to understand how ship design decisions may impact the operations of its complement of aircraft. In the event of an incompatibility across a ship/air interface, personnel from both sides must show care not to arrive at a suboptimal solution that works best for either the ship or the aircraft alone. Instead, they must strive for the synergy that comes by optimizing the performance of the total ship/air system.

[1] *Joint Strike Fighter Acquisition Strategy*, Joint Strike Fighter Program Office, Arlington, VA, dated 8 November 2000. (For Official Use Only)
[2] *Joint Strike Fighter Operational Requirements Document*, Joint Strike Fighter Program Office, Arlington, VA, dated 13 March 2000. (For Official Use Only)
[3] Ibid.
[4] Ibid.
[5] Lockheed Martin Aeronautics Company website, http://www.lmtas.com/products
[6] NAEC-ENG-7604, *Maximum Density Aircraft Spotting CV and CVN Aircraft Carriers, LPH, LHA, and LHD Class Ships*, Revision U, dated 13 Jul 1994.
[7] Department of Defense, Joint Service Specification Guide for Aircraft Structures, JSSG-2006, 30 Oct 1998.
[8] Department of Defense, Joint Service Specification Guide for Air Vehicle, JSSG-2001, 15 Mar 2000.

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AUTHOR'S BIOGRAPHY

Eric S. Ryberg earned a Bachelor's of Aerospace Engineering and a Master of Science in Aerospace Engineering, both from the Georgia Institute of Technology. He earned a Master of Science in Engineering Management from the Florida Institute of Technology. He is a graduate of the U. S. Navy Test Pilot School, having completed the Fixed-wing Flight Test Engineer's Curriculum. Mr. Ryberg began his career at the Naval Air Test Center, as a flight test engineer in the Carrier Suitability Department. He has led several ship suitability flight test programs involving a variety of ship-based aircraft. In 1995, he helped launch the Carrier Suitability Focus Group for the program now known as Joint Strike Fighter. In 2001, he was chosen to lead JSF's Basing and Ship Suitability IPT. Mr. Ryberg is a member of the U. S. Naval Institute and the Tailhook Association.

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