Marine System Integration De-risking for Type 26 Global Combat Ship

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Synopsis

In modern warships the electrical power and propulsion system is fundamental to the end capability of the vessel. The Type 26 Global Combat Ship will utilise an advanced CODLOG (Combined Diesel Electric or Gas Turbine) propulsion architecture. The integration of this advanced architecture poses a number of engineering challenges and risks. The general philosophy towards de-risking taken at BAE Systems Naval Ships is one of left shifting project risk, whereby risks are considered and mitigated at the earliest opportunity in the development lifecycle.

The electrical power generation and distribution system for Type 26 is considered to pose one of the largest integration risks within the Power &Propulsion (P&P) System. There are electrical power and propulsion integration risks in areas such as the overall quality of power supply (QPS), ship performance during transition modes and diesel generator ramp rates. Another key risk is the physical, functional and control integration aspects of the P&P system, with each piece of equipment needing to be integrated with the wider P&P system and the overarching Power Management System.

In this paper, the de-risking strategies that have been put in place to minimise risk in respect of the power and propulsion integration system for Type 26 are presented. Chiefly, these activities involve the development and utilisation of computer based mathematical models of the power and propulsion and electrical power systems, and the construction of shore based integration test facilities.

Keywords: Type 26, Integration, Marine Systems, Test Facility, Modelling, Frigate

Author Biographies

David Capper joined BAE systems in 2013 and is currently the Principal Engineer and Trials Manager for the Type 26 Electrical Integration Test Facility Project within the Marine Systems team. Prior to this, he spent several years within in-service support teams for various classes of warship within Portsmouth Naval Base. His background is in electrical and electronic engineering, having completed a Master’s degree with the University of Sheffield in 2012.

Thomas Groves began work with BAE Systems in September 2018, during this time he has worked directly with the Electrical Integration Test Facility focusing on electrical power systems data analysis in parallel to developing and validating the electrical power systems models for Type 26. His background is focused in software development, electronic engineering and digital signal processing and analysis which he developed through his time at the University of Kent. He is currently working to further develop specialist understanding through undertaking a second degree with the University of Manchester.

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Introduction

Figure 1 Type 26 Global Combat Ship

The Type 26 Global Combat Ship (T26 GCS) is a naval frigate currently under construction by BAE Systems. It is intended to replace the Type 23 Frigate currently in service with the UK Royal Navy; and has taken much of the design philosophies of the class, albeit, with significant increases in capability and with the benefit of years of learning from experience from the development and construction of naval warships.

The Power and Propulsion (P&P) equipment on board any vessel is of high importance, but on a naval vessel this criticality takes on a new level. The P&P equipment ultimately defines the vessel's ability to move and fight, underpinning the operation of all auxiliary and combat system equipment. If the P&P system does not prove resilient or reliable enough, or does not perform as expected, then confidence in the ability to fight the ship is greatly reduced, with the vessel and crew placed at an unnecessarily heightened risk.

P&P equipment is typically difficult to integrate into warships due to the sheer amount of interfacing required and unique weight, space and performance constraints. As such this equipment is specified well in advance of the rest of the ship's design being completed, and it invariably proves extremely expensive to make any significant changes to this equipment late in a warship delivery lifecycle. Therefore, ensuring the P&P design is correct well in advance of first of class trials would be of significant benefit to all stakeholders in the purchase, design, construction and operation of any new class of vessel.

BAE Systems has undertaken a significant 'de-risking' effort with the T26 GCS, aiming to left shift this integration risk as early as possible into the development process. This is achieved via a number of methods, including integration test facilities and computational modelling. The methods which are being employed within the Marine Systems aspect of T26 GCS are detailed within this paper.

Type 26 P&P Architecture

A Combined Diesel Electric or Gas Turbine (CODLOG) configuration is used on Type 26. This is a very similar configuration to the Type 23 which this class is intended to replace, which uses a Combined Diesel Electric and Gas Turbine (CODLAG) arrangement. This is a notable departure from other recent major Royal Navy vessels which have used an Integrated Electrical Propulsion (IEP) arrangement; however, a CODLOG arrangement offered the highest Technology Readiness Level and lowest risk compared to other arrangements for the specific requirements of T26 compared to those that have employed an IEP system.

The principal T26 P&P system consists of:

- 4x Diesel Generators, 2 per switchboard
- 1x Gas Turbine
- 2x Electric Propulsion Motors
- 1x Cross Connect Gearbox
- 2x 690V Switchboards
- 2x Ship Service Transformers (SSTx)
- 2x 440V Switchboards
- 5x Zonal Power Supply Units
- 4x Chilled Water Plants
- Power Management System
- Electrical Distribution Centre (EDC)

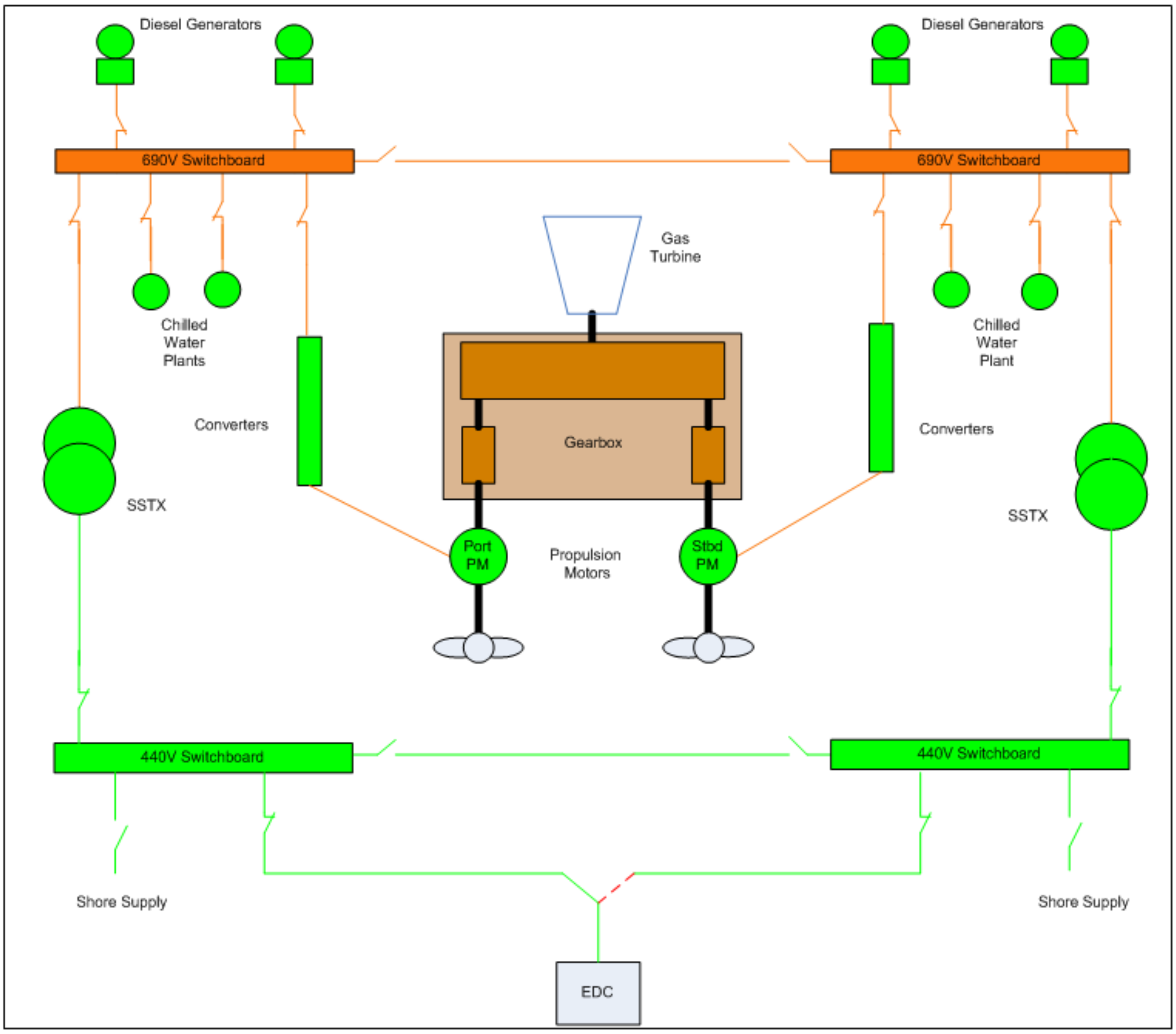

Figure 2 T26 GCS P&P Architecture

Issues with previous classes of naval vessels have highlighted the principal importance of the P&P system in confidently deploying a platform. Whilst the selection of a CODLOG system was designed to minimise this risk as much as possible at the outset, it could not eliminate it entirely. Residual risks with equipment, physical and functional integration, overall system architecture and operational concepts still inherently remain in any complex P&P design with stringent requirements on all aspects of it. As such, a de-risking strategy has been developed to 'left shift' as much of this risk as possible, allowing issues in design or equipment to be exposed at a point in the programme where it is possible to make an alteration without adversely affecting cost, delivery schedules or overall confidence in the solution.

This strategy involves a mixture of test facilities and computational modelling. Following analysis of the potential risks in delivering the T26 P&P system, a specific set of activities have been undertaken in order to de-risk the T26 GCS P&P system as effectively as possible. These activities, which are the focus of this paper, are:

- Integration Test Facilities
    - Electrical Integration Test Facility
    - Gearbox Test Facility
    - Shore Integration Facility & Land Based Integration Facility

- Computational Modelling
    - Systems Engineering
    - Electrical Power Systems
    - Mechanical

Test Facilities

Electrical Integration Test Facility (EITF)

The Electrical Integration Test Facility (EITF) is a key component of de-risking the electrical P&P system. Whilst Factory Acceptance Tests (FATs) prove the equipment within the confines of that equipment's individual requirements, it does not prove the integration into a wider system and any potential interactions with other equipment – this is often where risks become issues.

On previous vessels, the equipment FATs have been deemed enough to allow the equipment onto the ship before performing integration trials during commissioning. EITF aims to introduce another 'step' between equipment FATs and ship commissioning, whereby integration and operation is proven well before any the first of class is even built. An additional inclusion at EITF over and above equipment FATs is the ship's Power Management System – this allows testing and proving of the physical interfaces, the software control logic, and operating philosophy. It also presents an opportunity to familiarise the eventual operators with operation of the system much earlier in the lifecycle.

The EITF is a joint enterprise between BAE Systems and General Electric Power Conversion (GEPC), at a bespoke test facility based near Leicester. The facility has been developed, constructed and commissioned over the past two years, with first testing on a partial T26 system commencing mid-2019. Over the remainder of 2019, the full system was brought into commission and testing resumed in Q4 of the year. As the EITF is essentially an advanced integrated FAT not part of the current in service support requirement, the facility is due to be retired before T26 first of class trials.

The EITF consists of just over a 'half set' of T26 P&P equipment, listed below. This equipment is ship-fit, and will eventually be fitted to Ship 3. Using ship-fit equipment allows for the most accurate representation possible of the T26 system. The EITF also builds on GEPC's 'string test' arrangement, which was used to test the propulsion motor at a FAT level, with a National Grid power supply to the drives – this arrangement remains in place, with the T26 equipment added into the architecture replacing the grid supply, and the ship's control system placed on top.

- 2x Diesel Generators, 1 per Switchboard
- 1x Electric Propulsion Motor (PM)
- 2x 690V Switchboards
- 1x Ship Service Transformer
- 1x 440V Switchboard
- 1x Zonal Power Supply Unit (ZPSU)
- 2x Chilled Water Plant (CWP)
- Power Management System (PMS)
- Electrical Distribution Centre (EDC)

As of Q3 2020, the EITF has been in full operation for just under a year. In this time, hundreds of hours have been run on the equipment and over 200 tests have been completed. The results have been wide ranging, with the EITF providing much more de-risking value than originally envisaged for the facility. Examples include detailed physical and functional integration, systems integration, equipment functionality proving, and control software integration. It has also been used to rapidly develop new requirements and prototype the implementation of the solutions, for example in introducing actively managed load sharing.

As a result of the success of the facility to date, a contract extension has now been granted to keep the facility operational for an additional 8 months into 2021. The scope of the extension is to undertake environmental and endurance running – the ambient air and cooling water will be heated up the maximum temperature as set out in equipment requirements, whilst the equipment is run at full power for a length of time. This will simulate tropical conditions where equipment is under the most stress, with the aim to prove temperature withstands and graceful degradation of the equipment in this scenario. As the GCS is expected to operate in this type of environment as part of deployments, proving P&P equipment resilience in this scenario is a key piece of de-risking for the EITF.

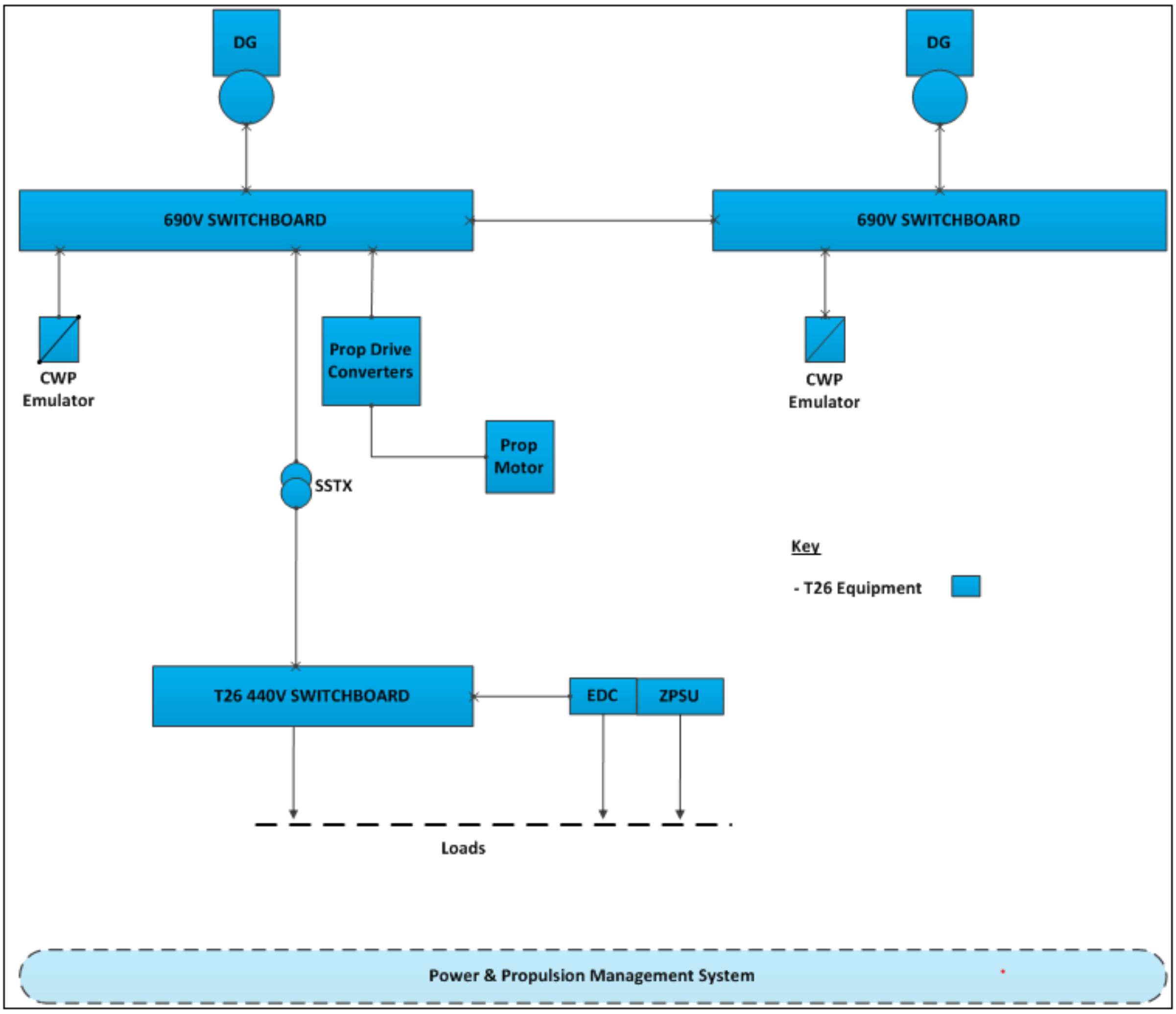

Figure 3 EITF Architecture

Load emulation has been employed at the EITF in two different forms: hotel load emulation and torque emulation.

Hotel Load Emulation

The T26 load chart was assessed for the types, magnitudes and harmonic profiles of load expected to be present on the ship's distribution system; this resulted in a mixture of linear and non-linear load banks, direct online motors and inverter driven motors.

Torque Emulation

A 4 Quadrant Load (4QL) machine is coupled to the PM. This 4QL is significantly oversized in rating compared to the T26 PM, which allows the effect of external influences (i.e. the Gas Turbine and ship's motion through the water) on the PM to be investigated. Additionally, a T26 hydrodynamic model has been implemented into the 4QL, which enables investigations into the effects of expected torque profiles to be conducted.

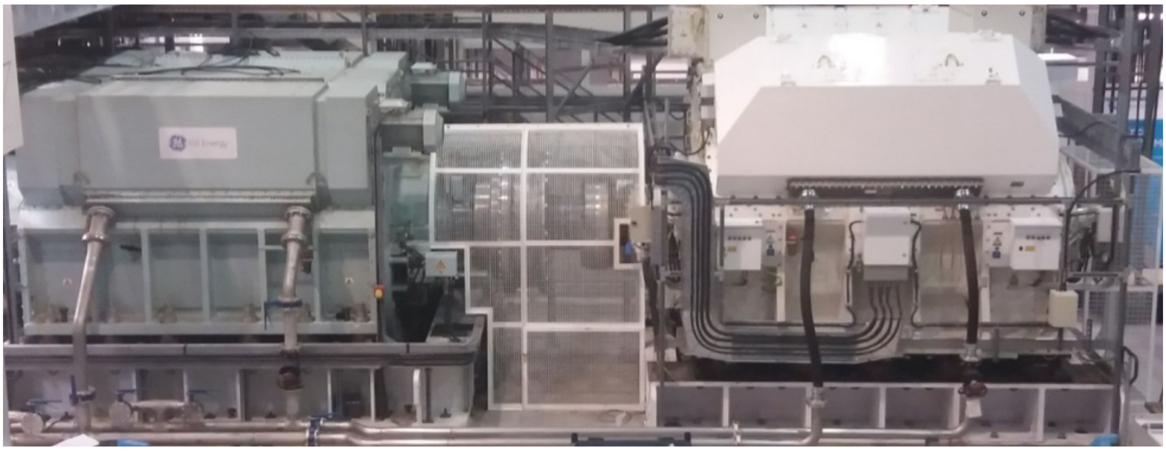

Figure 4 Torque Emulation: 4QL (Left) T26 PM (Right)

Over 200 test scenarios have been developed for the EITF which have been arranged into 29 'testing blocks'. Each of these testing blocks is targeted at a specific equipment, functional or system integration risk, and is ultimately mapped back to project level risks, equipment and whole ship requirements. This enables transparency of the de-risking value and assurance of EITF as each test completes. However, these test scenarios have also been developed to explore the 'unknowns' of the system and the envelope of equipment performance – ensuring that any assumptions on system design are challenged and that as many design issues are uncovered as possible.

In order to maximise usage of the facility, the traditional 'waterfall' of programme management has not been used at EITF. Instead, an agile programme has been developed and implemented around the 29 testing blocks with interdependences kept to a minimum; and, in support of this, a rapid method of creating approved test forms has also been applied. This ultimately enables the project to react to any unexpected result by altering the direction of the testing programme within hours, and minimising the administrative efforts of doing so.

Data capture has been a key focus of the EITF, as data is essential in interrogating the performance of the electrical T26 P&P system. At a high level, two types of data are captured: equipment telemetry and electrical.

Equipment Telemetry

Equipment telemetry is supplied from each individual piece of equipment via serial and discrete signals to the PMS – this allows the EITF to capture over 3,000 data points from around the system, from shaft RPM to diesel engine cylinder temperatures. This allows a picture to be built up of equipment performance over time, and also to investigate any anomalies that occur during tests.

Electrical Data and Analysis

Electrical data is captured in the form of volt and current traces. A power quality analysis system has been created at the EITF to enable data capture and analysis of high precision electrical data from various points around the system, generating data at a rate of >2GB per minute of testing. This volume of data is managed via a bespoke toolset created for EITF which post processes, and automatically analyses the data. This highlights any anomalous results, along with suspected breaches of the Quality of Power Standards, and outputs a summary report.

The result of each test is discussed between all stakeholders involved at the EITF, using the combination of the test scenario and its goals, the success or failure of the test and the post analysis work performed on the data sets collected at the facility. This forum agrees the de-risking value and assurance merits of the completed test, whilst also deciding how best to resolve any issues which may have been uncovered, which ultimately may lead to a design change or improvement for the T26 P&P system.

Gearbox Testing

Within Type 26 there are two overarching forms of prime movers; the diesel engines that drive alternators for generation of electrical power, and the gas turbine which provides mechanical power through a cross connect gearbox. While the electrical power generation from the diesel engines is de-risked functionally through the EITF, the gas turbine and cross connect gearbox could not be included as part of the EITF design. There are a few reasons that the gas turbine and gearbox are not considered at the EITF, with the principle reason being the physical space required to support this. In order to de-risk the gearbox, extended factory acceptance testing is being undertaken by BAE systems in collaboration with the supplier David Brown Santasalo.

The configuration for the gearbox factory acceptance test is intended to functionally test the control system, lubrication skids, lubrication distribution, clutches, brake and turning gear during the full speed, full torque test. The test configuration shows that the torque is locked into the closed loop circuits whilst being spun by the motor which is driving into the forward end of the slave cross connect gearbox. The two torque units create a twist in the shaft that links the slave cross connect and the ship cross connect box. The starboard torquer creates a torque that is locked into the starboard side and central high speed shaft of the cross connect gearbox system. The port torquer locks the torque in the port cross connect side which includes the pod gearboxes and the central high speed shaft of cross connect box. These torquers are able to wind the torque into the systems dynamically.

The current test scope allows the ship fit cross connect gearbox to be driven in the correct rotational direction and on the correct flanks of all gear teeth. The drive enters from the forward side of the cross connect gearbox and exits through the forward side due to the arrangement of the interconnecting test rig quill shafts. The pod boxes are both driven in their correct rotational directions; however the port pod gearbox is driven on its astern flanks.

The purpose of the load testing of the gearbox is to build confidence in its performance and significantly reduce the potential requirement for in ship modification. The key areas for validation are:

- To qualify the design of the gear system including the tooth contact up to full load, bearing performance, lubrication flows and the control system and,

- To enable measurement of key gearbox system performance parameters including airborne and structure borne signatures.

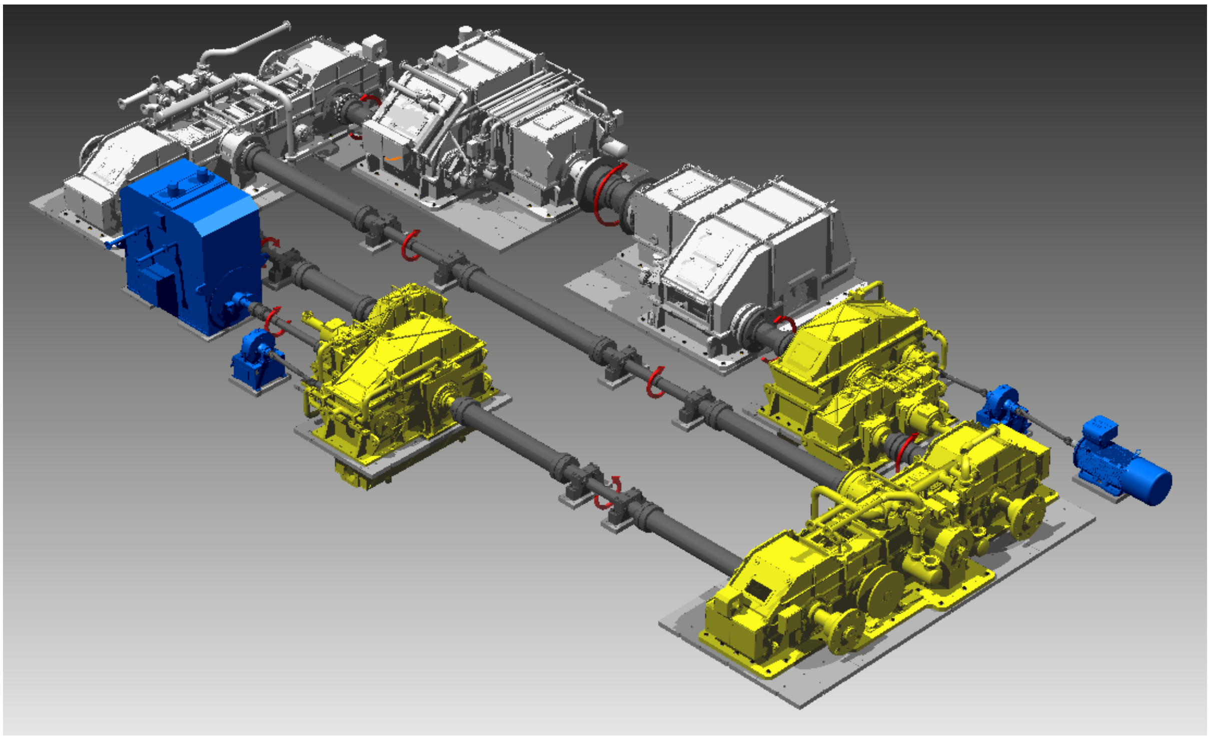

Figure 5 Gearbox Test Setup - shipset gearboxes coloured in grey, torque loading system components are coloured blue and the test rig, recirculating gearboxes are yellow

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Shore Integration Facility & Land Based Integration Facility

The Platform Management System (PMS) consists of two principal layers: the hardware required to interface to the ship's equipment, and the software which constitutes the control system itself. These layers have a significant number of interfaces to other equipment and systems on the ship to enable a high level of control and automation from a central control point. As the PMS is produced by a different equipment manufacturer to the vast majority of the equipment under its control, management of integration at a physical and functional level is of paramount importance.

PMS on T26 uses a Shared Infrastructure (SI) with the ship's Combat Systems, this, along with the clear integration risk with Marine Systems equipment resulted in the decision to utilise a number of test facilities to test and de-risk hardware interfaces, software integration, functionality integration and network compatibility with increasingly mature releases of the software. The two principal test facilities which enable this de-risking are the Shore Integration Facility (SIF) and the Land Based Integration Facility (LBIF). It should also be noted that whilst EITF has a significant role in the early stages of PMS development, it is the SIF and LBIF which will continue to provide support through life for PMS releases to T26 vessels.

Shore Integration Facility

The SIF contains a full ship set of the PMS hardware and an Integration Support Environment (ISE) with the objective of characterising the interactions between PMS and SI in order to improve end-user experience. A series of PMS/SI tests will be conducted throughout the programme to allow for early discovery of issues and de-risking the design programme. The SIF also allows for sub-system integration testing, system (acceptance) testing, end to end performance testing and load/stress testing.

Each software release is tested at the SIF as the first stage of acceptance before the software may progress in the delivery process, forming the equivalent of a FAT for the software release. Once a PMS hardware and software release configuration has passed SIF testing, they are implemented at the EITF (whilst EITF remains in service) and LBIF for the next stage of integration demonstration.

Land Based Integration Facility

The LBIF is a reference site for the ongoing integration and investigations support for the T26 Combat Systems, which aims to build up an agreed body of evidence that demonstrates the installed Combat System will function reliably, safely and to specification.

The primary purpose of PMS at LBIF is to de-risk the integration of PMS to the SI Network along with a representative set of Combat and Marine systems through the testing of each software release intended for the ship. This provides assurance that the combat systems are unaffected by the presence of PMS on the network, and vice versa, ultimately forming the integration testing gate before PMS software and hardware is released to the ship to undergo on board integration trials.

Modelling

Systems Engineering Modelling and De-Risking

It is recognised that the traditional marine systems design methodology has become unsustainable. P&P systems used to be designed as systems, the components used were servants to the system intent; and usually designed specifically to be so. However, Systems are now procured as sub-systems which need integration. Understanding this change to the way we work as marine engineers, a systems modelling team has been set up within this project; focussed on model based systems engineering and fault tree analysis (FTA) work. The principle aim of the team is to ensure that control may always be maintained to three critical areas: propulsion, electrical power and thermal control. Any deficiencies are identified by the team and documented, some captured deficiencies could be as simple as data not being uniform across documentation, however, some may be due to a lack of maturity in system operability.

Deficiencies are broken down into three high level categories and logged using Atlassian's JIRA software. The three major categories are:

- Observations - These are raised for standard deficiencies that require clarification of action by the System Lead;

- Assumptions - These are raised when not enough information is held and so we have to assume something is true in order to carry out the modelling of FTA. These assumptions are all traced through JIRA in order to ensure we are able to provide documented evidence that the assumption is true or is not true;
- Issues - These are raised if there is risk to the programme associated with an observation.

In line with the overall ethos of left shifting, identifying these risks at an early stage helps to de-risk the physical integration of the systems and proves more cost efficient in the long run.

The uptake of a model based systems engineering approach has proved invaluable in treating the entirety of Marine Systems as one integrated system and proving compliance with safety standards, using a system led safety approach. Furthermore the identification and documentation of all areas of risk helps to ensure that there is a central point of truth for lessons learned when beginning work on new projects.

Electrical Power Systems De-Risking by Computational Modelling

Computational modelling provides a cost and space effective alternative to physical testing. Software models of the T26 GCS provide a through life platform for ad hoc testing and de-risking. The models aim to provide an understanding of scenarios in which the ship's P&P system may experience strain without risking physical damage to expensive equipment.

Two discrete sets of models have been invested in in order to perform de-risking on the integrated P&P system. The first of these is a power and propulsion model covering all aspects of the propulsion chain at a high level, which is primarily focused on mechanical parameters, such as ship speed, with the capability of performing high level electrical analysis. The second is electrical models covering power generation, distribution and consumption in detail. The two models operate with focus on different scenarios and different focal points of investigation, therefore, it was not possible to combine the two models into one central platform. The propulsion model considers events from tens to hundreds of seconds while the electrical power system model considers transient behaviour of the power system such as harmonic behaviour on the hundredths of a second scale.

Once the first of class Type 26 enters active service, the primary vehicle through which any future changes to the P&P system will be designed and assessed is through the use of the dynamic mathematical models, hence the requirement for accurate data and real-world validation.

The propulsion model allows the whole ship's dynamic performance to be assessed, and allows parametric sensitivity analysis to be performed; thus highlighting areas in which the propulsion train is unlikely to meet specified ship performance criteria. The propulsion model is principally utilised to study whole ship integration risks. There is limited scope for this model to consider complex functional integration risks relating to the quality of the power supply; however, given the availability of detailed electrical power supply (EPS) models this is unlikely to be utilised.

Unlike the propulsion model discussed previously, there is no singular EPS model; instead there are a number of different models, each used for different purposes.

Steady-state power system models for the purpose of load-flow, fault-level and arc-flash calculations have been developed in SKM Power Tools; while time-variant models for considering transient and harmonic analysis have been developed in MATLAB Simulink / SimPowerSystems.

The time-variant EPS models are used primarily to perform transient and harmonic analysis of the power system, in addition to system stability analysis. These models may also be used to validate the load-flow and fault-level results obtained using the steady-state EPS model. The time-variant EPS models are mainly utilised to study physical integration risks and complex functional integration risks.

Shaft Line De-Risking

Shaft line and overall propulsion train vibration can cause a host of issues within many systems, for example shaft line vibration will incur additional stress on bearings and lower the mean time between failures. As Propulsion System Integrator for the Type 26 Global Combat Ship, BAE Systems Naval Ships is responsible for conducting an analysis of the propulsion train vibration characteristics and submitting this to Lloyds Register for approval.

In order to understand the propulsion train vibration characteristics and implement suitable mitigation actions, this project has performed a comprehensive investigation into shaft line modelling performed in parallel with physical testing of critical assemblies such as the gearbox, gas turbine and propulsion motor. Initial assessment of shaft line dimensions and vibration was undertaken against both Defence Standards & relevant Lloyds Register Rules.

The analysis of shaft line vibration assurance follows three key steps, these are: Class calculations which are performed in accordance with Defence Standards & Lloyds Register Rules; computational modelling of the shaft line considering critical damping; and modal system shaft line testing to validate models and boundary conditions prior to initial shaft turning.

Figure 6 Shaft Line Finite Element Analysis Model

The analysis of shaft line vibration is principally focused on whirl, torsional and axial vibrations. It is important to understand these vibration characteristics in order to appropriately place damping along the line. Three discreet sources of mathematical modelling have been used in order to validate calculations and provide confidence in the final modelled results; hand calculations, finite element analysis modelling and modelling using SKF Shaft Designer.

By performing in parallel to physical testing of the critical assemblies the shaft line models are able to be iteratively validated and improved providing a progressively more reliable model of shaft line vibrations. This final model will serve as the evidence of compliance that will be provided to Lloyds Register and the customer. Undertaking the shaft line modelling and informing the models using physical test data contributes to de-risking the Type 26 project by providing an understanding of vibrations across a frequency spectrum which can then be planned for and suitable damping can be implemented.

Conclusions

The development and integration of a complex power and propulsion system poses a significant risk, even when the constituent components are of a High Technology Readiness level. This is fundamentally the case as each aspect is generally created by a different manufacturer, which in turn has different processes, unique notations and development practices.

Identifying the risks as early as possible in the lifecycle of a project, and crucially, acting to resolve them via design change or otherwise before manufacturing, first trials or even in service operation has clear benefits for all stakeholders involved. This ‘left shifting’ philosophy often enables lower costs, faster delivery and a higher quality of the end product.

Within this paper are described the methods currently employed by BAE Systems to de-risk the Marine System aspect of the Type 26 Global Combat Ship as far and as early as possible within the programme. These methods are principally achieved by means of integration test facilities and the application of computational modelling techniques. These methods not only provide progressive assurance before the first of class of T26 is delivered, but also provide a continual in service support aspect to the class, further increasing the value of undertaking them.

It is not until T26 first of class trials when the results of this left shifting philosophy and the associated activities will be realised and the efficacy established. However, by taking a proactive approach and investing heavily in these early lifecycle de-risking activities, it is clear that the probability of an integration issue being encountered in the late project life cycle is minimised.

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