HULLFORM & HYDRODYNAMIC CONSIDERATIONS IN THE DESIGN OF THE UK FUTURE AIRCRAFT CARRIER (CVF)

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SUMMARY

An overview is provided of the manner in which hydrodynamic and hullform-related design considerations were addressed in the development of the BAE SYSTEMS team's design proposal for the UK Future Aircraft Carrier (CVF). It also outlines how broader design considerations such as aviation, survivability and supportability requirements influenced these aspects of the design. A summary is also provided of some of the more detailed requirements development, option assessment and performance evaluation work that has been undertaken. The aircraft carrier designs discussed in this paper correspond to the BAE SYSTEMS team's final design submission as it stood in January 2003, at the time it was discontinued by the UK Ministry of Defence, in favour of the rival Thales / BMT team design that has since been developed into the UK Royal Navy's new 'Queen Elizabeth' class aircraft carrier. This final BAE SYSTEMS design submission consisted of two distinct design variants - one configured to operate a CTOL-based air group, the other configured to accommodate a STOVL air group. Both variants were based on a common 'core' ship design. The discussion presented in this paper is applicable to both variants.

This paper was originally written for presentation at the June 2003 Royal Institution of Naval Architects 'Warships 2003 - Air Power at Sea' Conference. However, it was withheld from publication at the request of the UK Ministry of Defence, due to sensitivity surrounding the UK Aircraft Carrier project at that time. Following re-appraisal in June 2016, the UK Ministry of Defence has now authorised publication of this paper in full. The paper is presented here in its original (2003) form, with Section 2 added to provide historical perspective (given the passage of time).

NOMENCLATURE

AEW	Airborne Early Warning
ANEP	Allied Naval Engineering Publication (a type of naval design standard)
AR&M	Availability, Reliability & Maintainability
CTOL	Conventional Take-Off and Landing. The traditional 'Cats & Traps' mode of fixed wing carrier aircraft operation, whereby launch catapults are used for aircraft launch and the aircraft recovers by rolling landing using arrestor wires. Sometimes also referred to as 'CATOBAR' (Catapult Assisted Take-Off But Arrested Recovery)
CFD	Computational Fluid Dynamics
COEIA	Combined Operational Effectiveness and Investment Appraisal
CPP	Controllable Pitch Propeller
CVF	The Royal Navy's new 'Queen Elizabeth' class aircraft carrier, as it was referred to at the design study stage
CVSG(R)	The initial UK MoD name for the 'Invincible' Class Replacement
FCBA	Future Carrier-borne Aircraft. The generic term for the alternative fixed wing aircraft types originally considered for CVF (most notably JSF, F/A-18 E/F Super Hornet, navalised Eurofighter Typhoon, Rafale)
FPP	Fixed Pitch Propeller
GM	Metacentric Height
IAT	UK MoD-Industry Integrated Alliance Team for the CVF Future Aircraft Carrier
IFEP	Integrated Full Electric Propulsion
IMO	The International Maritime Organisation
JSF	The F-35 Lightning II Joint Strike Fighter aircraft
MIIs	Motion-Induced Interruptions (a statistical measure used to assess the effect of ship motion on human performance)
MoD	The UK Ministry of Defence
MSI	Motion Sickness Incidence (another statistical measure used to assess the effect of ship motion on human performance)
NATO	The North Atlantic Treaty Organisation
PTO	Percentage Time Operable (in representative sea conditions)
PV	Private Venture (funding)
RAOs	Response Amplitude Operators
RAS	Replenishment at Sea
RMS	Root Mean Square
SAWE	International Society of Allied Weight Engineers, Los Angeles, USA (www.sawe.org)
SDR	Strategic Defence Review
SLEP	Ship Life Extension Project
SRD	The industry team's Systems Requirements Document, that decomposes the MoD customer's high level URD requirements into a series of detailed and specific design requirements

STANAG	A NATO Standardization Agreement (defining common technical procedures between the member countries of the alliance)
STOBAR	Short Take-Off but Arrested Recovery. The mode of fixed wing carrier aircraft operation whereby the aircraft launches unassisted via a 'Ski Jump' ramp and recovers by rolling landing using arrestor wires
STOVL	Short Take-Off and Vertical Landing. The mode of fixed wing carrier aircraft operation whereby the aircraft launches unassisted via a 'Ski Jump' ramp and recovers by hovering and then landing vertically on deck
STUFT	Ship Taken Up from Trade
URD	User Requirements Document, detailing the MoD customer's high level requirements for the ship
WOD	Wind Over Deck

1. INTRODUCTION

This paper outlines the manner in which hydrodynamic and hullform-related design considerations were addressed in the development of the BAE SYSTEMS team's design proposal for the UK Future Aircraft Carrier (CVF).

The work presented is based on the final BAE SYSTEMS design proposal for CVF, as it stood at the end of 2002. It was subsequently announced in January 2003 that CVF will progressed through an Integrated Alliance Team formed of representatives from the UK MoD and the former BAE SYSTEMS and Thales-led industry teams for CVF, using a Thales CVF design concept as a basis. Consequently, references to design features contained in this paper do not reflect the current design configuration for CVF. Nevertheless, it is hoped the paper will provide an interesting overview of some of the key hydrodynamic design issues and options pertinent both to CVF specifically, and aircraft carriers generally, and provide an insight into design deliberations of the former-BAE SYSTEMS team.

2. PROJECT ORIGINS

The origins of the UK Future Aircraft Carrier (CVF) programme can be traced back at least as far as the 'Invincible' class replacement ('CVSG(R)') feasibility studies, commissioned by the UK MoD Procurement Executive in the mid-1990s (see Eddison & Groom, 1997). These studies, conducted with industry support from BAeSEMA (YARD) (Glasgow) and BMT Defence Services (Bath), included consideration of the following design concepts:

- **'CVSG(R) STUFT':** This was an aircraft carrier concept based on conversion of a container ship taken up from trade (i.e. following on from previous mercantile conversions of RFA Reliant and RFA ARGUS in the 1980s). Factors weighing against this concept were the limited availability of suitably sized twin shaft merchant ship hulls, the extent of the conversion required, and the compromises in naval standards and warship functionality that would result.

Figure 1: The BAE SYSTEMS Team's Final Design Proposal for CVF (STOVL Design Variant)

- **'CVSG(R) SLEP':** This was a concept for major upgrade and life extension of the existing 'Invincible' class hulls for a further 30 years of service, into the late 2030s and early 2040s (see Eddison & Groom, 1997). Several different SLEP options were considered, all of which would have involved cutting the existing hull at its maximum section to lengthen it *(by around 20m or approximately 10% of the waterline length, as the author recalls)* while retaining the existing main machinery.
  This lengthening of the ship would have resulted in the existing (unusually long) superstructure of the 'Invincible' class being split (between the funnels) into two separate Islands, which (at that time) was considered potentially sub-optimal for flight deck operations. In addition, the configuration of the 'Invincible' class, with its narrow hangar centre section ('bow tie'-shaped hangar deck plan) and aircraft lifts impinging onto the runway, was less than ideal for larger scale fixed wing aircraft operations and stowage (see Honnor & Andrews (1982) and Eddison & Groom (1997)).
  Consequently, the final SLEP option considered extensive re-work of the hull down to hangar deck level, to achieve a more usable (near-rectangular) hangar shape. It also relocated the axial runway to port (partially onto sponsons) in order to clear the aircraft lifts, with the after aircraft lift being moved inboard to assist in this. It also replaced the split Island superstructure with a single, entirely new (comparatively short) Island into which the existing main engine uptakes would be routed. All-in-all an extensive (and potentially expensive) undertaking!
  The relatively light structural scantlings of the 'Invincible' class and concerns regarding support and obsolescence of shipboard machinery and equipment 60+ years after the first-of-class entered service, were significant concerns with the CVSG(R) SLEP concept. At the time these 'Invincible' SLEP studies were being conducted, the hull lengthening and ship life extension refit of the landing ship RFA SIR BEDIVERE was running into some difficulty, in terms of emergent growth in cost and scope of the SLEP refit (due to age of the hull and equipment). This highlighted the potential risks and pitfalls of undertaking a SLEP refit on the 'Invincible' class. Irrespective, the option of performing a 'SLEP' life extension refit on the 'Invincible' class was never progressed beyond initial feasibility study.
- **Newbuild Carrier Concepts:** Initial newbuild carrier concept studies, conducted by the UK MoD with industry support from 1996 onwards, informed the 1998 UK Strategic Defence Review (SDR) decision to proceed with a newbuild aircraft carrier design, with the intent to build two larger carrier hulls to replace the existing three smaller 'Invincible' class ships.

From 1997 British Aerospace (now BAE SYSTEMS) undertook self-funded (PV) studies to prepare for the carrier project, partly in recognition that a large aircraft carrier had not been designed in the UK since the Royal Navy's 'CVA01' carrier was cancelled (at the design stage) some 30 years previously. The highlight of this PV-funded work was a 1998 British Aerospace concept design for a STOBAR-based aircraft carrier, capable of accommodating a 40-strong air group based around a 'navalised' variant of Eurofighter Typhoon. This work, included simulated STOBAR-type deck landings of Eurofighter on a carrier deck using the flight simulator at BAe (Warton), to demonstrate the feasibility of launching the aircraft via 'Ski Jump' and recovering it onboard using arrestor wires.

MoD-funded Industry studies for the newbuild carrier commenced in late 1999, under two rival teams headed by BAE SYSTEMS (newly-formed from the merger of British Aerospace and Marconi Electronic Systems) and Thales UK. Participants in the BAE SYSTEMS' team included Rolls Royce and Vosper Thornycroft. Thales were teamed with BMT Defence Services, Babcock and Lockheed-Martin.

The initial phase of these funded industry studies, which completed in May 2000, provided preliminary ship sizing, general arrangements and cost estimates for a range of different aircraft carrier sizes and capabilities. This fed into the MoD 'FCBA COEIA' studies on the choice of fixed wing aircraft for the carrier. High level carrier concept designs generated at this early stage included STOVL, STOBAR and CTOL modes of fixed wing aircraft operation, and a range of different air group sizes (with 'surge' capacity for additional aircraft in an emergency).

BAE SYSTEMS followed this up in mid-2000 by proposing a novel 'hybrid' carrier concept (never progressed) that was equipped primarily for STOVL operation, but with limited provision for CTOL aircraft operation. The primary motivation for this was to allow operation of fixed wing AEW aircraft (with their superior performance compared to helicopter-borne AEW) and also to provide scope for 'cross-decking' conventional CTOL fighter aircraft with allies.

In early 2001 the decision was taken by the UK government to discount the STOBAR mode of aircraft operation and instead progress solely with carrier design options based upon STOVL and CTOL variants of the F-35 joint Strike Fighter (JSF). At this time, the MoD also narrowed focus towards carrier options sized for larger air groups.

This led to the BAE SYSTEMS team progressing just two (larger) carrier design options, based around STOVL and CTOL F-35 air groups respectively. These two distinct variants were re-baselined around a common 'core' carrier design during 2002, leading to the final

STOVL and CTOL carrier design variants discussed in this paper (see Figure 1 and Table 1 respectively).

Final carrier design submissions by the two rival industry teams in November 2002 led to the UK government decision in January 2003 to discontinue the BAE SYSTEMS carrier designs and proceed instead with the rival 'adaptable' carrier design offered by the Thales / BMT team. The political decision was also taken at this point to progress CVF through a joint Alliance Team formed of representatives from the UK MoD and the former BAE SYSTEMS and Thales teams. Effectively absorption of selected representatives from the 'losing' BAE SYSTEMS team into the 'winning' Thales team, to create a MoD-industry 'rainbow team' (the Aircraft Carrier Alliance) to progress the Thales / BMT carrier design into detail and build.

14½ years on, in June 2017, the end result of this process is the aircraft carrier QUEEN ELIZABETH, which has just left Rosyth on builder's sea trials, and its sister ship, PRINCE OF WALES, which is still in build.

This paper is based on the discontinued (rival) BAE SYSTEMS team's aircraft carrier design submission to the UK Ministry of Defence, as it stood in January 2003, at the time it was discontinued in favour of the Thales / BMT carrier design. As such, this paper relates to discounted design proposals for the carrier, rather than the final design proposal taken forward into build.

Table 1: Ship Particulars for the Final BAE SYSTEMS CVF Design Proposal (CTOL Variant)

Displacement	62,300 tonnes **
Length Overall	296 m
Waterline Length	270 m
Beam Overall	74.0 m
Beam at waterline	40.0 m
Depth to Flight Deck	28.5 m
Draught	9.1 m **
Maximum Speed	In excess of 25 knots
Total Accommodation	1,400-1,700 ++
Nominal Air Group Size	40 Fixed & Rotary Wing Aircraft ^^
Hangar Capacity	Hangar stowage for approximately two thirds of the nominal air group.
Aircraft Lifts	3 x Deck Edge Lifts ##

** CTOL variant, in the start-of-life Deep Condition.
++ Including 'austere' accommodation.
^^ With capacity to embark and operate additional 'Surge' (overload) aircraft.
Each lift sized to accommodate a single F-35 aircraft.

3. BACKGROUND ON THE UK FUTURE CARRIER (CVF) PROJECT

The UK Future Carrier (CVF) programme aims to provide a new class of aircraft carrier for the Royal Navy. The requirement is for a class of two ships to replace the Royal Navy's three current 'Invincible' class STOVL aircraft carriers (see Honnor & Andrews (1982) for an overview of the design and development of the 'Invincible' class). Unlike the ships that they will replace, which were originally designed primarily[1] to satisfy a Rotary Wing anti-submarine scenario (Friedman, 1988), the emphasis in the design of the new ships is on power projection capability and through-life flexibility.

To these ends CVF is to be larger, more capable and more flexible than its predecessors, and, as only two ships are planned, the emphasis is on increased Availability and rapid re-roling. Current requirements (as of May 2003) are for an 'adaptable' CVF initially designed to operate an air group configured around the STOVL variant of the F-35 joint Strike Fighter (JSF), but with the capability for conversion to operate a CTOL-based air group if necessary at a later stage in the vessel's life.

Key customer-imposed constraints (imposed at the outset of the MoD-funded industry design studies in 1999) were that CVF will not be nuclear powered, must be of conventional monohull design and should be capable of operating for extended periods without docking (e.g. by making use of 'in-water' maintenance/repair techniques where appropriate).

As of May 2003, plans envisaged the award of the contract for the detailed design and manufacture of the ships in 2004, with the first vessel to enter service in 2012 and the second in 2015.

4. REQUIREMENTS DEVELOPMENT

4.1 OVERALL APPROACH

In accordance with the UK MoD's Smart Procurement Initiative, CVF is a requirements-led design. Essentially, this means that the capabilities and features of the ship design, and associated costs, can be traced back to (and justified against) the high-level requirements for the ship, specified in the customer's User Requirements Document (URD). This approach aims to avoid the unnecessary design cost, risk and complexity, or indeed design under-performance, that can result from inappropriate specification of design features and capabilities, for example based on preceding classes of vessel.

A key focus of the industry teams during the Assessment Phase studies was to produce a draft Systems Requirements Document (SRD) for CVF that decomposes these high level URD requirements into a more detailed and quantifiable form. The resulting SRD will ultimately form the contractual basis for the detailed design, construction and acceptance of the vessel.

[1] The referee for this paper advises that the design of the 'Invincible' class included provision for the (subsequently cancelled) P1154 supersonic STOVL aircraft. Significantly, this governed the design of the aircraft lifts (size and strength) and the strength limit of the flight deck.

Requirements decomposition work of this type, conducted as part of the hullform and hydrodynamics studies reported in this paper, are given in the following subsections:-

4.2 SHIP SPEED REQUIREMENTS & ASSOCIATED MARGINS

Particular emphasis was placed on the decomposition and analysis of requirements relating to maximum ship speed because of the impact this has on the resultant installed power, initial/through-life cost, and on broader aspects of the ship design (e.g. ship dimensions, hullform shape, shaftline arrangement and internal layout). To these ends, analysis of required maximum speed was based on the following four URD scenarios, which were considered to represent the fundamental drivers of required maximum ship speed for CVF:-

Scenario 1: Maintaining Speed of Advance During Transit. Under this scenario the vessel must be capable of maintaining a prescribed average speed of advance, allowing for the time lost when the vessel turns off course to launch/recover aircraft and the subsequent time taken for the ship to 'catch up the fleet'.

- Scenario 2: Launch of Aircraft in Conditions of Low Ambient Wind. This scenario requires that the maximum speed of the vessel must be such that it can generate sufficient wind-over-deck to allow launch/recovery of aircraft (with a prescribed payload) in conditions of low ambient wind, allowing a small margin to ensure that the ship can accelerate up to this speed in a timely manner.
- Scenario 3: Conduct of Aircraft Operations in a Fixed Geographic 'Box'. Under this scenario the vessel must be capable of sufficient speed to allow a specified level of flying operations to be sustained within a limited size of sea area.
- Scenario 4: Turning and Accelerating into Wind to Launch Deck Alert Aircraft. This scenario requires that, to obtain maximum operational flexibility, the ship should be capable of being turned into wind and accelerated to a minimum aircraft launch speed within Deck Alert time limits. This is an important requirement, for it maximises the scope for defensive air cover to be maintained using shipborne alert aircraft, minimising the need for Combat Air Patrol. It represents something of an implicit ship speed requirement, in that it influences maximum achievable ship speed indirectly through its impact on installed power.

In the case of a CTOL-based air group, the key driver of required maximum ship speed was found to be launch of fully laden CTOL aircraft in conditions of low ambient wind (i.e. Scenario 2). For a STOVL-based air group the principal drivers were found to be the launching of fully laden Rotary Wing aircraft and, to a lesser extent, speed of advance requirements.

It is important to note, however, that these findings are sensitive to detailed analysis assumptions, most notably those regarding aircraft payload, length of take-off run, Wind Over Deck requirements, intensity of flying operations, and assumptions regarding wind and sea conditions. Moreover, survivability/redundancy considerations, such as the desire to launch/recover aircraft at some reduced-capacity following loss or damage to a shaft, can *implicitly* tend to result in a higher required ship speed than that implied from the above. For the design studies reported in this paper, survivability assessments were conducted for a range of damage scenarios, although the sensitive nature of this work prevents details being presented here.

Table 2: Proposed Margins on CVF Powering & Ship Speed

	Margin	Description
Margins on Resistance & Powering Estimates	Fouling Allowance	To allow for increased resistance due to the deterioration of the hull surface finish in service due to such issues as biological fouling and corrosion. Dependent on assumed hull coatings and maintenance policy, operating area and intervals between hull cleaning and painting.
	Confidence Margin	To allow for uncertainties in the accuracy and reliability of resistance and powering predictions, and detailed issues (e.g. the effect of minor hull openings) that cannot easily be explicitly modelled as part of powering assessment.
	Appendage Form Factor	Factor applied in the calculation of appendage resistance.
	Ship-Model Correlation Allowance	Correction applied to achieve correlation of estimates with empirical data for full scale ships.
Margins on Maximum Ship Speed	Sea Margin	To allow for increased shaft power requirements to maintain a given speed in a seaway (i.e. in wind and waves).
	Allowance for Uncertainties in Maximum Ship Speed Requirements	The purpose of this margin is to:- • Allow for uncertainties associated with CVF ship speed requirements (e.g. required WoD); • Provide operational flexibility; • Ensure that the ship can accelerate up to maximum required Wind Over Deck speed in a timely manner. • Make allowance for redundancy/survivability issues pending the outcome of more detailed survivability analysis.
	Other Margins	Maximum ship speed (including margins) to be achieved in the End-of-Life Deep Condition, in specified sea water and air temperatures.

A range of supporting margins were formulated for application to the resulting requirement for maximum ship speed and in the powering assessment of the ship design, as indicated in Table 2. A key point to note is that CVF is required to achieve its required maximum speed under quite onerous conditions. For a significant proportion of its service life the vessel will therefore be able to achieve a higher ship speed.

4.3 SEAKEEPING REQUIREMENTS

4.3(a) General

There are two key sets of seakeeping performance requirements that need to be addressed within the design of an aircraft carrier, such as CVF:-

- Requirements for Normal Shipboard Activity (i.e. those specifying the limiting sea conditions in which routine shipboard and aviation activity is possible, without appreciable hazard to either personnel or equipment);
- Requirements for Extreme Weather Survival (i.e. those specifying the performance and integrity required of the ship and shipboard equipment in extreme seas, in order to ensure the safety of the ship, its equipment, personnel and payload).

Requirements for extreme weather survival are generally addressed through the adoption of appropriate design standards, such as established standards for ship stability, structural design, aircraft lashing point specification and equipment design limits, which are not considered further here.

4.3(b) Requirements for Normal Shipboard Activity

There is a range of openly published guidance on design criteria for use in evaluating the safe limit of operation of aircraft carriers in a seaway[2]. This guidance, supplemented where appropriate by criteria adopted for previous UK MoD ship designs, formed the basis of the decomposed seakeeping requirements/criteria proposed for CVF. The resulting measures of seakeeping performance, as adopted in the assessment of the CVF design proposal, are summarised in Table 3.

An important point to note is that whilst the ship motion criteria for launch/recovery of Rotary Wing and STOVL aircraft are essentially identical to each other, the criteria for launch/recovery of CTOL aircraft are fundamentally more onerous, with particular regard to acceptable levels of Pitch and Pitch-related motion. This (i.e. operability in higher sea states) represents a key advantage of STOVL aircraft over conventional (CTOL) fixed wing carrier aircraft.

Table 3: Summary of Key Measures of Seakeeping Performance for CVF

Activity	Limiting Parameters
Launch/Recovery of STOVL & Rotary Wing Aircraft	RMS pitch
	RMS roll
	RMS vertical velocity at landing spot
Launch/Recovery of CTOL Aircraft	RMS pitch
	RMS roll
	RMS lateral displacement at round-down
	RMS vertical displacement at round-down
	RMS vertical velocity at touch-down point
Aircraft Handling	RMS pitch
	RMS roll
	RMS lateral acceleration at aircraft location
	RMS vertical acceleration at aircraft location
Aircraft Lift Operability - Side Lifts	Wetnesses per hour on underside of lift structure
Aircraft Lift Operability - Inboard Lifts	As for aircraft handling (above).
General Flight Deck & Hangar Operations	Natural roll period
Overall Hull Performance	Green seas per hour on flight deck
	Bow slamming incidences per hour
	Incidences of sponson immersion per hour
	Observations of stern slamming during tank tests
	Propeller emergences per hour
Crew Comfort, Safety & Effectiveness	Motion sickness incidences (MSIs) at key points around vessel
	Motion-induced interruptions (MIIs) at key points around vessel

4.3 (c) Consideration of the Need for Explicit Limits on Natural Roll Period

A seakeeping parameter that assumes particular importance in the design of an aircraft carrier is that of natural roll period, due to its significant impact on flight deck and hangar operability. Moreover, it represents a parameter that the ship designer has an inherent ability to specify and control provided that it is addressed at a sufficiently early stage of design, for example through the judicious choice of hull parameters and through-life stability management (e.g. ballasting) strategies.

In general, to optimise flight deck and hangar operability for a large carrier such as CVF, it is beneficial to achieve the longest practicable natural roll period as this will tend to:

- Minimise both roll amplitudes and associated levels of deck velocity/acceleration (i.e. by moving the resonant roll frequency of the ship away from the spectral peak of the seaway, and by also reducing the roll "stiffness" of the vessel);

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[2] See: Comstock *et al* (1982), Ricketts & Gale (1989), Pattison & Bushway (1991), Crossland et al (1998) and also STANAG 4154 (2000).

- Maximise the quarter-cycle of roll motion - something that is regarded as key to facilitating movement of aircraft in limiting sea states (Pattison & Bushway, 1991);

Maximising natural roll period in this manner is achieved by minimising the metacentric height of the vessel within the constraints imposed by broader ship design considerations, most notably those associated with ship stability and heel-in-turn performance (see Section 6). Of particular note in this regard were the difficulties encountered following the second blistering refit of USS MIDWAY in the mid-1980's (Ricketts & Gale, 1989)[3]. In this instance fitting substantial blisters to the hull, to improve ship stability, resulted in a marked reduction in the vessel's natural roll period and consequentially a significantly adverse impact on flight deck operability.

For the purposes of the CVF design studies reported in this paper, it was assumed that the minimum natural roll period for CVF should not be less than 18.5s, and should ideally exceed 20.0s. The former (18.5s) value approximates to the natural roll period of USS MIDWAY prior to her unsuccessful (2nd) blister addition (see Table 4 and Ricketts & Gale (1989)), while the latter (20.0s) limit corresponds to the somewhat higher value indicated by the trends in fixed wing aircraft handling characteristics proposed by Pattison & Bushway (1991) and in STANAG 4154 (2000).

Although similar issues of flight deck operability resulted in some consideration also being given to the need for equivalent limits on natural pitch period for CVF, the following factors mitigated against this:

- The effect of forward speed means that it is Encounter Period rather than natural pitch period *per se* that is importance to determining pitch-related motions in a seaway.
- Once the length of the ship has been set, the designer has very little practical control over natural pitch period and the key parameters that determine it (i.e. pitch radius of gyration and longitudinal metacentric height). Rather these parameters tend to be constrained by fundamental higher-level design considerations (e.g. internal arrangement issues and broader hullform design considerations).
- For those activities where the quarter-cycle of pitch motion is likely to be of principal importance (e.g. launch/recovery of CTOL aircraft), the proposed limits on pitch amplitude are so onerous that natural pitch period is unlikely to represent a significant additional driving constraint.

[3] An earlier (first) blistering refit on USS MIDWAY, conducted 30 years earlier in the mid-1950s, had been a success (Ricketts & Gale, 1989).

Table 4: Quoted Values of Natural Roll Period for US NAVY Warships & Other Vessels (Ricketts & Gale (1989) and Sims (1989))

Ship Type	Ship	Natural Roll Period (s)
Aircraft Carriers	USS MIDWAY (CV 41) <u>prior</u> to unsuccessful 1986 blister refit	18.6
	USS KITTY HAWK (CV 63)	22.2
	WWII Fleet Aircraft Carrier	14-16
Other Warships	Battleship	14-16
	Cruiser	11-12
	Destroyer	7.5-9
Commercial Vessels	Liner *(designed to commercial ship stability standards)*	20-24

4.4 MANOEUVRING & COURSE-KEEPING REQUIREMENTS

There is only limited established guidance on desirable levels of manoeuvring and course-keeping performance for aircraft carriers, and indeed warships generally. Standards of manoeuvring performance for new classes of warship appear generally to have been based largely upon the achieved performance of existing similar vessels, and desired improvements relative to such established benchmarks. Looking to the future, ongoing NATO studies are currently (2003) addressing the issue of common (role-dependent) standards for warship manoeuvring performance, with a view to compiling a NATO standard ('ANEP') on the issue.

As regards commercial standards of manoeuvring and course-keeping performance, these are laid down in IMO Resolution A751(18) (1993) *(now superseded by IMO Resolution MSC 137(76) (2002))*. Being based on fundamental ship safety considerations (e.g. directional stability, collision avoidance, stopping performance), and being intended to encompass very large commercial vessels (e.g. VLCCs), they may be regarded as bare minimum standards of manoeuvring performance that must be achieved by any warship. The IMO requirements clearly do not explicitly address either aircraft operating requirements nor the broader military operational issues of relevance to aircraft carriers, for example:

- Manoeuvring and maintaining station in proximity to other vessels (e.g. during RAS);
- Survivability requirements (e.g. maintaining steerage after damage, emergency evasive manoeuvres, optimisation of countermeasures performance, positioning for self-defence).

Given the foregoing, the approach adopted for the CVF studies reported here was to define a set of minimum (safety-related) criteria for CVF manoeuvrability based on IMO Requirements, and then supplement these with CVF-specific manoeuvring criteria derived from the customer's high level User Requirements, and, where appropriate, manoeuvring criteria for previous UK MoD vessels. The resulting measures of manoeuvring and course-keeping performance, as adopted in the assessment the CVF design proposal, are summarised in Table 5. Pending further investigation, and in the absence of substantive evidence to the contrary, the levels of course-keeping performance required for CTOL, STOVL and Rotary Wing aircraft operations were assumed to be identical.

5. KEY DRIVERS OF SHIP DIMENSIONS & PROPORTIONS

An important prerequisite to the commencement of design development, and one in which hydrodynamic considerations play a key part, is the selection of dimension and proportions for the ship - an activity that is naturally somewhat iterative and subject to refinement as the design of the ship evolves.

For the CVF design proposal covered in this paper, overall length and overall beam were, understandably, governed by the flight deck outline, as determined from sortie generation requirements and aircraft launch/recovery considerations (e.g. aircraft, 'ski jump', catapult and arrester gear characteristics). While CTOL launch/recovery requirements were found to be the dominant factor in this area, overall sortie generation requirements meant that movement to a wholly STOVL/Rotary Wing-based air group would only allow a modest reduction in ship length.

Waterline length was, in the first instance, found to be driven simply by flight deck length. However, the desire to best utilise the resulting surplus space within the hull subsequently led to the adoption of enhanced standards of crew accommodation, modularised/containerised stores facilities and more spacious aviation facilities, resulting in a more volume-critical design. As weight estimates and supporting margins were refined, the freeboard of the damage control deck, and to a lesser extent extreme draught and side lift freeboard became more of a concern. These issues, allied with a desire to avoid the powering penalties associated with further increases in block coefficient, meant that any further displacement growth would have been better accommodated by a further increase in waterline length. In this regard the final CVF design proposal covered by this paper may be considered to be weight, volume and flight deck driven. Hangar size was not found to represent a primary driver of waterline length, due to the inherently good spatial characteristics of the selected above and below water form, and the assumed size of hangar required. Analysis clearly showed the powering benefits of maximising waterline length, and consequently the option of adopting a significant stern overhang (a so-called 'counter stern') was rapidly discounted.

Having fixed waterline length, waterline beam was based on achieving an appropriate operating metacentric height (see Section 6), with account also being taken of available build and support infrastructure (e.g. dry docks).

There are clear limits on extreme draught for CVF imposed by base port, build and through-life docking considerations. Other constraints include the need to achieve an acceptable freeboard for the damage control deck, deck edge lifts and hangar deck, and the need to achieve a reasonably fine underwater form consistent with near-optimal powering performance. These factors drove the choice of moulded design draught, block coefficient, propeller tip projection and the projection of other hull appendages below the keel line.

Hull depth was evaluated as the sum of the following constituents:

- The design draught of the ship;
- The design freeboard of the damage control deck (i.e. the deck beneath the hangar deck), as determined from damaged stability considerations;

Table 5: Summary of Key Measures of Manoeuvring Performance for CVF (evaluated for specified ship speeds, wind/sea/tidal conditions and ship loading conditions)

Requirement	Functional Description	Manoeuvre	Performance Parameter
Basic Ship Safety-Related Criteria	Turning Ability	Turning Circle Manoeuvre	Tactical Diameter
			Advance
	Initial Turning Ability	IMO 10° - 10° Zig-Zag Manoeuvre	Distance Travelled to First Rudder Execute
	Yaw-Checking & Course-Keeping Ability	IMO 10° - 10° Zig-Zag Manoeuvre	Value of the First Overshoot Angle
			Value of the Second Overshoot Angle
		IMO 20° - 20° Zig-Zag Manoeuvre	Value of the First Overshoot Angle
	Stopping Ability	IMO Full Astern Stopping Test	Track Reach
	Directional Stability	Spiral Test or Pull-Out Manoeuvre	Directional stability
General Operational Tasking	Accuracy of Heading Control	Straight Line Course at Constant Ship Speed	Error bound to within which heading can be maintained in prescribed wind and sea conditions
Low Speed Manoeuvring	Berthing	Maintaining Position Against a Beam Wind/Current while Stationary	Vessel at zero forward speed to be capable of generating sufficient lateral thrust at the bow and stern to allow it to maintain position and heading unaided against specified combinations of wind, tidal current and clear water depth under the keel.
Survivability	Emergency Evasive Manoeuvres	Turning Circle Manoeuvre	Rate of Turn average over first 180° of the turn
Accessibility & Navigability	Canal Transit	Transit of International Canals	Ship Length, Waterline Beam, Overall Beam, Draught and Air Draught
	Passage Under Bridges	Passage Under Specified Bridges	Overall Beam, Draught and Air Draught.

- The required 'tween deck height of the damage control deck, as determined by clear headroom requirements, deckhead services and larger items of equipment sited on this deck level (e.g. switchboards).
- The required hangar height, determined by aircraft maintenance requirements and structural allowances/clearances;
- The tween deck height of the gallery deck above the hangar, as determined by flight deck structural considerations and the decision to use this deck to accommodate containerised stores.

Consideration was also given to the freeboard of the hangar deck, which represents a key determinant of the operability of the ship's deck edge lifts in a seaway.

A level keel design trim was selected, noting the tight limits on static trim for CTOL operations (Pattison & Bushway, 1991).

Finally air draught (i.e. mast top height) was constrained by an assumed requirement to pass beneath the Forth Bridges, in order to facilitate access to proposed build and support facilities located at Rosyth.

6. CHOICE OF METACENTRIC HEIGHT

As alluded to elsewhere in this paper, the choice of operating metacentric height (GM) for an aircraft carrier, such as the CVF, is effectively constrained by the following principal considerations:-

- Ship stability requirements (intact and damaged), heel-in-turn considerations, and the need to limit the heel induced by aircraft movements, all of which tend to prescribe minimum acceptable operating GM;
- Minimum acceptable natural roll period, as determined from ship motions considerations, which tends to determine maximum acceptable operating GM.

The result is that there tends to be a well-defined 'window' of acceptable operating GM which needs to be satisfied in all through-life ship operating conditions, if ship safety and operational effectiveness is to be maintained. In the case of CVF, these limits on acceptable through-life operating GM prove particularly challenging to satisfy, for the following reasons:-

- The highly variable load and onerous through-life growth requirements for the ship, which tend to accentuate through-life variations in metacentric height;
- The strong desire for benign flight deck motions in order to facilitate intensive aircraft operations in higher sea states;
- The high lower bound limits on metacentric height imposed by warship intact and damaged stability standards, heel-in-turn considerations, and to a lesser extent the desire to minimise heel induced by aircraft movements;
- Any scope to relax the constraints imposed on metacentric height by damaged stability considerations tends to be limited by internal layout considerations specific to CVF (e.g. aircraft lift, magazine and machinery space sizes), which effectively constrain bulkhead spacing.

The first step in achieving acceptable operating metacentric height for the carrier lay in the judicious choice of waterline beam for the design (see Section 5) - something which in turn required reliable weight and centroid estimation from the earliest stages of design. Thereafter, as the design progressed in detail, appropriate layout of tanks, careful weight and centroid management and appropriate weight margins policy were all key to ensuring that metacentic height remained within reasonable bounds in the start-of-life ship condition.

It was also necessary to consider appropriate through-life stability management strategies for the design (e.g. through-life ballasting, weight management and weight margins policy) in order to ensure that GM would be maintained within acceptable bounds across all likely through-life operating conditions. Allied to this was the necessity to establish a reliable estimate of roll radius of gyration to allow the upper bound limit on operating GM, as determined from natural roll period considerations, to be confirmed (see Section 13.5).

7. HULLFORM DESIGN

7.1 DESIGN OF THE UNDERWATER FORM

The choice of parent underwater form was based on a review of three alternative parent forms that were collectively considered to cover the likely range of desired CVF hullform characteristics, viz:-

- A resistance-optimised parent form, based on practice for previous Royal Navy aircraft carriers;
- A parent form representative of design practice for modern cruise liners;
- A 'low pitch' concept hullform, constructed around established guidance for minimising pitching motion[4], noting (see Section 4.3(b)) that pitch-related motion represents a key factor in limiting the operability of aircraft (specifically CTOL aircraft) from aircraft carriers in a seaway.

Key characteristics of each of the three candidate forms are summarised in Table 6.

[4] See: Lewis (1989), Purvis (1974), Kehoe et al (1980), Kiss (1990), Smitke et al (1979), Walden & Grundmann (1985), Bales & Cieslowski (1981), Comstock & Keane (1980) and Kehoe et al (1987).

Table 6: Key Characteristics of Each of the Three Candidate Underwater Forms

Option 1: **'Resistance-Optimised' Warship Form**	**Option 2**: **'Cruise Liner' Form**	**Option 3**: **'Low Pitch' Form**
Narrow after lines and a correspondingly fine design waterplane aft.	Broad, relatively flat after lines and correspondingly full design waterplane aft.	Very full after waterplane.
Zero transom immersion.	Zero transom immersion.	Wide, shallow transom immersion
A relatively full forward waterplane and a correspondingly high angle of entrance.	Fine design waterplane forward and correspondingly low angle of entrance forward. Comparatively pronounced shoulder forward.	A relatively long, fine entry and very smooth shoulder forward.
Fullest midships section of the three options.	Full midships section.	Low midships section coefficient (i.e. well-rounded bilges, flared sides and Rise of Floor).
Minimal Flat-of-Side below the waterline.	Significant vertical Flat-of-Side below the waterline.	Flared sides below the waterline.
Design Waterline maintains its maximum breadth for only a short length close to midships.	Design waterline maintains its maximum breadth for a significant proportion (i.e. in excess of 40%) of ship length.	Design waterline maintains its maximum breadth for a significant proportion of ship length, but less than cruise liner form.
Zero Rise of Floor.	Zero Rise of Floor.	Modest Rise of Floor.
No Parallel Middle Body.	No Parallel Middle Body.	No Parallel Middle Body.
No Bulbous Bow. **	Resistance-Optimised Bulbous Bow.	Large seakeeping-optimised bulbous bow.
		Low vertical prismatic coefficient.
		Large separation between the LCB and LCF.
		A relatively long, shallow, cut-up.

** The presence or otherwise of a bulbous bow was neglected in the comparative assessment of the three candidate underwater forms, on the basis that the potential benefits and required configuration of a bulbous bow for CVF were the subject of separate study, and that a bulbous bow could in any case be readily applied to whichever parent form was selected.

It was readily apparent that CVF would likely to require a skeg of some form for structural/docking reasons and also to achieve an appropriate balance between manoeuvrability and course-keeping characteristics. Accordingly a single centreline skeg was applied to the design. An alternative arrangement based upon twin skegs was also considered, ostensibly on grounds of the potential supportability benefits of enclosing the two conventional shaftlines, and potential resistance/powering benefits (Watson, 1998). However, more detailed consideration, taking into account specialist hydrodynamic advice and the likely weight penalties led to this option being discounted.

To provide a fair basis for comparison, the three candidate forms were scaled to a common set of underwater dimensions and a displacement representative of CVF, and then subjected to both qualitative and quantitative (computational) assessment in terms of a range of hydrodynamic and broader CVF design considerations. Key discriminators identified were as follows:

- Of the three candidates, the resistance-optimised warship form appeared to offer markedly superior resistance characteristics across the entire speed range, while the low pitch form displayed the poorest resistance characteristics of all three candidates (i.e. of the order 10%-15% higher than the resistance-optimised form at maximum speed). However, the inherently lower metacentric height of the resistance-optimised warship form (see below) will be likely to result in the need for increased waterline beam, thereby tending to erode (at least partially) its apparently superior resistance characteristics.
- Analysis (Section 13.3(b)) indicated that adoption of the low pitch form might typically reduce pitch amplitudes by 10% - slightly more if pitch damping mechanisms, that cannot be adequately modelled by strip theory, are accounted for (e.g. viscous damping associated with its large seakeeping-optimised bulbous bow). While certainly not insignificant, this level of pitch reduction is unlikely to offer any significant scope for extending aircraft operations into higher sea states. Meanwhile, the improvements in pitching performance must be weighed against the form's inherently inferior roll motion characteristics, associated with its more rounded bilges (analysis indicated roll amplitudes around 50% higher than for the other forms).
- There was some evidence from strip theory analysis that the full after waterplane of the cruise liner and low pitch hullform might result in much "stiffer" pitching motions (i.e. higher pitch-induced accelerations), and hence a less benign flight deck motions than the resistance-optimised warship form.
- For a given set of ship particulars, the cruise liner and low pitch forms, with their full after waterplanes, provide an inherently higher value of metacentric height than the resistance-optimised form, with its narrow after lines. By the same virtue, these forms will also tend to result in a greater proportion of the reserve of initial stability being invested in their after lines.
- The resistance-optimised warship form, with is full forward lines, comparatively full midships section and relatively short cut-up, tends to result in very good ship layout characteristics, in spite of its narrower after lines. Its full forward lines tend to maximise tank top width forward, and, when extrapolated to the above water form, also maximise side shell clearance at the forward end of the hangar (Figure 2), easing the routing of access routes and services around the outside of the hangar. By contrast the flared sides, rounded bilges and

correspondingly low Midships Section Coefficient of the 'low pitch' form tend to minimise space available low in the hull, and its relatively long, shallow cut-up potentially increases required shaft lengths and limits space available low in the hull around the aft end.
- Given that significant amounts of curvature are required in the underwater form to ensure acceptable hydrodynamic performance, the relative proportion of flat *vs* single-curvature *vs* double-curvature surfaces is not considered to represent a fundamental discriminator between the producibility characteristics of the three candidate forms. Nonetheless, the cruise liner form appeared to offer the best producibility characteristics, for it maximises the extent of flat of side and flat of bottom, minimises the length of the after cut-up, provides a full midships section, and maximises the proportion of ship length over which the design waterline remains parallel to the ship's centreline. All these features tend to improve the scope for adopting modular build and outfit principles.

On balance, the resistance-optimised warship form was considered to offer the best all-round characteristics for CVF, and accordingly was adopted as the basis underwater form for the CVF design proposal covered in this paper.

As part of the subsequent refinement activity, a bulbous bow was applied to the form, shaped and sized so as to optimise resistance characteristics at maximum speed. It was anticipated that the bulb would reduce resistance by around 5%-10% at maximum speed, and that it would remain broadly beneficial for ship speeds down to about 11 knots. Although consideration was given to reshaping/resizing the bulb to bias its performance more towards cruise speeds, analysis based on empirical data and an assumed CVF operating profile indicated that this would increase installed power by a small (but not insignificant) margin, whilst being roughly neutral in terms of overall fuel burn. The separate option of substituting a seakeeping-optimised bulb (see Lewis (1989) and Schneekluth & Bertram (1998)) in order to minimise pitching motion for CTOL operations was rejected, as any reduction in pitching motion was likely to be small and unjustified in the context of the likely resistance penalties.

In accordance with established (Froude number-based) guidance on resistance optimisation, the transom was configured to give zero immersion at the nominal design draught of the vessel. Although consideration was given to introducing a stern wedge or flap, this was rejected given the significant variations in operating draught of the vessel, and in light of expert advice that any resistance benefit was likely at best to be limited.

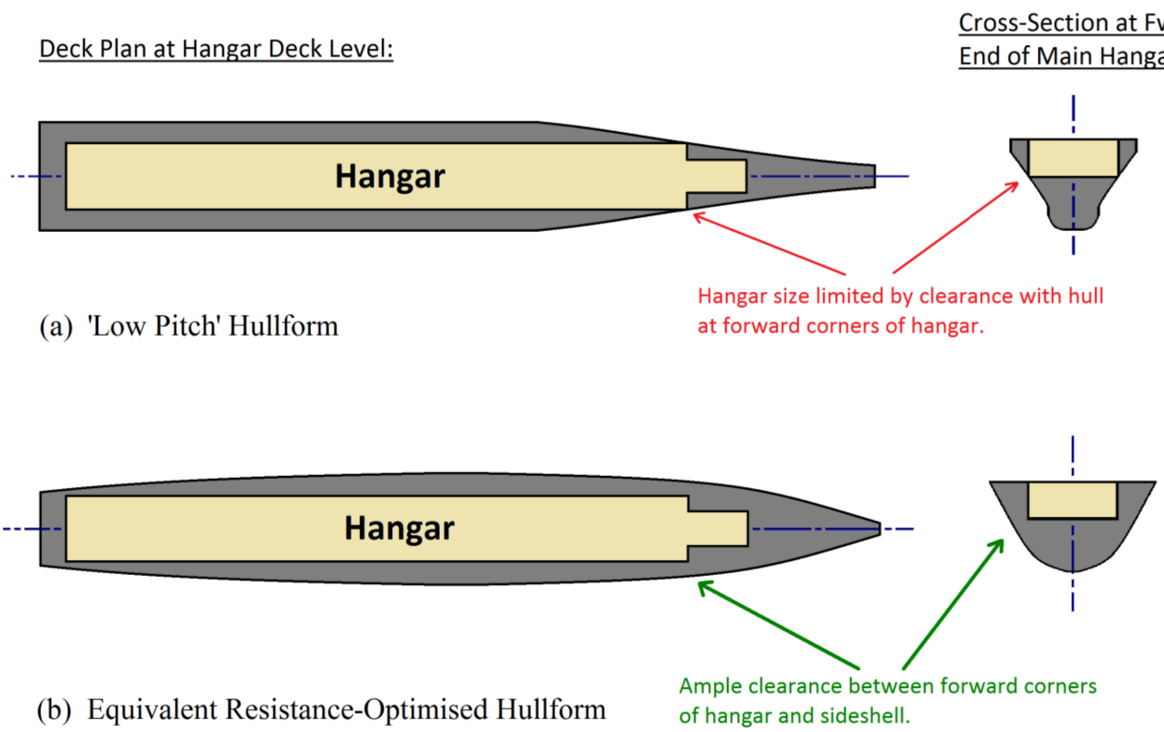

Figure 2: Comparison of the Spatial Characteristics of a Low Pitch Parent Form with an Equivalent Resistance-Optimised Hullform - note how the latter is more readily able to accommodate a large hangar

Other detailed refinements applied to the selected underwater form included: adjustment of longitudinal centre of buoyancy; refinement of the entrance to optimise resistance characteristics; refinement of afterbody lines to reflect shaftline, powering and noise/vibration considerations; and application of modest flare to the midships section beneath the waterline to reduce target echo strength.

Although not incorporated within the baseline design proposal, established empirical 'design lanes' (Saunders, 1957) indicate that there is at least limited scope for incorporating parallel middle body on CVF without incurring marked resistance penalties. Possible reasons for introducing parallel middle body include potential improvements to producibility and ship layout, minor adjustments to ship length at the design stage, or to facilitate possible lengthening of the vessel through-life.

7.2 DESIGN OF THE ABOVE WATER FORM

Given the fundamental disparity between overall ship dimensions for CVF (which are driven principally by aircraft operating/stowage requirements) and waterline dimensions (which are determined by broader ship design considerations), two fundamental alternative styles were identified for the above water form, viz:

- A traditional style of carrier above water form, employing a wall-sided form and sponsons;
- A novel 'highly flared' style of above-water form, employing above water flare as a means of minimising the need for sponsons.

With the traditional style of above water form (Figure 3) the basic envelope of the above water form is wall-sided (or near wall-sided), and sponsons are appended to this basic envelope to achieve the required flight deck plan. The origins of the approach can be traced at least as far back as the early 1950s to the retrofit of angled runways to existing (axial-runway) CTOL carriers, where appending a sponson onto the existing wall-sided form proved to be the simplest and most practical way of achieving the required local change in flight deck outline. Since then, this approach has been adopted universally on new-build carriers where there is a fundamental mismatch between waterline dimensions and desired flight deck outline.

In practice there is considerable variation in the depth and shape of the sponsons adopted on a given design, both along the length of the ship and between the port and starboard sides of the hull. Along the starboard side of the hull, where space is at a premium (and there is often an offset Island superstructure to support), the sponsons tend to be deeper and more box-shaped, to maximise the amount of utilisable internal space within the sponson. Down the port side of the hull, where internal space is at much less of a premium, and the overhang of the flight deck tends to be greatest, the sponsons tend to have steeply sloped sides, presumably to minimise steel weight and associated weight centroid implications. Additional, smaller, shallower sponsons tend to be appended around the above water form of the ship as required, to meet specific localised requirements (e. g. to provide platforms for sensors or self-defence/decoy systems). Major sponsons (i.e. those supporting flight deck extensions on both sides of the hull) tend to extend over the full depth of the hangar.

By contrast, the fundamental feature of the 'highly flared' style of above water form (Figure 4) is its use of straight line flare extending down to, or close to, the waterline[5], in order to minimise or avoid the need for the large sponsons traditionally associated with aircraft carriers. To these ends, the basic angle of side flare is maintained from the transom to a point as far forward on the hull as practicable.

Direct comparison between the two styles of above water form is somewhat subjective, for in the case of the traditional style of above water form there is considerable flexibility in the configuration (e.g. shape, location, extent) of the sponsons. Nonetheless, potentially key discriminators identified in the course of the CVF studies were as follows:

- The highly flared approach offers a number of features that are attractive from the point of view of producibility, ship layout and modular construction/outfit. Specifically, it ensures symmetry of the above water form up to the highest possible deck level, simplifies internal structural arrangement (e.g. by eliminating of the need for a longitudinal bulkhead at the interface between the sponson and the main hull, to maintain structural continuity), and tends to maximise the amount of flat/single curvature plating and parallel side in the above water form. It also tends to maximise the breadth of hull at hangar deck level, easing the routing of access/service routes, uptakes/downtakes and stores/weapons lifts around the outside of the hangar.
- The highly flared approach offers an inherently spacious above water form for a given set of ship dimensions.
- The highly flared approach potentially offers enhanced levels of intact and damaged stability performance, in terms of large angle stability and increased metacentric height at damaged draughts.
- There are a range of potential discriminators between the two styles of above water form in terms of structural characteristics (e.g. longitudinal, torsional and shear strength characteristics, global

[5] Although the side flare can, in principle, be initiated at the turn of bilge, the implications for metacentric height at lighter draughts, together with hydrodynamic concerns, meant that this sub-option was not explored as part of the present studies.

and local wave loading, residual strength characteristics). On balance, it was considered that the highly flared style of above water form offers scope for achieving a simpler, lighter, more efficient and more produceable hull structure than would otherwise be the case.

- The highly flared style of above water form is likely to place additional constraints on the berthing and docking of the vessel due to the high angles of flare close to the waterline (i.e. at around the level of the quayside or dockside).

Provided that due attention is paid in the design of the above water form, radar cross-section and air wake characteristics should not represent significant discriminators between the two styles of above water form.

The seakeeping characteristics of the highly flared above water form were initially deemed a potential area of concern, due to risks associated with immersion/re-emergence of the side flare in a seaway, although subsequent seakeeping experiments (see Section 13.3) alleviated these concerns. At this point it should be noted that the seakeeping characteristics of the traditional style of carrier above water form are also not without risk. Specifically, careful attention must be paid to the design of the sponsons, particularly their freeboard relative to the still water line, their outreach, and the shape of their undersides, if the risk of flare slamming, local freeboard exceedance and undesirable interaction effects (e.g. spray generation around side lift openings) are to be minimised.

Having taken the above factors into account, the decision was made to proceed with the highly flared style of form for the CVF design proposal covered in this paper. In line with the findings of de-risking experiments (Section 13.3(d)), this was implemented based on a basic flare angle of 35° and initiation of the flare approximately 3.0m above the deepest operating waterline. To reflect structural and producibility considerations, the principal knuckle lines of the above water form were sited so as to lie slightly above the deck lines.

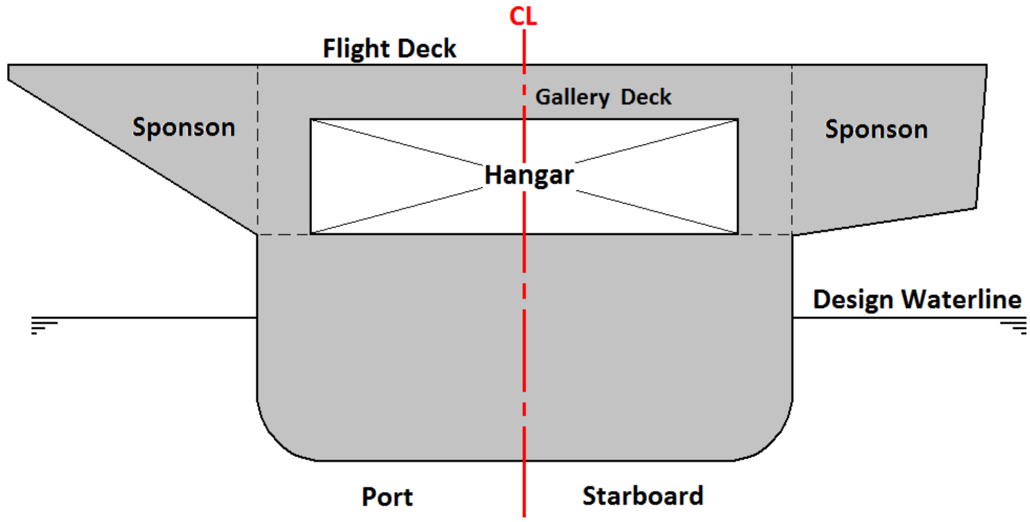

Figure 3: Traditional (Sponson) Style of Carrier Above Water Form for a representative midships section

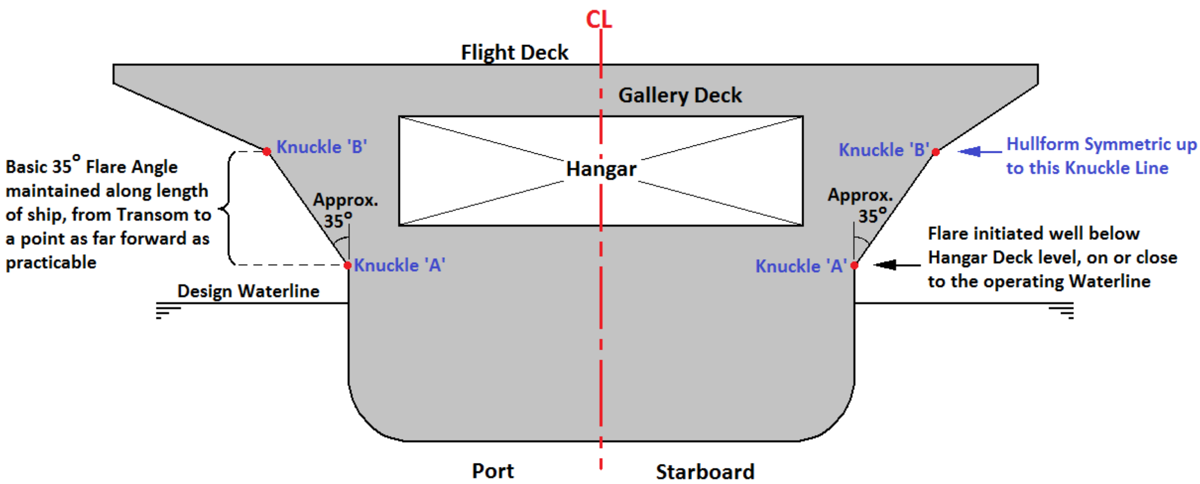

Figure 4: 'Highly Flared' Style of Carrier Above Water Form for a representative midships section

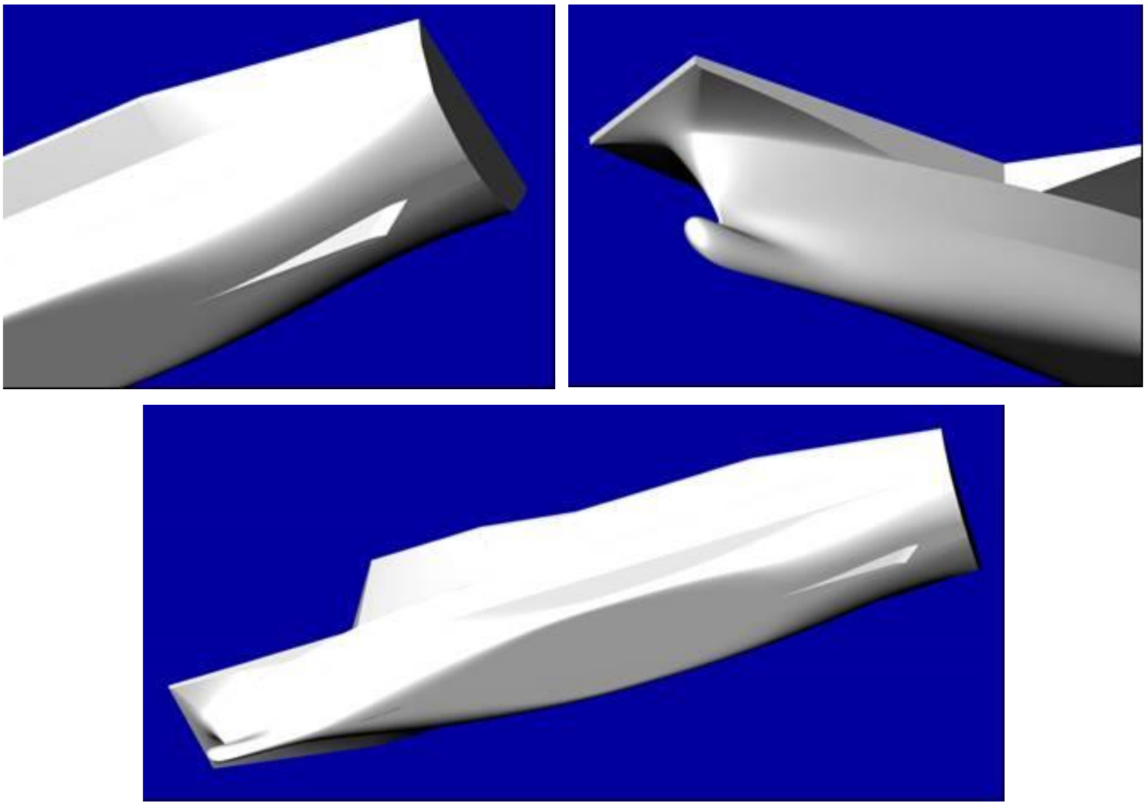

Figure 5: Hullform Definition for the CVF Design Proposal covered in this paper

In terms of the shaping of the above water form around the bow, efforts initially focussed on developing a simplified bow shape composed predominantly of flat and single curvature surfaces, in a bid to improve producibility (Figure 12). Subsequently, consideration of seakeeping performance in extreme seas (e.g. mitigation of the effects of immersion/re-emergence of the upper region of the bow, deflection of spray/green water clear of the flight deck), supported by observations during seakeeping experiments, led to a decision to adopt a more traditional rounded bow shape.

The resulting hullform arrangement is shown in Figure 5.

8. SHAFTLINE & PROPULSOR CONSIDERATIONS

8.1 DELIBERATIONS ON SHAFTLINE CONFIGURATION

The choice of shaftline arrangement was the subject of some deliberation during the CVF design studies, due to its fundamental impact on broader ship design considerations (e.g. cost, ship layout, producibility, vulnerability and signatures), and the potential offered by more novel propulsor types. Ability to sustain flying operations (at least in some reduced capacity) following loss of a shaftline to damage/flooding/failure was a particularly key consideration for CVF, as an aircraft carrier. Given the Integrated Full Electric Propulsion (IFEP) power system proposed there were a range of possible shaftline configurations for CVF, employing conventional shaftlines, azimuthing podded propulsors, waterjets, and combinations thereof.

For the purposes of the CVF studies outlined in this paper, options employing triple or quadruple conventional shaftlines were discounted due to the relatively low shaft power levels anticipated for CVF, and because of the likely implications for the cost and ship layout. Single shaft solutions were also discounted, on grounds of lack of redundancy, survivability, and achievable shaftline rating. Solutions based wholly around waterjets were rejected due to the perceived risks associated with applying such novel propulsors to a large warship, such as CVF. Specific concerns with waterjets included shock performance, likely degradation in performance in a seaway due to inlet aeration, likely impact on ship layout (i.e. around the aft end), and inherently low propulsive efficiency except at the highest CVF operating speeds. The acoustic characteristics of waterjets are also a concern, although there is some evidence (Källman, & Li (2001)) to suggest that the potential drawbacks in this area may not be as great as might at first be thought.

Other shaftline configurations identified as being of potential interest for CVF included:-

- The twin conventional shaftline option;

- Options based wholly around fixed/azimuthing podded propulsors (Warship Technology, 2003);
- Hybrid shaftline arrangements employing one or two conventional shaftlines, in conjunction with one or two azimuthing podded propulsors;
- Hybrid shaftline arrangements employing twin conventional shaftlines in conjunction with one or two waterjets. Here the conventional shaftlines would power the vessel at low-intermediate speeds and in extreme seas, with the waterjets providing 'boost' for higher speeds and in calmer seas where their performance penalties are less marked. The waterjets would also offer potential for improvements in manoeuvring and stopping performance (i.e. using steerable nozzles and/or reversing buckets).

The key options were assessed in terms of a broad range of design issues, including vulnerability, noise and vibration, manoeuvrability, ship layout, propulsive efficiency, supportability characteristics, cost, risk, required shaftline rating, and the scope for modularisation of the entire propulsion train for build purposes.

This led to the shaftline arrangement of the final design proposal, shown in Figure 6, which is a hybrid arrangement employing twin conventional shaftlines and a single 'tractor' ('pull-mode') azimuthing podded propulsor. To avoid manoeuvring ability being invested wholly in the pod, this arrangement includes a rudder sited downstream of both conventional shaftlines.

Given the degree of redundancy inferred by the presence of the pod, it was deemed acceptable for the motors of the two conventional shaftlines to be collocated in the same longitudinal compartment, rather than longitudinally staggered for survivability reasons (i.e. as would have normally been required in applying a twin shaft configuration to a front line warship design). This feature greatly reduces the ship layout implications of adopting twin conventional shaftlines on CVF, by minimising the amount of internal space consumed low in the hull and forward of the cut-up, where space is at a premium (i.e. due to the demands imposed by power generation machinery and weapons magazines). By reducing the proportion of ship's length over which the shaftline components are distributed, it also greatly improves the scope for the adoption of modular build practices, and it also results in a shaftline arrangement that is wholly symmetric about the ship's centreline.

The design included provision for a watertight cofferdam (double bulkhead) on the centreline of this compartment, to segregate the two conventional shaftline motors into separate (port and starboard) motor rooms, and thereby minimise the risk of both being put out of action simultaneously in the event of flooding or action damage.

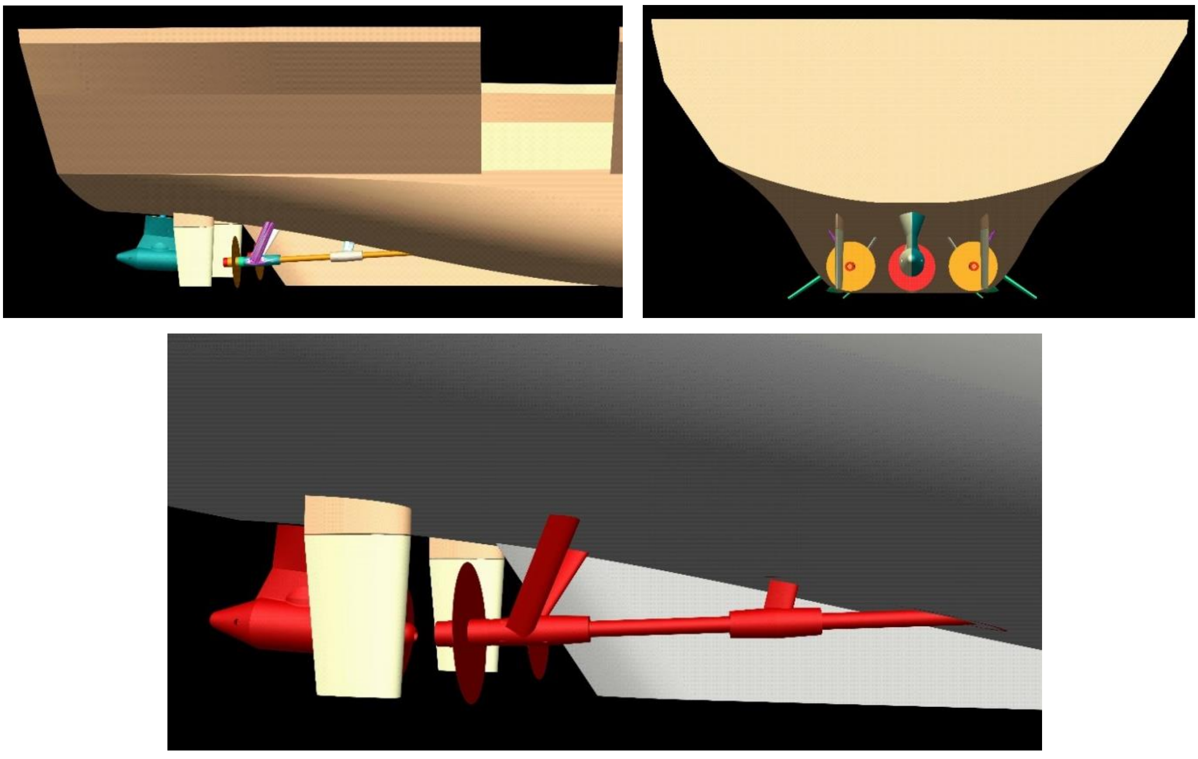

Figure 6: Final Shaftline and Hull Afterbody Arrangement for the CVF Design Proposal covered in this paper (Conventional Twin Shaftlines/Rudders, Single Azimuthing Podded Propulsor, Centreline Skeg)

In terms of manoeuvring characteristics, simulation work (see Section 13.4) based on this hybrid shaftline arrangement indicated little appreciable difference in manoeuvring performance at ocean going speeds compared to an equivalent twin conventional shaftline design without a pod. Nonetheless, the ability of the pod to generate lateral thrust during low speed manoeuvring is clearly beneficial.

In general it is expected that the pod would be operated in parallel with the conventional shaftlines over the entire range of forward ship speeds. However, for quiet operation at low-intermediate ocean-going speeds, it was anticipated that the pod's propeller would be 'windmilled'/idled to eliminate (or at least minimise) pod machinery noise.

8.2 PROPULSOR CONFIGURATION

Following a high level review of alternative propulsor types (including novel propulsor types) conventional Fixed Pitch Propellers (FPPs) were adopted as the baseline for the CVF design proposal covered in this paper, on grounds of proven performance, relatively low technical risk, simplicity and low through-life cost. Although Controllable Pitch Propellers (CPPs) can offer improvements in efficiency at off-design conditions and improved stopping performance, considerations of design point efficiency, likely acoustic performance, mechanical complexity and through-life cost led to their provisionally being discounted. The baseline assumption of IFEP propulsion for CVF, where shaft rotation can be readily reversed, also weakened the case for CPPs.

The preliminary choice of directions of rotation for the propellers (Figure 7) was based on specialist advice and took high level account of the likely impact on manoeuvring and directional stability characteristics, propulsive efficiency (i.e. inflow swirl), and, of particular importance for CVF, propeller-induced vibration and cavitation performance. In the case of the conventional shaftlines, cavitation and vibration considerations were the dominant consideration, and, taking into account cruise liner experience (Kinns & Bloor (2000)) and the alignment of the shafts, led to a provisional decision to adopt inward turning propellers - a choice that was provisionally confirmed by unpowered (nominal) wake field experiments. In the case of the centreline (podded) propeller, the clean inflow characteristics arising from the 'pull-mode' pod configuration and the location of the pod on the centreline meant that the direction of this rotation for this propeller was based on steering bias considerations and utilisation of the paddle wheel effect during normal berthing (i.e. starboard side to) - issues that led to the adoption of a left-handed propeller.

It will be noted that the choice of shaftline arrangement effectively precludes full shaft synchronisation (i.e. to minimise underwater signature and noise and vibration), although it would be possible to synchronise the two conventional shaftlines.

9. MANOEUVRING DEVICE FIT

9.1 GENERAL

The fit of primary manoeuvring devices is highly dependent on the shaftline arrangement. Given the hybrid shaftline arrangement proposed in Section 8 (Figure 5), twin conventional rudders were proposed, supplemented by the manoeuvring capabilities of the podded propulsor, with twin tunnel-type bow thrusters provided for low speed manoeuvring.

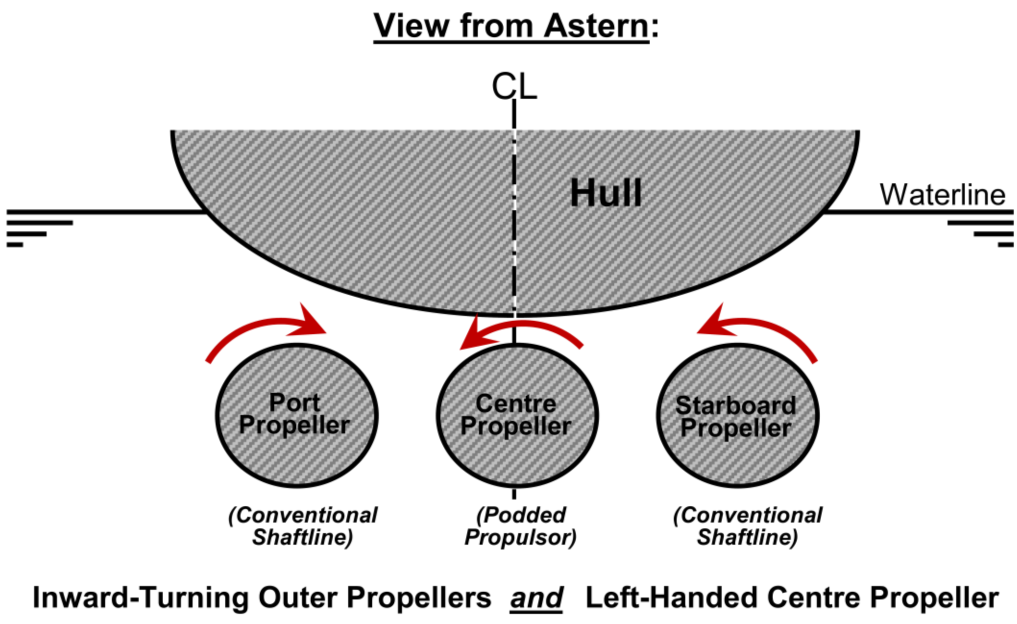

Figure 7: Proposed Propeller Directions of Rotation

As noted in Section 8, it was considered prudent to include two conventional rudders, to supplement the manoeuvring and course-keeping capabilities of the pod, both for survivability/redundancy reasons and to avoid the need to use the pod for routine course-keeping (e.g. during long transits). As a starting point, rudders of the all-movable (balanced spade) type, fitted with a fixed headbox to avoid mechanical interference with the hull, were proposed on grounds of simplicity, maintenance considerations and minimisation of rudder torque. Subsequent calculations indicated that the required diameter of rudder stock could prove prohibitive (e.g. in terms of weight and required rudder thickness), and consequently it is likely that horn-type rudders would have been substituted as part of the next stage of design development.

The azimuthing podded propulsor was configured so that it could be azimuthed to ±90° during low speed manoeuvring (e.g. berthing operations), thereby allowing significant amounts of purely lateral thrust to be developed at the stern, without the need for dedicated stern thrusters. At higher forward speeds the azimuth of the pod was to be limited to ±35° to minimise the hydrodynamic forces on the pod, limit the cross flow at the pod propeller, and reduce the risk of undesirable hydrodynamic interactions with the races of the conventional shaftlines. It was anticipated that during long transits the pod would be locked, to avoid wear on the pod azimuthing mechanism, and the conventional rudders used for course-keeping.

The principal area of concern relating to the final shaftline arrangement shown in Figure 5 is that, for certain combinations of rudder incidence and pod azimuth during manoeuvring, the rudders might deflect the races of the conventional shaftlines onto the podded propeller, resulting in cavitation and adverse levels of noise and vibration. A four-stage approach was proposed for de-risking this issue, based around:-

- Refining the siting of the conventional shaftlines and the hull afterbody appendages, to minimise the risk of undesirable hydrodynamic interactions occurring;
- Use of Computational Fluid Dynamics (CFD) analysis to assess the likelihood of undesirable interactions;
- Cavitation tunnel testing to evaluation the implications of undesirable interactions occurring;
- Consideration of the need for limitations on allowable combinations of rudder incidence and/or pod azimuth.

9.2 DELIBERATIONS ON THE CHOICE OF BOW THRUSTER

The potential need for bow thrusters onboard CVF stems from a desire that, in order to minimise the need for tug support, the vessel should ideally be capable of berthing unassisted (i.e. without tugs) in various conditions of cross wind and tidal cross-flow. To these ends, three principal types of bow thruster were considered (Figures 8, 9 & 10).

Of these, the azimuthing ‘drop-down’ type of thruster is attractive in that it remains effective at forward speed, offers an inherently high efficiency, and because it offers considerable scope for use as a means of emergency propulsion. However, as this type of thruster projects below the keel line when in use, its suitability for adoption on a draught-limited vessel, such as CVF, was considered questionable.

Pump-type thrusters offer similar advantages to ‘drop down’ thrusters in terms of their ability to provide an emergency means of propulsion through directable thrust. Additional advantages arise from the fact that the installation does not project significantly below the keel line. However, the efficiency of this type of thruster is markedly lower than for the other types of thruster, with implications for installed weight, space and power requirements, and cost. For CVF the need for pump thrusters to be sited low in the hull on a reasonably wide and flat part of the hull underside means that they tend to occupy a large amount of relatively high value space that could be used for a range of other purposes (e.g. aviation fuel stowage).

Tunnel Thrusters represent low risk, low cost technology, and are arguably mechanically simpler and require less maintenance than other types of thruster. They can be located wholly within the lines of the hull and therefore do not impose additional draught constraints on the vessel. Additionally, they can be located well forward in the narrow portion of the hull, where internal hull space is at less of a premium and where their effectiveness at countering wind/current-induced hull moments is maximised. In terms of drawbacks, their performance deteriorates sharply with rising forward speed due to cross flow effects, and they can only generate lateral thrust, thereby offer no prospect of providing emergency propulsion. Additionally, there is a small (but not insignificant) drag penalty and potential flow noise concerns unless closures are fitted.

From the point of view of hydrodynamics and propulsion, a bow thruster fit based around pump thrusters was considered to represent an attractive option, principally because of the emergency propulsion capability offered. However, pending clarification of the need for such an emergency propulsion capability, broader considerations of cost, weight, required power and ship layout led to the decision to proceed with a baseline bow thruster fit based around tunnel thrusters. Two such thrusters were provided on grounds of required rating and redundancy in the event of one failing during operation.

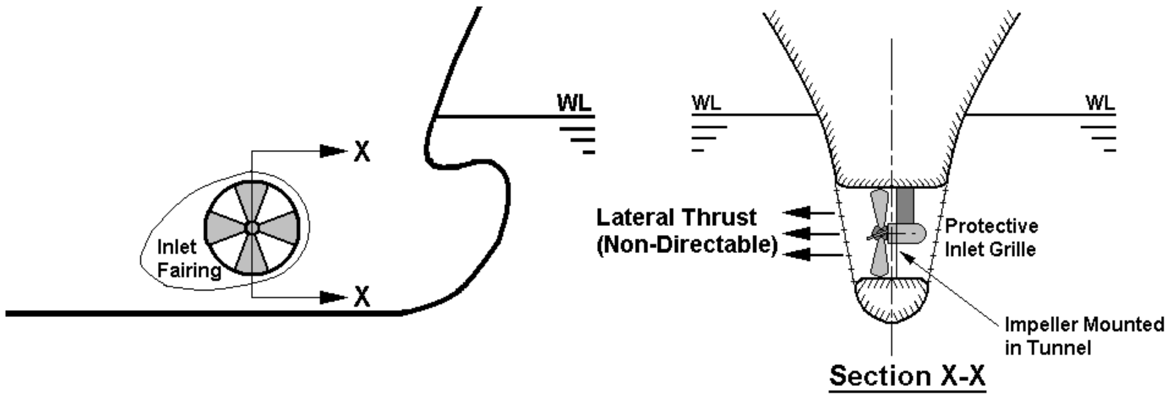

Figure 8: Transverse Tunnel-Type Bow Thruster

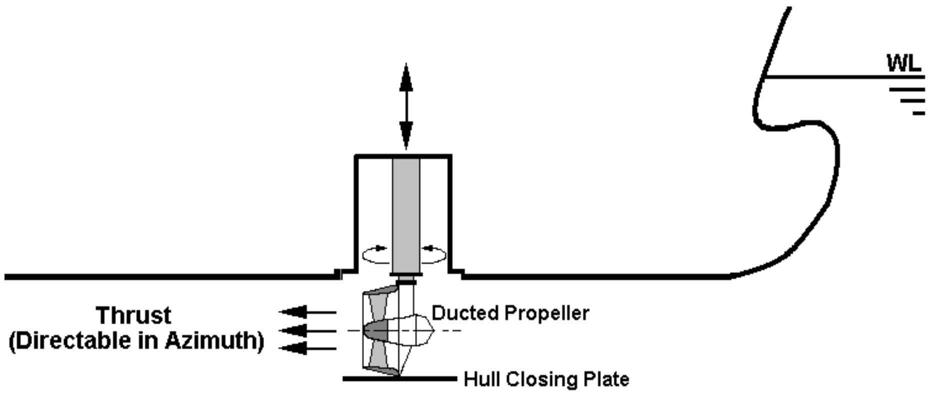

Figure 9: "Drop-Down" (Retractable) Azimuthing Bow Thruster

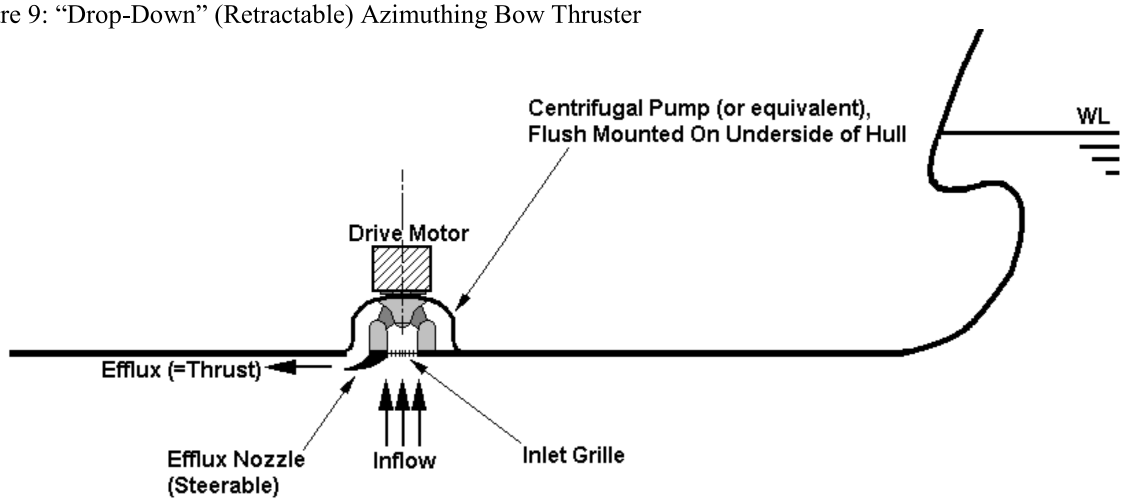

Figure 10: Pump-Type Thruster (Flush-Mounted with Underside of Hull) (see: www.schottel.de/marine-propulsion/spj-pump-jet)

10. MOTION-REDUCTION FIT

Noting that pitch-related motion represents a key factor limiting the operability of CTOL aircraft in a seaway, the initial review of motion-reduction measures for CVF considered not only means for reducing roll, as is common practice in ship design, but also those for reducing pitch.

Whilst there are a number of specific measures which could be applied to the CVF in order to minimise its pitching motion, these have generally not been widely adopted on either warships or merchant ships. This is essentially because they tend to impose significant penalty in terms of either broader aspects of ship performance (e.g. the 'low pitch' parent form and a seakeeping-optimised bulb considered in Section 7.1), ship size (i.e. tank-based pitch stabilisation) and/or risk and development cost (e.g. anti-pitch fins[6]). Consequently, explicit measures for minimising pitch motion were discounted.

As regards roll-reduction measures for CVF, these are principally intended to maximise the range of headings and ship speeds on which unrestrained aircraft handling is possible, and ensure general ship habitability (i.e. crew comfort, safety and effectiveness) in a seaway. However, they do not tend to significantly influence the range of sea states in which aircraft launch and recovery is possible, at least for Fixed Wing operations, because wind-over-deck considerations generally dictate that launch/recovery is conducted into the principal wave direction where rolling motion is generally minimised. It will be further noted that the specification of roll reduction measures for CVF is somewhat subjective, given:

- The random nature of a seaway, which could make unrestrained aircraft handling in beam seas a hazardous operation even in moderate seaways;
- The subjective issue as to which scenarios to meet when sizing the stabilisers for a given sea state (e.g. parametric roll in head/following seas, resonant roll in beam seas, or simply statistically-averaged conditions which are likely to be significantly less onerous);
- Difficulties in accurately modelling fin stabiliser performance and their effect on ship roll motion, computationally or at model scale;
- The potential secondary role of the fin stabilisers in correcting heel-in-turn (see Section 12.3 (below).

For the CVF design proposal covered in this paper, the decision was taken to proceed with a baseline roll reduction fit based around one pair of bilge keels sited between two pairs of high-outreach retractable fin stabilisers.

Bilge keels essentially represent standard fit for a warship, such as CVF, as they represent a simple, effective and low-cost means of reducing roll at all ship speeds. Although they result in a slight increase in ship resistance and flow noise, this can be minimised through correct flow alignment. In the case of the CVF design proposal covered in this paper, 'V'-section bilge keels were adopted, to allow outreach (and hence bilge keel effectiveness) to be maximised within the turn-of-bilge of the ship.

As regards the active fin stabilisers, these were adopted as they represent established low-risk technology and readily lend themselves to higher speed, volume-critical ships, such as CVF. They are very effective at higher forward speeds, although their performance deteriorates markedly at lower forward speeds. The choice of fin stabiliser configuration (i.e. retractable vs non-retractable) essentially represented a trade-off between survivability considerations (i.e. shock performance) versus fin performance during normal operation (i.e. fin outreach), with cost and internal space requirements being additional considerations. Ultimately retractable fins were selected because of the much higher outreach that can be achieved, which considerably enhances performance during normal operation[7]. Concerns associated with the increased vulnerability of retractable systems have been mitigated, at least in part, by the adoption of two well-separated pairs of fins per ship, which provides some degree of redundancy.

In terms of other potential roll-reduction measures, while tank stabilisation offers the benefit of being effective at lower ship speeds, where fin stabilisers are rendered ineffective, likely weight and internal space requirements led to this option being discounted. Likewise, whilst rudder roll stabilisation (Baitis et al, 1983) represents a potentially a low cost approach, that makes beneficial use of the increased flow velocities within the propeller races, it has only appears to have been applied to a limited number of vessels, most notably onboard the French aircraft carrier CHARLES DE GAULLE (Kummer et al (1998) and Autret & Deybach (1997)). Concerns regarding the development costs and risks, together with the complexity it could add to the ship's safety-critical manoeuvring system, led to this option being considered more as a candidate for possible substitution at a later date rather than as a baseline solution for CVF.

11. AIRCRAFT LIFT CONFIGURATION

The three basic aircraft lift configurations generally adopted for aircraft carriers are shown in Figure 11. Of these stern lifts are generally restricted to vessels operating solely Rotary Wing and STOVL Fixed Wing aircraft.

The choice of aircraft lift configuration impacts on a range of ship design issues, including flight deck/hangar layout and operability, structural design, hydrodynamics, damaged stability characteristics, internal ship layout, availability, reliability & maintainability (AR&M), vulnerability, storing/replenishment routes, and radar cross section. In the case of an aircraft carrier designed for intensive air operations, such as CVF, issues of flight deck/hangar layout and operability tend to predominate.

[6] For discussion of anti-pitch fins, see: Abkowitz (1959), Conolly & Goodrich (1970), Ferreiro et al (1994) and Ochi (1961).

[7] The outreach of non-retractable fins tends to be limited by the local beam and draught of the hull, in order to afford them some degree of protection from damage during berthing and docking.

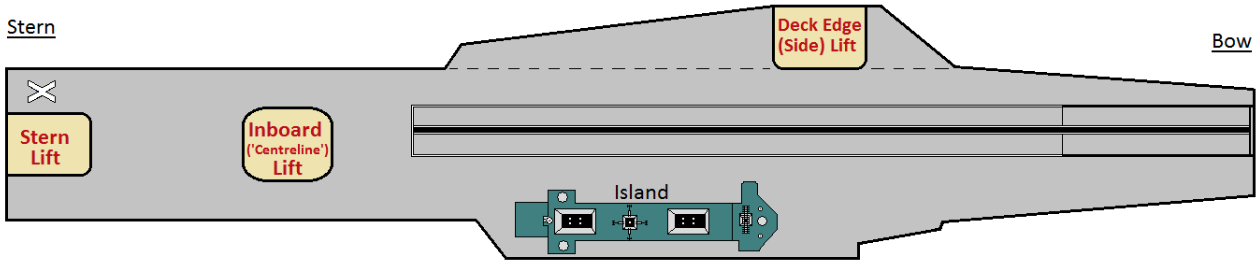

Figure 11: Alternative Aircraft Lift Configurations, shown on a Generic Aircraft Carrier Deck Plan

(Note: As indicated by Figure 1, the final BAE SYSTEMS aircraft carrier design proposals (both CTOL and STOVL variants) employed three (3) deck edge aircraft lifts, one of which emerged into an opening in the Island superstructure. Preceding design variants (from 2001) were based on just two (2) larger deck edge lifts, capable of accommodating two aircraft simultaneously.)

Specific advantages of deck edge lifts in this context include:

- Location of the aircraft lifts well away from the main operating areas (e.g. runways and taxiing routes) of the flight deck;
- Minimal encroachment into hangar stowage space;
- Increased flexibility in terms of the ability to accommodate large aircraft, in that the physical size of aircraft that can be accommodated is not so rigidly constrained by the size of lift platform (e.g. aircraft tails can overhang the edge of the lift platform);
- Improved scope for adopting larger lift platforms (e.g. to allow two aircraft to be accommodated simultaneously).

Notwithstanding this, there are a number of hydrodynamic issues associated with deck edge lifts that are worthy of further comment.

The key point is that deck edge lifts are inherently much more exposed to the elements than comparable inboard lifts, which places limits on their operability in a seaway. Specifically, under the influence of ocean waves, ship motion and the ship's running wave pattern, the lowered platform of a deck edge lift is subject to wave slamming loads, green seas and spray in relatively low sea states - factors that will tend to prevent safe aircraft movement between the hangar and flight deck in comparatively low sea states. Indeed, the work of Comstock et al (1982) suggests that for large US carriers operability of deck edge lifts is limited above Sea State 5.

Key factors determining the operability of deck edge lifts in this regard are:

- The freeboard of the hangar deck in the deepest through-life loading condition. This represents a fundamental geometric constraint on the design of an aircraft carrier, in that once deck heights have been fixed early in the design process, the likelihood of lift platform immersion is largely prescribed, and any deficiency in this regard is difficult to subsequently correct. Moreover, it tends to preclude the adoption of side lifts on smaller aircraft carriers;
- Metacentric height. For the reasons outlined in Section 4.3, adopting a relatively low operation metacentric height consistent with maximising natural roll period will tend to reduce roll amplitude and therefore reduce the incidence of lift platform wetness in a seaway. The down side of this is that angles of turning-induced heel will tend to be inherently higher, resulting in increased risk of the lowered lift platform immersing during manoeuvring (see below);
- The depth of supporting structure beneath the lift platform, noting that the spray generated by waves impinging on the lift platform structure can limit aircraft lift operability (e.g. due to the risk of aircraft skidding as they are manoeuvred on/off the lift platform (Comstock et al, 1982);
- The longitudinal position of the lift platform, noting that the operability of side lift platforms mounted significantly further forward than midships will tend to be particularly poor;
- The presence and configuration of flight deck sponsons immediately adjacent to the lift platform, which on one hand might afford some degree of shelter from green seas and wind, but on the other hand might generate unfavourable interactions and exacerbate the incidence of wetness and spray on the lift.

The minimum freeboard of the hangar deck was of the order of 6.5m (21 feet), which after allowing for the depth of lift platform structure, is comparable to figures quoted for larger US carriers (Comstock et al, 1982).

In terms of the evaluation of the likelihood of deck edge lift wetness in a seaway, two specific points are worthy of note. Firstly, seakeeping experiments conducted as part of the CVF studies (see Section 13.3) indicated a clear tendency for strip theory, such as that commonly embodied in seakeeping assessment software, to markedly underestimate the occurrence of side lift wetness compared to experimental measurements. This, together with operability issues that cannot be modelled using strip theory (e.g. the occurrence of undesirable hydrodynamic interactions around side lift openings) strongly suggests that reliable assessment of deck edge lift wetness is best achieved through model testing. Secondly, it will be noted that the established criteria for assessing the deck edge lift wetness at the design stage (e.g. the commonly quoted limit of 5 wetnesses per hour presented by Comstock et al (1982)) is essentially concerned with minimising the occurrence of lift wetness based on statistically-averaged performance, rather than minimising its consequences. Clearly lift wetness is a safety issue, in terms of the risk to aircraft and personnel, and moreover, its occurrence in a given seaway will tend to be random. It is therefore important that appropriate consideration is given to minimising the consequences of lift wetness in the design and location of the lift platforms, and in the design of the surrounding above water hullform (e.g. through the judicious location and sizing of sponsons).

A separate issue influencing the operability of deck edge lifts, even in calm conditions, is the risk of a lowered lift platform becoming immersed as the vessel heels while manoeuvring, resulting in noise, spray, vibration, and risk to personnel and equipment. Analysis of the CVF design proposal covered in this paper indicated that, at least in flat calm conditions, such immersion only occur at heel angles of greater than around 10° - something that was considered acceptable, given that likely heel limits for unrestrained aircraft handling are much lower (i.e. around 3.5°), and because of the scope for raising the lift platform to avoid this type of immersion. Adoption of a suitably high operating metacentric height is key to minimising manoeuvring-induced heel, and hence immersion of this type.

It will be noted that inboard lifts, such as those traditionally fitted to Royal Navy carriers, are sheltered from the elements and are not prone to immersion in a seaway or under the influence of manoeuvring-induced heel. As such they might be expected to remain operable in all sea states in which aircraft handling is possible. Consequently, there are strong arguments in favour of the adoption of inboard lifts on aircraft carriers where the air group is based solely around STOVL and Rotary Wing aircraft, as this ensures that the enhanced operability offered by these aircraft types in a seaway (i.e. compared to CTOL aircraft) will be maximised. Likewise, for smaller aircraft carriers, the adoption of inboard lifts (or at least a stern lift) is likely to be a necessity if air group operability is sought in anything other than relatively calm conditions.

12. HEEL-IN-TURN CONSIDERATIONS

12.1 THE SIGNIFICANCE OF HEEL-IN-TURN FOR AN AIRCRAFT CARRIER

Turning-induced heel assumes special significance in the design of an aircraft carrier, for it fundamentally affects the operational flexibility and responsiveness of the ship, in terms of:-

- Allowing flight deck preparations (e.g. aircraft movements) to be undertaken whilst manoeuvring the ship into wind to launch or recover aircraft;
- Ensuring that Deck Alert requirements (i.e. the ability to launch defensive aircraft at short notice) can be satisfied from the widest range of initial headings, ship speeds and wind/sea conditions, without the need to constrain routine flight deck activity (e.g. aircraft movements) before or during the manoeuvre.

In pursuit of the above objectives, it is highly desirable that combined angles of heel/roll that develop in the turn (i.e. under the combined influence of wind, waves, ship turning and aircraft movement) do not exceed established limits for unrestrained aircraft handling. In addition it is desirable that the lowered platforms of deck edge lifts (where fitted) do not become immersed - see Section 11 for discussion of this latter issue.

12.2 MEASURES TO LIMIT HEEL-IN-TURN

For a given ship speed and helm angle, the fundamental parameter determining angles of turning-induced heel is metacentric height. Accordingly, the aim of the ship designer in the first instance should be to minimise turning-induced heel by maximising the metacentric height of the vessel within the constraints imposed by broader design considerations (see Section 6). Allied to this, appropriate strategies should be adopted (e.g. through-life ballasting strategies) to ensure that adequate metacentric height is maintained across all through-life loading conditions.

If further improvements on heel-in-turn characteristics are sought there are a range of alternative heel correction systems that can be installed onboard the ship, each of differing performance potential and ship impact. Options of this type considered as part of the CVF studies covered in this paper are summarised in Table 7.

Of these, dedicated (tank-based) fluid transfer systems were discounted due to inherent weight and space penalties, and the general feasibility and associated power levels required to transfer the working fluid at a rate sufficient for effective heel correction. Circular movement of solid weights in a horizontal plane was also discounted on grounds of general ship impact and feasibility. Of the remaining options it was concluded that none would be capable of fully meeting CVF heel correction requirements for all 'loiter' speeds and rates of turn, although:

- A system based around use of the ship's fin stabilisers would provide a partial heel correction capability at low cost, risk and ship impact;
- A dedicated transverse moving weight system (i.e. similar to that fitted onboard the French aircraft carrier CHARLES DE GAULLE)[8], used in conjunction with the ship's fin stabilisers, would maximise the range of turn rates, ship speeds and sea states over which unrestrained aircraft handling would be possible in the turn. However, the moving weight component of the system would adversely impact on ship weight/centroids and on internal layout (e.g. on fore-aft access and the layout of modular stores facilities located on the gallery deck) and impose additional cost, risk and maintenance requirements.

Table 7: Heel Correction Options Considered for CVF

Type	Option
Fluid (Tank)-Based Systems	Transfer of Fluid from One Side to Another by Pumping
	Transfer of Fluid from One Side to Another by Compressed Air
	Discharge of Fluid Overboard from One Side or Other of the Ship
	Use of the Ship's Main Ballast System
Moving Solid Mass Heel Control System	Transverse Movement of Solid Weights
	Circular Movement of Solid Weights in a Horizontal Plane
Hydrofoil-Based Systems	Use of Active Fin Heel/Roll Stabilisers

12.3 ANALYSIS & CONCLUSIONS ON THE NEED FOR A HEEL CORRECTION SYSTEM ONBOARD CVF

Analysis of turning-induced heel was based on empirically-based simulations of manoeuvring performance under Deck Alert scenarios, obtained as part of the work described in Section 13.4. This analysis of heel-in-turn, which considered a range of initial speeds, helm angles and wind conditions, was based on a 'turn and accelerate' manoeuvre, whereby the ship turns through 180° into wind, applying power (to maximise rate of turn and speed on exit from the turn), before accelerating and steadying on the new course to reach aircraft launch speed. This assumed a limiting combined angle of heel/roll in the turn of 3.5°, which corresponds to the limiting significant single roll amplitude value quoted by Comstock et al (1982) for aircraft handling in a seaway. Conclusions were:

- Given appropriate management of metacentric height there was adequate scope for CVF to satisfy aviation-related heel-in-turn limits in calmer seas, without the need for a dedicated heel correction system;
- In intermediate and higher sea states dynamic roll, rather than turning-induced heel, would represent the key factor preventing unrestrained aircraft handling during the turn;
- There are various 'work arounds' that could be employed by the ship's command to mitigate or avoid those scenarios where unrestrained aircraft handling in the turn is not possible (e.g. placing limitations on ship heading, restrictions routine aircraft movements, or unlashing aircraft after the point of maximum heel has passed in the turn).

This led to the overall conclusion that the broader ship design penalties of adopting a dedicated heel correction system, such as a transverse moving weight system, were not warranted for CVF, but that the potential use of the ship's fin stabilisers to provide a heel correction capability should be explored further.

12.4 OTHER POTENTIAL HEEL CORRECTION REQUIREMENTS

Minimisation of the heel induced by aircraft movements on/off the ship represents a potentially key consideration for an aircraft carrier, such as CVF, where intensive flying operations are required. Indeed, the limits on heel (typically 0.5°-1.0°, see Pattison & Bushway (1991)) are potentially much lower than those associated with turning-induced heel (typically 3.5° - see above). This is because the determining factor is likely to be requirements for ongoing aircraft launch/recovery operations, rather just unrestrained aircraft handling.

Nonetheless, measures to limit heel-in-turn (see above) will also tend to minimise or offer scope for counteracting the heel induced by aircraft movements.

The CVF studies covered by this paper indicated that, provided operating metacentric height is sufficient to satisfy heel-in-turn requirements, there is generally adequate scope to counteract the heel induced by aircraft movements in a timely manner using the ship's main ballast system, without the need for a dedicated heel correction system. However, this conclusion is clearly sensitive to such issues as metacentric height, flight deck dimensions/configuration, aircraft weights, assumed flying programme and ballast system design, and therefore requires confirmation through analysis in the context of a given ship design.

[8] See Kummer et al (1998) and Autret & Deybach (1997) for an overview of the moving weight heel correction system onboard the CHARLES DE GAULLE.

13. HYDRODYNAMIC PERFORMANCE EVALUATION

13.1 HYDRODYNAMIC TANK TESTING

Two phases of hydrodynamic tank testing work were conducted as part of the CVF studies covered in this paper, both conducted at SSPA, Gothenburg (Sweden) during 2002.

The first phase of tank tests, which were conducted at 1/60 scale (Figure 12), focussed on addressing the key areas of hydrodynamic risk and uncertainty, namely:-

- Preliminary confirmation and hydrodynamic de-risking of the characteristics of the above/below water hullform;
- Validation of powering characteristics to allow the power system, shaftline configuration and fuel capacity to be confirmed.

The scope of this initial testing included expert review/refinement of the hullform and appendage arrangement, followed by seakeeping and naked hull resistance experiments, and supporting estimation of powering characteristics using empirically-based estimates of propulsive efficiency.

The second phase of tank tests were conducted late in 2002, at larger scale than the initial tests (i.e. 1/35 scale, see Figure 13) and to an updated set of design particulars. The scope of work consisted of a more detailed expert review/refinement of the hullform/appendage arrangement, naked hull resistance measurements and empirical estimation of propulsive efficiency, and nominal (unpowered) wake surveys on both the podded and conventional shaftline propellers.

13.2 EVALUATION OF RESISTANCE & POWERING CHARACTERISTICS

The fundamental approach adopted in the assessment of CVF powering characteristics centred around the use of commercially available regression-based powering prediction software.

Having produced initial estimates on this basis, the resulting predictions were compared against towing tank predictions for the design as they became available. The output from this validation activity was a set of revised empirical correction factors (e.g. revised values of ship-model correlation allowance, appendage form factor and propulsive efficiency elements) for use in future runs of the regression software.

This approach of calibrating the regression software against the tank test predictions allowed the tank test results to be extrapolated with a good degree of confidence to revised ship particulars and loading conditions as the design of the ship developed.

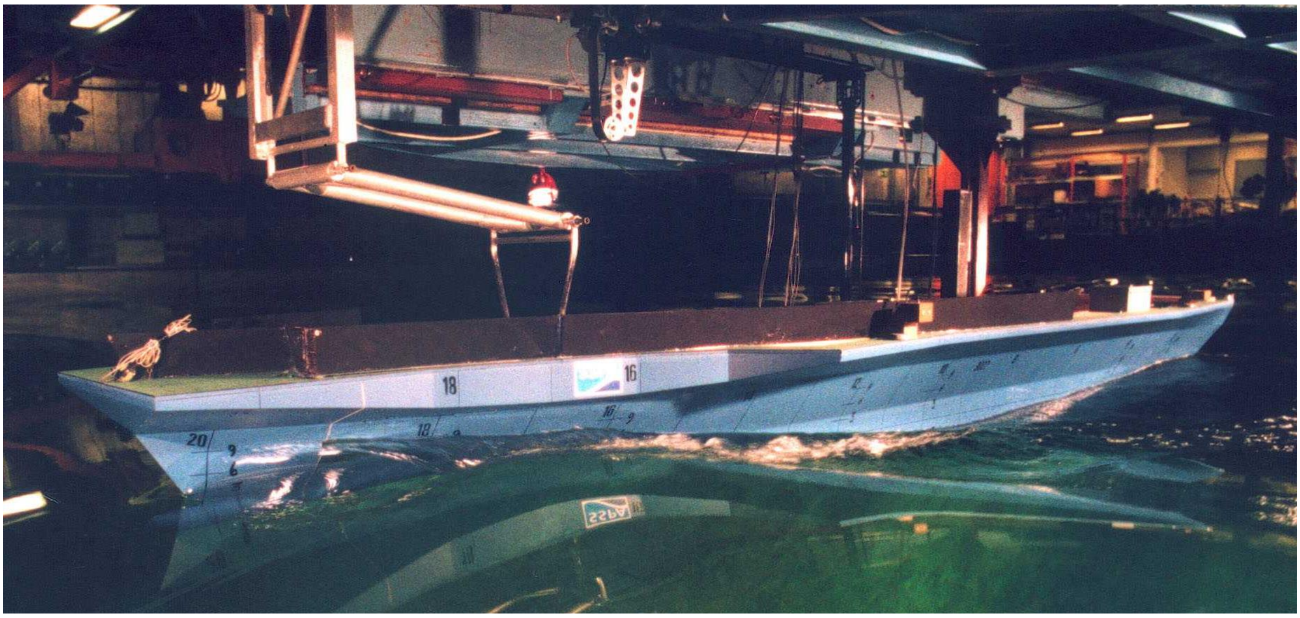

Figure 12: Initial 1/60 Scale Seakeeping Tests on the BAE SYSTEMS CVF Design Proposal (CTOL Variant) (Source: SSPA, June 2002)

Figure 13: 1/35 Scale Model of the Final BAE SYSTEMS CVF Design (CTOL Variant), Rigged in Preparation for Propeller Wake Survey Measurements (Source: SSPA, December 2002)

(Note: The upper portion of above water form and side lift recesses were not modelled in these final 1/35 scale tests, as seakeeping tests were not part of the itinerary. Also, note the revised (fuller) above water bow shape compared to earlier tests of Figure 12 - see Section 7.2 for discussion of this.)

13.3 SEAKEEPING ASSESSMENT

13.3 (a) Approach

The detailed seakeeping assessment of the CVF design proposal was based on commercially available strip theory analysis software. This approach readily lent itself to the rapid and low cost evaluation of the relative large number of metrics and assessment locations required to assess compliance with the derived seakeeping criteria for CVF (see Section 4.3). It also generated data required to perform follow-up assessment of percentage time operable (PTO) of the CVF air group in different worldwide ocean areas, and readily allowed sensitivity studies into such issues as the effect of sea spectra, wave directionality, metacentric height and roll radius of gyration on seakeeping performance.

Separately, a set of 1/60 scale seakeeping experiments were conducted (see Section 13.1) to assess phenomena that could not be adequately assessed using strip theory, namely parametric roll and phenomena pertaining to the above water form. In addition, the experiments generated seakeeping data for a representative CVF design against which the strip theory predictions could be validated.

13.3 (b) Strip Theory Results

The findings of the strip theory analysis of CVF were broadly in line with the findings of Comstock et al (1982), clearly demonstrating the inherent benefits of STOVL and Rotary Wing aircraft over CTOL aircraft in terms of operability in higher sea states.

In terms of the operability of CTOL aircraft in a seaway, the key limiting factor is pitch-related motion, specifically pitch amplitude and limitations on absolute vertical displacement at the round-down (i.e. at the aft end of the angled runway). While increasing ship length within practicable bounds will tend to reduce pitch amplitude, its effect on vertical displacement at the round-down is much less marked. Meanwhile, although such measures as adopting a large (seakeeping-optimised) bulbous bow and 'low pitch' underwater form may reduce pitching motion (see Section 7.1), the effect is unlikely to be so marked as to allow any appreciable extension of the operating envelope of CTOL aircraft into higher sea states. On this basis it was concluded that there is a well-defined safe sea state for the operation of CTOL aircraft from CVF, that is inherently lower than for STOVL and Rotary Wing aircraft.

With STOVL and Rotary Wing aircraft, the constraints on acceptable ship motions are inherently less onerous. Accordingly, broader factors will tend to represent more of a limiting factor in the operability of these aircraft types in higher sea states, specifically the operability of deck edge lifts (where adopted), or maximum safe Wind Over Deck as determined such issues as:-

- The ability of flight deck personnel to stay upright under the combined influences of wind and ship motions;
- The risks to pilots who may need to eject during a failed launch/recovery;
- The risk of damage to aircraft (e.g. damage to opened aircraft canopies);
- For Rotary Wing operations, rotor spread, fold and engage operations.

The guidance of Crossland et al (1998) and STANAG 4154 indicates a safe wind over deck limit of 35 knots. For the typical ocean conditions of STANAG 4194 and zero ship speed, this corresponds to around Upper Sea State 5.

13.3 (c) Validation Results

One key use of the results from the 1/60 scale seakeeping experiments was validation of the computational (strip theory) predictions that underpinned the detailed seakeeping assessment of the design proposal. Parameters compared in this validation work included Response Amplitude Operators (RAOs) (i.e. regular seas predictions), RMS motions amplitudes in irregular seas, zero speed Relative Motions predictions at the deck edge lifts, and natural roll period.

This validation exercise showed that, at least for zero ship speed, experimental predictions of Relative Motion at the deck edge lift locations were significantly (i.e. up to 50%) greater than those predicted by strip theory. Given the potential implications for lift operability in a seaway, a more thorough assessment of deck edge lift wetness was planned for subsequent phases of seakeeping experiments. Additionally, in accordance with the established limitations of strip theory, roll RAO predictions were somewhat lower than those indicated by the seakeeping experiments. Other than this, the validation work showed a good degree of correlation between the strip theory and experimental seakeeping predictions (i.e. in terms of pitch and heave motion, irregular seas roll, and natural roll period).

13.3 (d) De-Risking of the Above Water Form

Another key aspect of the 1/60 scale seakeeping experiments was the de-risking of the seakeeping characteristics of the proposed ‘highly flared’ above water form. These de-risking tests were conducted both for a representative normal operating sea state and for a representative extreme sea state (i.e. Sea State 9), and considered both head seas at zero and forward ship speed and beam seas at zero ship speed. The results indicated that, provided the lowest knuckle of the highly flared form is sited well above (i.e. around 3.0m above) the deepest operating draught of the vessel and a flare angle of no more than 35° is adopted, as was the case with the design proposal, the potential risks associated with immersion of the flare should be avoided. The latter risks were considered to be excessive motions, sudden accelerations/decelerations and parametric roll.

These findings went a considerable way to alleviating concerns associated the seakeeping implications of the highly flared style of above water form, pending more detailed de-risking proposed for subsequent stages of testing (e.g. oblique seas tests and measurement of hydrodynamic loading on specific areas of the highly flared form).

13.3 (e) Parametric Roll

As part of the 1/60 scale experimental tests to de-risk the above water form, head seas tests were conducted to assess the occurrence of parametric roll in head seas. This work concluded that, provided that the flare is initiated sufficiently high above the deepest operating waterline (i.e. in line with the design proposal), the occurrence and severity of parametric roll for the ‘highly flared’ form was likely to be no worse for than for an equivalent traditional (i.e. sponson) style of above water form. Nonetheless, the tests provided an apt demonstration of the consequences of parametric roll occurring on a large aircraft carrier and so are worthy of description here.

Firstly, it should be noted that, at least for the long-crested head seas case tested, parametric roll is an instability-related phenomena triggered by slight disturbances - for example small angles of yaw, list or roll. As such it is not detected by off-the-shelf computational (e.g. strip theory-based) seakeeping assessment software. Given the presence of such disturbances, a succession of waves of exactly the right encounter period (i.e. half the natural roll period of the ship) can cause a resonant roll motion to develop. For the head seas case tested, the results indicated that large angles of resonant roll motion of between ±10° and ±15° could develop. The effects of this are exacerbated by the very short period of motion (i.e. half the natural roll period of the ship), which would result in high levels of deck velocity and acceleration. Clearly this would preclude safe aircraft launch/recovery and would place any unlashed aircraft and ground support equipment on the flight deck (or in the hangar) in jeopardy, while additionally placing personnel at risk.

In mitigation, the probability of a succession of waves of exactly the right frequency being encountered is small, and the resonant motion will take a period of time to develop. Moreover, the occurrence of parametric roll is sensitive to encounter frequency, and so simply adjusting ship speed by a knot or two will tend to cause the motion to subside.

Nonetheless, parametric roll represents a phenomena that can occur on a range of headings (i.e. head, following or oblique seas) and can place personnel, support equipment and aircraft at risk, and so is worthy of note.

13.4 MANOEUVRING ASSESSMENT

During early CVF design studies, which assumed a conventional shaftline arrangements, and where the scope of the analysis was more limited, manoeuvring performance was assessed using a commercially-available manoeuvring simulation software package based upon empirical data. This allowed evaluation of manoeuvring performance in a range of standard IMO-type manoeuvres (e.g. Turning Circle, Zig-Zag and acceleration/stopping manoeuvres).

As design work progressed, a hybrid shaftline arrangement was substituted for the more conventional arrangement, employing an azimuthing podded propulsor (Figure 6). The latter effect could not be reliably modelled using readily available commercial packages. Moreover, with progress towards increasing design maturity, there was a pressing need to model manoeuvres and phenomena of specific importance to aircraft carrier operations, but which are not typically provided for in commercial software. These carrier operations specifically need to address heel-in-turn characteristics, the effects of applying power in the turn, and Deck Alert 'turn-and-accelerate' type manoeuvres.

Accordingly later phases of manoeuvring assessment were sub-contracted to MARIN, who undertook bespoke simulation of manoeuvring performance based on empirical data for vessels of similar size, windage and hydrodynamic characteristics to CVF. This specialist simulation work considered a range of IMO-type and Deck Alert-type manoeuvres, for a range of wind speeds, helm angles and ship speeds. In addition, the work package included limited validation against historical data, expert review of the rudder/skeg arrangement, and independent (empirically-based) evaluation of lateral wind and current forces to support confirmation of the proposed bow thruster fit. The work was conducted in two phases, the first phase evaluated an early shaftline concept based around twin podded propulsors and a single conventional shaftline. The second phase investigated the final hybrid shaftline proposal shown in Figure 6. In both instances equivalent ship designs employing a twin conventional shaftline arrangement (without pods) were also evaluated, to provide a benchmark against which the likely manoeuvring benefits/drawbacks of the hybrid shaftline arrangements could be assessed.

This manoeuvring simulation work required a number of key supporting assumptions to be made regarding the characteristics of the ship's IFEP power system, steering gear and propulsion train. The required assumptions included assumed rudder/pod azimuth rates, shaftline torque limitations, control of power during crash-stop and acceleration manoeuvres, and whether dynamic braking resistors should be fitted to assist in decelerating the vessel.

A key benefit of basing the manoeuvring assessment on computational simulation was that it allowed rapid evaluation of a wide range of scenarios and comparison of alternative shaftline configurations at significantly lower cost than would have been possible through tank testing. It also generated detailed histories of manoeuvring parameters during the turn (e.g. position, yaw rate, turning-induced heel) for use in future studies, and quality computer animations of the results (Figure 14), which proved a useful means of interpreting and disseminating the results. In terms of drawbacks, the simulations were limited in that they took no account of wave action, and were based on empirically-derived windage/hydrodynamic coefficients, rather than design-specific data. As the latter issue clearly places limits on the degree of confidence that can be placed in the predictions, follow-up phases of hydrodynamic experiments were scheduled to include:

- Captive manoeuvring experiments and wind tunnel tests to generate hydrodynamic and windage coefficients for use in place of empirical data in future manoeuvring simulations;
- Self-propulsion manoeuvring experiments for a limited range of key manoeuvring scenarios, to validate overall manoeuvring characteristics predicted by the simulations, and assess the effect of ocean waves on manoeuvring performance;
- Assessment of lateral current forces and moments on the hull;
- Wind tunnel tests to confirm air wake characteristics.

Relevant findings from the manoeuvring simulation work are included in the discussion of shaftline arrangement in Section 8.1.

13.5 EVALUATION OF ROLL RADIUS OF GYRATION

Roll radius of gyration represents a key parameter determining the natural roll period of the vessel, and by virtue of this, the upper bound limit on an acceptable operating metacentric height for an aircraft carrier, such as CVF (see Section 6). Given initial indications that the limits on operating metacentric height for CVF would be particularly onerous, particular importance was therefore attached to establishing a reliable estimate of roll radius of gyration for CVF.

For most ship designs similarities with preceding vessels mean that roll radius of gyration can be estimated with reasonable accuracy, for example from established 'rule of thumb' guidance, such as that presented by Lloyd (1998), the International Society of Allied Weight Engineers (SAWE Recommended Practice No. 14, (2001)) and Cimino & Redmond (1991). For CVF, however, the availability of such type specific ship data is at best limited, particularly once the bespoke nature of the above water form (e.g. the effect of flight deck overhangs) is taken into account, as this tends to distort trends between roll radius of gyration and waterline beam.

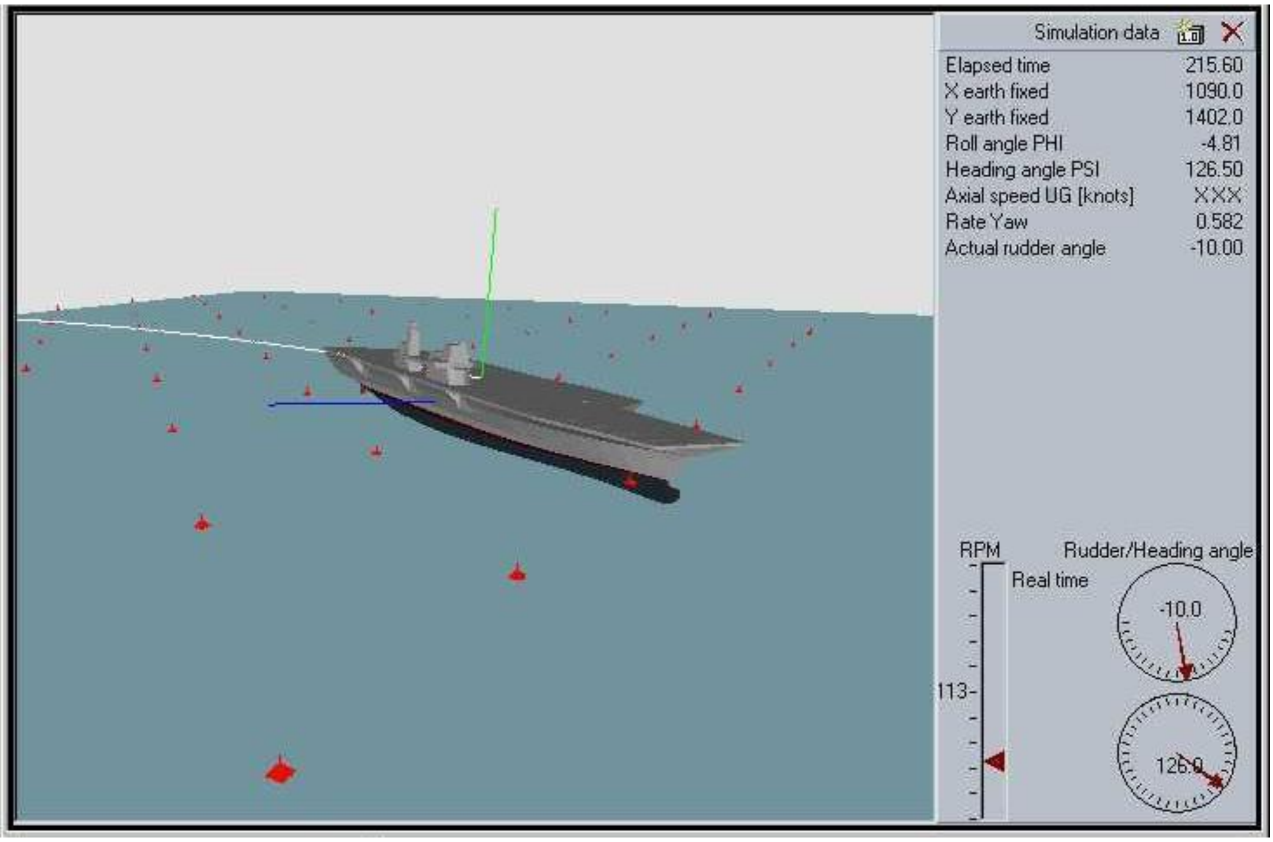

Figure 14: Snapshot from one of the Computer Animations Output from the Manoeuvring Simulation Work (Source: MARIN)

Accordingly, it was considered appropriate to construct a "bottom up" spreadsheet estimate of roll radius of gyration for CVF from weight breakdown data. The procedure adopted was based on that presented in SAWE Recommended Practice No. 14 (2001) and Cimino & Redmond (1991). These split the component moments of inertia down into the 'self-inertia' of each item, about its own centre of gravity, and the 'transference inertia' of each item, due to the separation of its centre of gravity, from that of the whole ship. The level of effort required was greatly reduced by the availability of a NAPA STEEL[9] model of the primary hull structure, which allowed a reliable radius of gyration estimate for the majority of the steel weight to be downloaded and input into the calculation as a single line item.

The calculations indicated a 'dry' radius of gyration value of around 43.0% to 44.5% of waterline beam, depending on loading condition and through-life growth. This is slightly higher than the figure of 40.9% waterline beam quoted by the International Society of Allied Weight Engineers (2001) for a US 'Nimitz' class Carrier employing a more traditional style of above water form. To this 'dry' radius of gyration must be applied a correction to allow for the effects of entrained water. Roll decay tests conducted as part of 1/60 scale seakeeping tests (see Section 13.1) indicated that such entrained water effects could be allowed for by multiplying the 'dry' radius of gyration by a correction factor of around 1.056. This is in close agreement with the generic correction factor of 1.05 presented by Rawson & Tupper (1984).

9 See: www.napa.fi/Design-Solutions/NAPA-Steel

13.6 PROPULSOR WAKE FIELD SURVEYS

As noted in Section 13.1 (above) the final stage of tank tests for the design proposal included nominal (unpowered) wake surveys at the propeller discs of both the conventional shaftlines and the podded propulsor of the proposed hybrid shaftline arrangement (Figure 6).

These tests were aimed predominantly at providing a library of wake field data (e.g. circumferential wake field variations) to support underwater signatures and noise & vibration studies. However, they also allowed preliminary confirmation of the choice of optimum propeller direction of rotation based on noise and vibration considerations, provided nominal wake figures for use in estimating propulsive efficiency, and also gave an indication of the hull afterbody flow pattern for consideration in further hullform refinement work.

14. CONCLUDING COMMENTS

This paper has provided an overview of hullform and hydrodynamics-related design experience accumulated in the course of BAE SYSTEMS team's design studies for CVF, in terms of:

- Hydrodynamics design requirements;
- Hullform and hydrodynamics-related design options, including some of the more innovative proposals considered;
- The manner in which hydrodynamic performance was evaluated, the balance achieved between computational and experimental approaches, and how the level of performance evaluation has been matched to the level of design maturity;
- Other key hydrodynamic design issues of relevance to CVF.

As stated earlier, CVF is now (2003) being progressed to a different design under a joint UK MoD-Industry Integrated Alliance Team (IAT). Nonetheless, it is hoped that the work presented here serves a useful purpose in highlighting some of the key design issues of importance in aircraft carrier hydrodynamic design, identifying readily available sources of design guidance available to the designer, and highlighting appropriate design methodology and design options.

15. ACKNOWLEDGEMENTS

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Firstly, thanks are due to James Swan of BAE SYSTEMS Land & Sea Systems, and Ralph Bonfield and Richard Irvine of VT Shipbuilding, who together undertook the bulk of the detailed studies that underpin the findings presented here. Thanks are also due to representatives from BAE SYSTEMS, VT Group and Rolls Royce - unfortunately too numerous to list here - whose specialist advice provided substance to the work presented, and whose spirit of teamwork and collaboration as part of the BAE SYSTEMS CVF proposal sets an example for others to follow.

Proposals for the 'highly flared' style of above water form are attributable to original concepts by the late Professor Louis Rydill, who also provided a range of other guidance on the BAE SYSTEMS design proposal. Likewise, much of the discussion pertaining to propulsor-induced noise and vibration is attributable to specialist advice received from Dr. Roger Kinns of RKAcoustics.

The work presented draws heavily on hydrodynamic tank testing and supporting specialist advice received from SSPA of Sweden, and specialist manoeuvring simulation work undertaken by MARIN of the Netherlands. In this regard thanks are due to Lennart Byström of SSPA and Frans Quadvlieg and Giedo Loeff of MARIN.

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