CVF ski-jump ramp profile optimisation for F-35B

A. Fry, R. Cook and N. Revill
anthony.fry@baesystems.com

BAE Systems
Warton
UK

ABSTRACT

This paper presents a summary of the principles and processes used to design a ski-jump ramp profile for the UK's Future Aircraft Carrier (CVF) optimised for the Joint Strike Fighter (JSF).

The paper includes an overview of the CVF and JSF programs, a history and summary of the ski-jump ramp and the principles of its use in the shipborne Short Take-Off (STO) manoeuvre.

The paper discusses the importance of defining optimisation boundaries including specified objectives, aircraft configurations and environmental conditions. It then demonstrates the process of balancing the design drivers of air vehicle performance and landing gear loads to achieve an optimum profile. Comparisons are made between the proposed candidate CVF ramp profile and the current in service ski-jump design as designed for the Harrier family of aircraft.

The paper briefly covers some of the important issues and factors that have been experienced when a theoretical profile is translated into a physical ramp fitted to a ship, principally the effects on aircraft operations due to build and in-service variation from the nominal profile.

NOMENCLATURE

3BSM	3 Bearing swivel module
ACA	aircraft carrier alliance
CG	centre of gravity
CTOL	conventional take-off and landing
CV	carrier variant
CVS	anti submarine carrier (descriptor for the *Invincible* class of ships)
CVF	UK future aircraft carrier project
CVFIST	CVF integration support team
DEFSTAN	UK MoD defence standard publication
Dstl	Defence Science and Technology Laboratory
EC	environmental condition (e.g. Hot/ISA day)
JCA	UK joint combat aircraft project
JSF	Joint Strike Fighter
SDD	system development and design phase
STO	short take-off
STOVL	short take-off and vertical landing
TJSF	Team JSF

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1.0 THE JSF AND CVF PROGRAMS

1.1 Overview of the JSF program

Team JSF (TJSF) comprises Lockheed Martin, BAE Systems and Northrop Grumman and will produce the JSF aircraft in three variants: conventional take-off and landing (CTOL); carrier based variant (CV); and a short take-off and vertical landing (STOVL) aircraft. This paper deals with the STOVL aircraft, designated F-35B, which is currently selected by the UK as its Joint Combat Aircraft (JCA), to be operated by the Royal Navy and Royal Air Force replacing the existing Harrier fleet.

1.2 overview of the CVF programme

The Future Aircraft Carrier (CVF) programme is managed by the Aircraft Carrier Alliance (ACA), an industry and government consortium, and will produce two new carrier vessels entering service from 2014 to replace the existing Invincible class of ships and is illustrated with the F-35B in Fig. 1.

These carriers will act as the UK's mobile air-base, operating and supporting a wide variety of aircraft in support of UK expeditionary operations – obviating the need to rely on other countries co-operation. The embarked air group will primarily consist of JCA but will also include Airborne Surveillance and Control, Maritime, Support, Attack and Battlefield helicopters depending on the mission.

In the Carrier Strike role, up to 36 JCA will be embarked, capable of operating in all weathers, day and night; providing a long range strike capability in addition to air defence and offensive support to the fleet and ground troops.

1.3 CVF integration support program

This program and team was established as part of TJSF and tasked to provide existing and newly generated engineering information to support the ACA in the integration of F-35B with CVF.

Figure 1. Artists impression of CVF and F-35B.

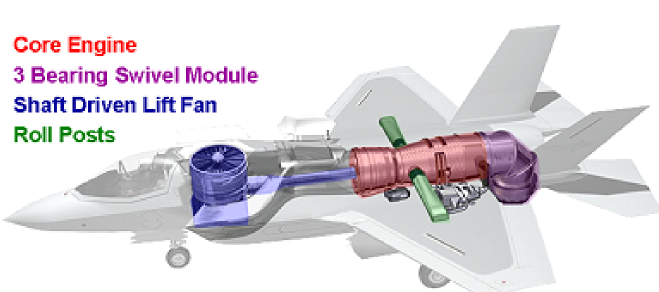

Figure 2. F-35B and its STOVL Propulsion and Lift System.

Although the ramp is physically part of the ship and responsibility for its manufacture and installation lies with the ACA, its profile is entirely based on the aircraft characteristics and for this reason the development of a profile optimised for the F-35B was conducted by the CVF Integration Support Team (CVFIST) on behalf of Team JSF in 2006 and 2007.

1.4 F-35B STOVL lift and propulsion system

The F-35B has a number of unique elements that facilitate its STOVL capability, and these are critical in the optimisation of a ski jump ramp profile for the aircraft. A basic description of the layout and function of the lift and propulsion system is shown in Fig. 2 and described below:

- a Lift Fan driven by a shaft from the main engine which provides vertical lift through a variable area vane box nozzle using louvered vanes to vector thrust between vertically downwards and partially aft.
- a three-bearing swivel module (3BSM), which vectors the main engine exhaust thrust from the core engine through vertically downwards to fully aft – the latter being the default for conventional mode flying.
- roll nozzles, ducted from the engine and exiting in each wing providing roll control and vertical lift. These are closed off during the initial portion of the short take-off (STO) in order to maximise forward thrust from the main engine, opening towards the end of the ramp in order to provide control and lift during the fly out.

2.0 THE SKI JUMP RAMP

2.1 Background and history of the ramp

The ski jump ramp was conceived by a Royal Navy officer in the 1970s and subsequently developed by the UK services, industry and Government as a way of increasing the STO launch payload for the Harrier. It has since become an integral part of embarked operations for UK and most foreign Harrier operators.

The first operational ramp was fitted to HMS *Hermes* (see Fig. 3) in 1979 and was a 12 degree ramp; as defined by the angle to the horizontal of the tangent at the last point on the profile.

The Invincible class of Anti-Submarine Carriers (CVS) were modified during building to accommodate the Sea Harrier aircraft and were completed with a 7 degree ramp in the early 1980s. This lower angle was chosen to avoid obstructing the firing arcs of the Surface to Air Missile system fitted to this class although giving less launch performance benefit. Due in part to the success of the Harrier in the 1982 Falklands war these ramps were replaced by a larger 12 degree design later in the 1980s. The ships and their ramps have given valuable service to the UK through to this day with successive generations of the Harrier family, as Fig. 4 illustrates.

Figure 3. HMS *Hermes* with first 12° ski jump ramp.

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Figure 4. HMS *Illustrious* with retrofitted 12° ramp.

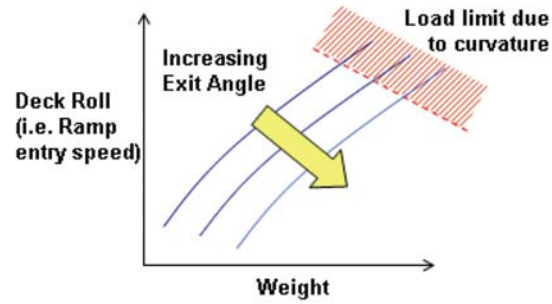

Figure 5. Ramp design drivers.

2.2 Principles of the ski jump

The ski jump ramp works by imparting an upward vertical velocity and ballistic profile to the aircraft, providing additional time to accelerate to flying speed whilst ensuring it is on a safe trajectory. This additional time is manifested either in a reduced take-off length for a given weight, or increased weight (i.e. launch performance) for a fixed take-off distance as in a ship based STO.

The additional performance does not come for free, with a significant increase in landing gear loads above those of a standard take off (which are very low compared to a landing). The increase represents the energy transferred to the aircraft as it translates up the ramp; and if the angle and curvature of the ramp are increased to obtain greater performance benefit, so are the loads. This is tolerable up to a point because the gear strength is defined by landing events and thus has the ability to accept the increased take-off loads, but loads act as an upper boundary on permissible ramp size, as illustrated in Fig. 5.

The ideal landing gear vertical load time history for a ski jump ramp STO is sketched in Fig. 6, with a rapid increase to a steady maximum where the area underneath the curve represents the energy imparted by the ramp. However, the actual loads are different, and reflect the complex dynamic response of the gear components as they enter and travel up the curvature of the profile.

References 1, 2 and 3 describe in further detail the principles behind the ski jump and its advantages as part of a STO manoeuvre compared to a flat deck launch and the design of the profile is described later.

It should be noted that non-STOVL aircraft can benefit from a ski jump manoeuvre, as illustrated by the Russian use of ramps with conventional type aircraft from their carriers. STOVL aircraft are unique however because of the flexible and complex manner in which the thrust and control effectors generate combinations of thrust and forward speed in conjunction with the speed dependent wing lift.

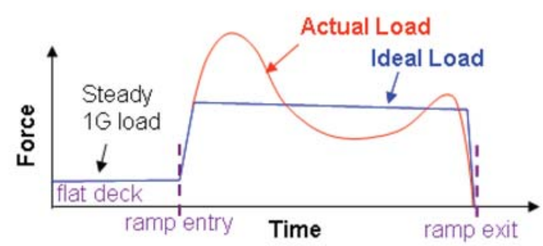

Figure 6. Ideal and Actual Ramp Landing Gear Vertical Load Profiles.

3.0 RAMP DESIGN PROCESS

Figure 7 illustrates the overall concept adopted for the design of the CVF ramp and this was strongly influenced by the documentary evidence and guidance from previous ramp design tasks. References 4 to 7 and the acknowledgements reflect drawing on past experience and knowledge, and the team's contribution was to then optimise it to the F-35B aircraft using TJSF analysis tools.

4.0 REQUIREMENTS

4.1 Defining optimisation parameters

An essential first step in the process was to specify criteria that would bound the task and provide measures for driving the design and evaluating its success. Without having these to reduce the design space to manageable boundaries, optimising for the 'best' ramp could be equated to 'how long is a piece of string ?'.

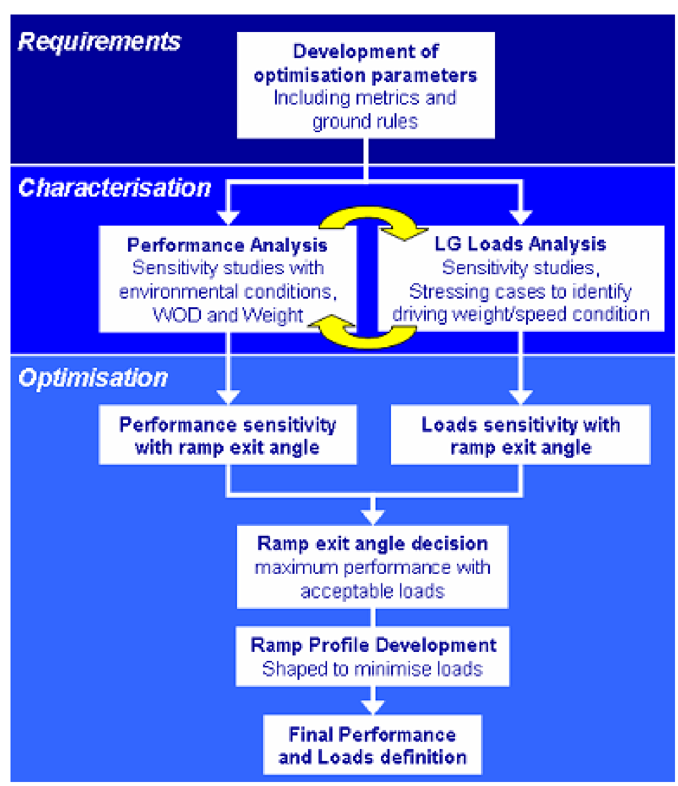

Figure 7. Ramp Design Process.

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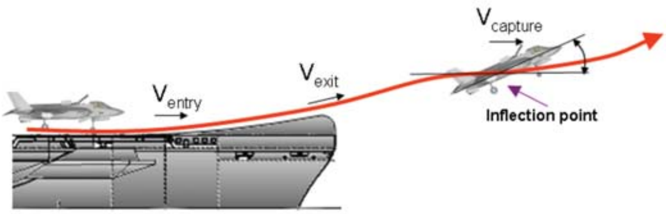

Figure 8. Ski-jump launch profile.

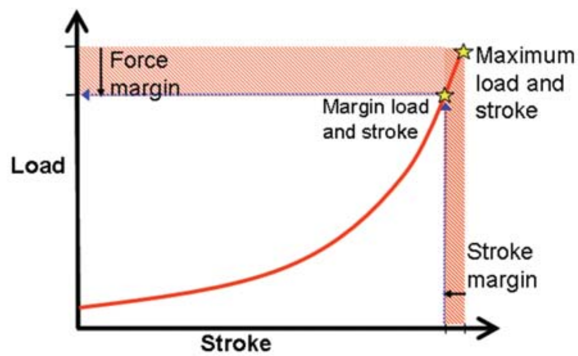

Figure 9. Landing gear loads/stroke margin.

Reference 8 details the work performed by Dstl to examine the key factors and CVF/JCA requirements which influenced this task, in particular, development of the key performance and loads cases in terms of aircraft configurations and environmental conditions which formed the customers objectives. Other ground rules such as take off distances, maximum ramp length and height constraints, wind over deck speeds (WOD) and ship motion factors were also generated prior to the main analysis which was based on legacy experience with Harrier analysis, TJSF SDD best practice, and sensitivity studies of performance and loads to identify sensible values and ranges.

Previous assessments considered pilot view of the sea and deck as well as handling qualities which were found to be benign for ski-jump STOs and since they do not drive the design of the ramp, are not discussed further.

4.2 Safe launch metric

At the core of a ski jump performance analysis is the assessment of whether a launch case is achievable or not. The minimum safe launch is defined where the ramp exit speed does not result in any rate of descent during the trajectory until the aircraft has transitioned to fully wing-borne flight. This results in the launch profile shown in Fig. 8, with an inflection point at which the criteria for a successful launch are assessed.

There are two safe launch criteria derived from legacy STOVL experience that are used on the JSF program, of which the more stressing is adopted: (a) subtracting a margin from the WOD and requiring zero sink rate (known as Operational WOD); and (b) using the full value of WOD but requiring a defined positive rate of climb. Both also require a threshold forward acceleration.

4.3 Landing gear loads metric

In a ski jump STO event, the gear axle load is almost entirely in the vertical direction represented by Fz. Additionally, because the rate of application of load is relatively slow in comparison to a landing event, the load and stroke can be considered to approximately track the airspring force/displacement curve as shown in Fig. 9.

The maximum load and stroke are defined by the limit load and bottoming stroke of the landing gear, but it is necessary to set an optimisation metric below this in order to generate an engineering margin.

This margin primarily accounts for variation between the mathematical profile derived during the analysis and the 'as-built' steel structure that flexes with the operation of the ship and can develop a permanent deformation. Legacy experience is explicit that this build and in-service physical variance can result in gear load increases of a severity requiring operational performance restrictions.

Graphically illustrated in Fig. 9, the load margin is obtained by specifying a minimum remaining strut stroke in the worst loading case based on legacy experience, applying this to the load/stroke curve and using the resulting load/stroke point as the metric against which launch cases are assessed.

5.0 CHARACTERISATION

5.1 Performance

The sensitivity studies initially used the existing CVS ramp profile as a baseline, and showed that the high weight configurations at higher ambient temperatures were the most stressing in terms of what payload capability was achievable. Figure 10 displays a performance characterisation at different environmental conditions (EC 1 to 4) with the CVS ramp, and showing the target configuration (weight) is achievable bar the most stressing condition.

A nominal case from which comparisons could be made against past and baseline predictions of performance was developed, as were a range of weight cases in order to provide the on-ramp schedules of control effectors (nozzle angles, thrust split and elevator angle) for use in the landing gear loads analysis. The effects of varying WOD and aircraft CG were also investigated.

For the F-35B, optimum scheduling of thrust and control effectors is a vital component of maximising the performance benefit of a ski jump ramp and this was assumed possible based on SDD practice. Optimum scheduling after leaving the ski-jump was achieved using a theory developed by Dstl and outlined in Ref. 9.

5.2 Loads

For loads, the gear response on entering the ramp is essentially a function of energy, i.e. mass and speed, and it was necessary to investigate a range of weight and speed cases in order to identify the worst case in order to then use that as a 'working' case for the optimisation phase. This balance is not intuitive since the highest weights are only achievable with higher WOD speeds and the gear loading may be offset by the additional wing lift. The opposite case, at lighter weight but with excess deck run and thus high entry speed, was included for balance.

The sensitivity to changes in the control effector scheduling was investigated in order to understand how changes to these to optimise for performance can impact loads – as were centre of gravity (CG) variations, different WOD speeds, use of external stores (for their aerodynamic drag increment effect on speed, forces and moments) and different methods of modelling the strut internal pressures.

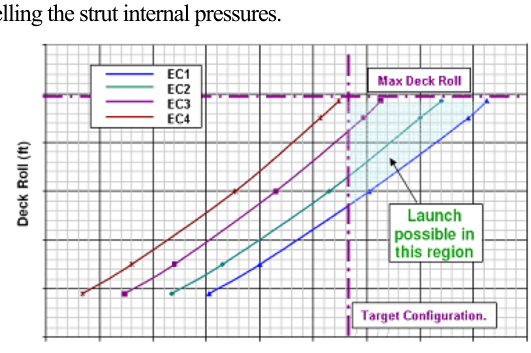

Figure 10. Launch envelope for CVS ramp.

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To account for ship motion due to the sea state, a delta was added to the value used for gravity (ΔG). This is a legacy approach and replaces the huge matrix of pitch, roll and yaw attitudes, velocities and accelerations of the ship and aircraft with a single factor.

Figure 11 shows the main gear axle load for the worst weight and and speed case at 1G and 1+ΔG, using both short and long ramps of the same exit angle as a way of examining the effect of ramp curvature on gear loads.

This phase of the work demonstrated that for the worst case launch the CVS ramp would breach the load metrics applied, but also indicated that using additional length, thus reducing the curvature, could alleviate this.

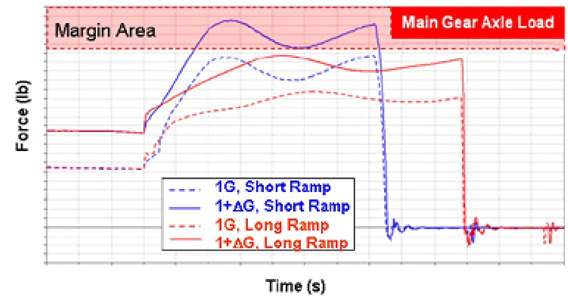

Figure 11. Axle loads for long and short ramps, 1 and 1+ΔG.

6.0 OPTIMISATION

This phase centred on the selection of a ramp exit angle and the shaping of the ramp profile to achieve this.

6.1 Performance

Analysis showed that performance is affected primarily by the exit angle, with diminishing aircraft performance returns from increasing exit angle. Figure 12 shows the trend of launch benefit 'flattening off' as the exit angle increases above the CVS datum.

This flattening off is more severe than seen in legacy Harrier analysis, but exists due to the fundamental differences in the F-35Bs STOVL propulsion system. For the F-35B, with increasing ramp exit angle, the nozzle vector angles and thrust split (between lift fan and core) required to trim the aircraft mean the propulsion system is not operating at the point at which maximum total system thrust is generated, thus reducing the air path acceleration. At higher weights the acceleration reduces below the minimum threshold, as shown in Fig. 13.

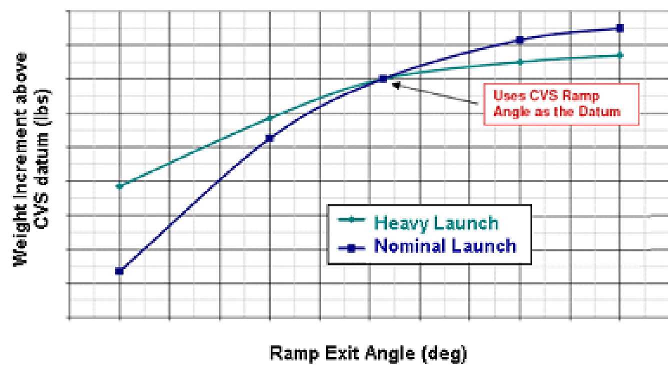

Figure 12. Performance variation with ramp exit angle.

This lower air path acceleration results in the initial post-exit increased height rate benefit of higher exit angles being washed out to approximately the same as lower exit angles by the end point of the analysis, as demonstrated in Fig. 14.

This balance is indicative of the complexity of optimising the performance, other factors including the need during the STO manoeuvre to angle the core nozzle downwards slightly in order to offset the lift fan vertical thrust (since its aft angle is restricted) and ensure a minimum nose gear load for adequate steering.

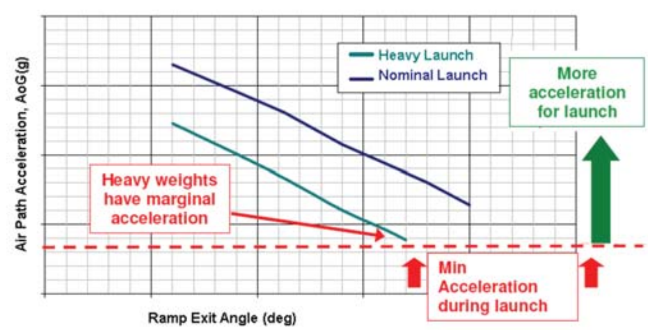

Figure 13. Air path acceleration against ramp exit angle.

6.2 Loads and exit angle decision

Using the loads metric as an upper boundary achieves the most efficient ramp, as defined by imparting the maximum upward momentum without exceeding the loads metric. A range of ski jump ramps were created using the longer version of the CVS angled ramp as a template to design higher angled ramps. Figure 15 shows the nose and main peak gear loads generated.

From this it can be seen that the nose gear is well below the metric for all angles, and that a maximum exists for the main gear.

The maximum exit angle dictated by the gear loads is 12·5 degrees, slightly greater than the CVS angle, and was selected as the ramp exit angle for the following reasons:

- The loads are at their maximum tolerable threshold as defined by the metrics.
- The level of performance derived from this angle is comparable with the requirements.
- CVS ramp performance capability is achieved, but with acceptable loads.

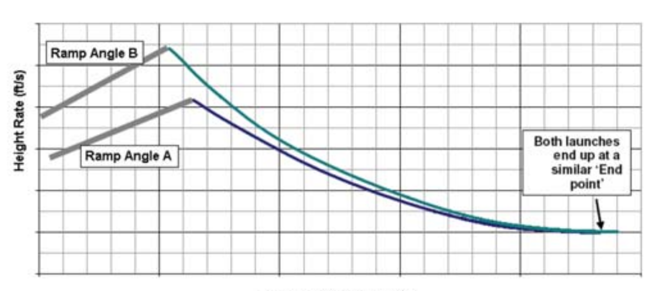

Figure 14. Height rate against air speed for varied ramp exit angle.

6.3 Ramp profile design

Having identified a suitable exit angle, effort was then focussed on developing a detailed profile. A ski jump ramp can be characterised as having three distinct parts, as illustrated in Fig. 16.

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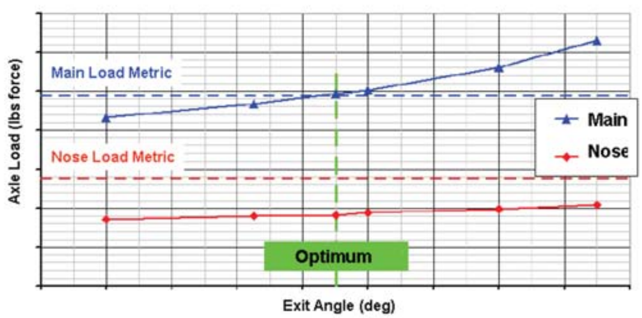

Figure 15. Gear load variation with ramp exit angle.

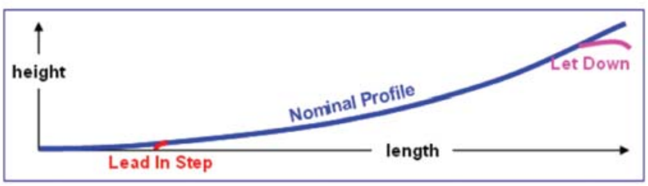

Figure 16. Elements of a ski-jump ramp profile.

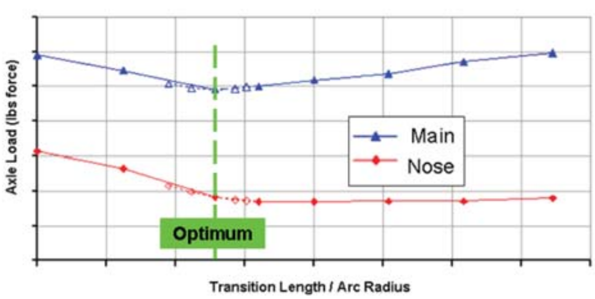

Figure 17. Gear Loads against ramp profile index.

The method used to generate the nominal profile was that of a cubic transition into a circular arc, consisting of a fixed transition length and a fixed radius of curvature, an approach common in engineering disciplines, e.g. railway track transitions from straight sections into corners and aerodynamic streamlining. Geometric relationships are used to match the tangency at the end of the cubic transition curve with the start of the circular arc. Overall height and length are outputs and creating a ramp to satisfy constraints in these requires iteration. The key advantage is that the curvature can be controlled in two easily understood and modifiable variables that relate directly to the profile and loads.

There are alternative ways of generating the nominal profile, described in the references, but the 'cubic plus transition' was deemed the most effective. Trials with other methods proved them to be significantly more complex to use with no observable benefits.

The lead-in step intersects the nominal profile allowing the section prior to this, which consists of negligible height (and thus of minimal benefit whilst also being difficult to manufacture) to be eliminated so the length freed up can be used for a higher radius of curvature. The resulting load spike at the step is within load limits and actually aids the overall process by rapidly increasing the load towards the steady maximum as in Fig. 6, which also reduces the peak of the overshoot on ramp entry, particularly for the nose gear.

The let down was added to previous ramps when it was discovered that the rapid unloading of the gear at ramp exit caused loading problems and there was a requirement to provide a section of ramp that would restrain the gear from uncompressing too quickly. Note that the CVS 12° ramp is actually now 11·26° as a result of converting the last section of the ramp to a let down – and entailing a slight performance reduction.

6.4 Profile development

This looked at a large number of ramp profiles using a wide range of transition length and arc radius values, of which the key conclusions were:

- Short transition lengths produce high load overshoot peaks and oscillations on the first part of the ramp. These outweigh the benefit of reduced loads from the higher circular arc radius later in the ramp.
- Long transition lengths produce much lower initial load peaks, but to remain within the overall design length the circular arc radius has to be increased, producing a counteracting load peak.

The combined effect of varying transition length and circular arc radius is to vary the concentration of curvature in different parts of the ramp. With both of these linked by the requirement to fit an overall length constraint, it was necessary to combine transition length and circular arc radius into a single variable, and in Fig. 17 this is plotted against the peak gear loads for the ramps that demonstrated broadly acceptable loads.

The minimum point in each curve represents its optimum, and it is clear that it differs for the nose and main gears. With the main gear identified as driving the ramp optimisation (see Fig. 15) – then it is from this optimum point that the detailed profile is derived.

6.5 Quartic profile

The use of a polynomial equation to represent the ramp profile is reflected in that the transition is a cubic and the circular arc a quadratic. The use of a single cubic or quartic equation to define a profile was mentioned previously as a method but, although unsuccessful in direct application, the effort did highlight the advantage that a curve to a quartic equation has a smoother variation of curvature and offers the advantages of a less oscillatory load profile and a lower peak. A least squares fit method was used to convert the optimum cubic transition plus circular arc profile to a quartic curve, and the variation of curvature is plotted in Fig. 18.

This demonstrates the subtle change in curvature, and Fig. 19 shows the significant change in gear loads resulting.

In addition to the slight reduction in peak gear loads, the load trace exhibits beneficial features with less oscillatory behaviour and a marked turndown towards the end of the ramp. The latter is of considerable value as it eliminates the new load peak being generated in the original profile. Note also that the nose gear sees a slight increase in both peak load and its oscillatory tendencies, although there is still a large margin available.

6.6 Lead in and let down

Figure 19 also shows the rapid load increase at the ramp entry and the lead in, in this case a rounded step. Assessment of different sized steps, as well as using much longer lead-ins was conducted with little or no difference noted. A decision was taken to use a similarly sized step as the CVS ramp on the grounds that this approximated the diameter of runway arrestor wires used for trampling analysis in the main SDD program and which show similar acceptable loadings.

The let down was designed as an ellipse, blending from the tangent at the end of the nominal profile to the horizontal, where it would interface with the proposed aerodynamic fairing that sits ahead of the ramp.

7.0 CANDIDATE RAMP DEFINITION

The CVF candidate ramp was defined as a 12·5 degree angled ramp with the profile achieved by combining a nominal profile based on a quartic fit to an optimum cubic transition plus circular arc, a rounded step lead in and an elliptic let down. Definitive performance and landing gear loads data were generated to demonstrate the resulting capability and compliance with the metrics.

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8.0 OTHER RAMP DESIGN ISSUES

In addition to the single event performance and loads analysis used to optimise the ramp profile, other aspects were considered for CVF ramp optimisation:

- Cyclical loading: fatigue impact was assessed and found to be significantly lower for the candidate ramp than a CVS ramp.
- Weapons physical clearance: to ensure that the carriage of bulky external stores (e.g. stand-off missiles or fuel tanks) does not result in parts of these breaching minimum clearance distances due to the curvature of the ramp. Worst case store loadings with combinations of fully flat tyres and compressed struts confirmed no clearance breaches.

8.1 Manufacturing

The ramp profile must be transformed into a physical structure, and to do this build tolerances on the candidate profile are required. Figure 20 illustrates the elements of the ramp profile and the issues related to manufacturing.

As discussed earlier, a margin was applied to the loads metrics in order to account for variations between the mathematical profile derived during the analysis and the 'as-built' structure. To ensure this margin was sufficient and to provide the ship builders with useful guidance regarding build tolerances, analysis was conducted on each of the elements and issues:

- Segment size: this is the discretisation of the ramp when specifying ordinates and represents the size of each flat plate that forms the curve. Increasing segment length raises the angle between each plate leading to load spikes.
- Co-ordinate accuracy; this represents the accuracy to which the theoretical curve is converted into a set of 'design-to' points at an accuracy level appropriate for manufacturing, with loads affected due to the change in angle between each point.
- Bumps and dips: These are variations from the 'design-to' profile when designed, fabricated, installed and subject to usage, which result in raised and/or sagged parts of the ramp. A modified DEFSTAN approach (Ref. 10), using bump/dip depth and length parameters based on legacy experience was utilised to produce a suitable build tolerance.

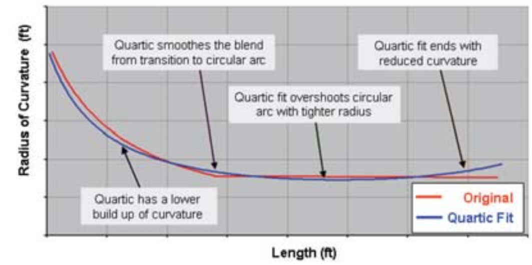

Figure 18. Variation of curvature against length for original cubic transition plus circular arc, and quartic fit.

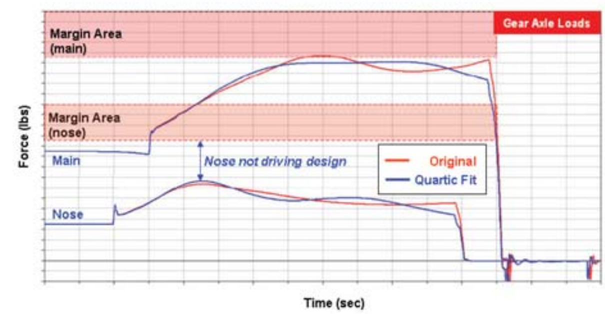

Figure 19. Main and nose gear loads for original and quartic fit.

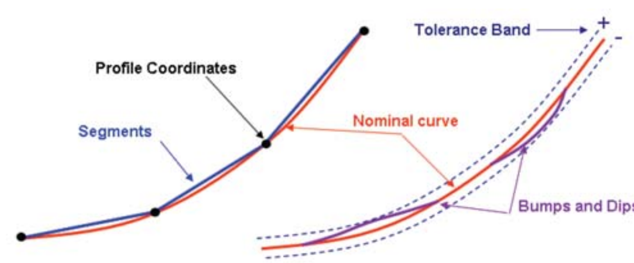

Figure 20. Ramp profile, manufacturing elements and issues.

9.0 CONCLUSION

The paper has covered all the principles and processes used in designing a candidate ski-jump ramp profile for the CVF, optimised for the F-35B.

With loads metric eventually dictating the choice of exit angle and the ramp profile shape, this demonstrates the importance of developing and defining the optimisation metrics.Compared to the CVS ramp, the candidate ramp offers comparable performance but with acceptable loads.

The key issues involved in converting a mathematical profile to a physical structure have been explained.

The team and customer are now taking this profile forward as part of the continuing integration of the F-35B aircraft onto CVF.

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