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08.30-09.00 **COFFEE AND REGISTRATION**

09.00-09.35 **KEYNOTE**
John Hudson, BAE Systems Maritime - Submarines, UK

09.35-10.10 **SET-BASED REQUIREMENTS, TECHNOLOGY, AND DESIGN DEVELOPMENT FOR SSN(X), Morgan C. Parker, Matthew D. Garner, Joseph T. Arcano, Norbert Doerry, NAVSEA, USA.** Maintaining affordable undersea capability will require modern design methodologies to minimize costly design changes while continuing to address evolving threats throughout the lifecycle. An aggressive timeline and broad uncertainty around design requirements has led the U.S. Navy towards a set-based strategy for requirements, technology and design development for a future class of submarines, SSN(X) [1]. Set-based methods enable informed and defendable decisions by systematically understanding trade-offs prior to commitment [2], and have successfully been implemented on several ship programs [3]. This paper will provide an introductory background on set-based methods including: definition and clarification of terminology, a history of application within the Naval Sea Systems Command, and a qualitative comparison to traditional point-based methods. Next, the paper will discuss the motivation for adopting set-based methods for SSN(X). Finally, a detailed overview of a set-based strategy for future submarine requirements, technology, and design development will be presented, including an example specific to SSN(X).

10.10-10.45 **MANAGING EARLY STAGE DESIGN UNCERTAINTY AND ESTABLISHING POLICY FOR A LOW RISK DESIGN, Scott Daley, Robert Dvorak, Morgan Parker, NAVSEA, USA.** With the high cost of submarines, critical performance requirements and a low tolerance for risk, modern U.S. Navy submarine programs place a high value on risk management. Risk Management is not only a formal process, but is engrained in the culture of U.S. submarine designers. The U.S. government's role in submarine design is to set requirements and manage the acquisition. It includes concept design naval architects who lead the early stage design effort and guide it down the right path by establishing policy to ensure the design configuration is managed with an acceptable level of risk. This paper does not focus on the formalities of ship acquisition, but will describe the early stage (preprogram) processes and policies developed and used by naval architects, including setting key ship characteristics, margins, and inter-related system trade-offs, to achieve a low risk design.

10.45-11.15 **COFFEE**

11.15-11.50 **SUBMARINE DESIGN IS NOT SHIP DESIGN, David Andrews, University College London, UK.** The author's long involvement in submarine design and subsequently teaching submarine design and leading research into the design of these most complex of vessels provides the basis for this paper. The argument in the title is justified not just by the fact that the naval architecture of submarine is distinctly different to that for surface ships due to modern submarines operating largely in one medium rather than on the interface of two. But it is also the case that the design process followed in the earliest phases of designing a submarine and the over-riding design pre-occupation are also both quite different to that for a major surface warship. A brief outline of the particular nature of warship design provides a benchmark to which to compare submarine design practice. Then the very specific nature of submarine naval architecture is outlined, given it tightly bounds the scope for novelty in submarine design options. This is followed by consideration of certain critical submarine design issues that effectively constrain the conduct of submarine concept design studies, in a manner quite different to the very open exploratory process that should be adopted for proper Requirements Elucidation of complex (surface) ship design. Finally some further wider policy issues that reinforce the thesis of the paper conclude the argument.

11.50-12.25 **A CONCEPTUAL DESIGN OF A HYBRID SURFACE-UNDERWATER VEHICLE FOR UUV APPLICATION, M H Mukti, Indonesia Endowment Fund for Education, Ocean Engineering Department, Texas A&M University, USA.** The U-Boat is one of the most successful underwater vehicles in submarine war history. The notion of reviving the underwater vehicle that performs well on the surface like the U-Boat, is an interesting concept to be examined. Direction des Constructions Navales (DCNS), a France submarine manufacturer, developed their SMX-25TM radical submarine concept that offers a high-performance submarine on the surface that allow SMX-25TM to reach the target location as quick as possible. However, this concept is complicated for manned operation, which requires pressure hull and safety constraints that affect the cost and complexity of the hull design. On the other hand, it can be potentially applicable in the UUV application. This paper describes the conceptual designs of two hybrid, surface-underwater unmanned vehicles, namely the MAKARA-04 (M-04) and MAKARA-02 (M-02). M-04 is a 'SMX-25TM' concept for UUV version. It is designed to have self-righting capability, utilizing a fully submerged waterjet e.g. AWJ-21TM is for high speed, high efficiency propulsion performance and a low resistance inverted axe-bow to achieve significant performance during surfacing condition. Meanwhile, M-02, also known as Sea Ghost, acts as the unmanned mobile platform that offers an integration between a UUV and USV. This concept enables flexibility in using renewable energy sources for the unmanned support, including solar power and wind energy from the surface.

12.25-13.00 **HUMAN FACTORS ISSUES FOR UNMANNED UNDERWATER VEHICLES, Caren Soper, QinetiQ, UK.** The use of autonomous vehicles is a significant growth area widening in scope of application to deliver greater military effect for those dull, dirty and dangerous tasks. This brings a range of associated Human Factors (HF) issues, which can have significant safety, security, and legal / ethical implications. The focus of this paper is on the HF issues associated with more truly autonomous systems, extending to those that incorporate artificial intelligence. It draws on data collected during the mine countermeasures work within Unmanned Warrior 2016, the largest demonstration of its type ever undertaken in the world. The HF assessments centred on the control of unmanned underwater vehicles in live demonstrations and on the usability of the human computer interface features and recorded observed tasks, equipment used and levels of automation.

13.00-14.00 **LUNCH**

14.00-14.35 **DEVELOPMENT OF AN AUV LAUNCH AND RECOVERY SYSTEM FOR THE PORTUGUESE MANNED SUBMARINES TRIDENTE VIA TORPEDO TUBES, Henrique Vieira da Silva, Miguel Cavique, UNIDEMI_CINAV Portuguese Naval Research Center & Naval Academy, Portugal, João Borges de Sousa, Faculdade de Engenharia da Universidade do Porto, Portugal.** The use of Autonomous Underwater Vehicles (AUVs) on the military Navy has increased in the last few years to perform missions including Mine Countermeasures (MCM), Search and Rescue (SAR), seabed mapping, and remote environmental assessment. The Portuguese Navy has an active dual-use Autonomous Underwater Vehicle (AUV) development program in which the capability of launch and recovery (L/R) of AUVs from Trident-class manned submarines is under development. The development of this capability is receiving significant attention worldwide because it enables discreet operations in areas of interest. This paper discusses L/R systems for manned submarines and presents the design methodology of a L/R system for Trident-class submarines. The design takes into consideration user and design constraints defined by the submarine flotilla especially in what concerns to the use of the torpedoes tubes to launch the AUVs. The proposed solution has to modular and minimally intrusive to enable launch and recovery with no major modifications to the submarine. This is achieved with an add-on L/R station that can be easily removed at sea to preserve all submarine capabilities.

14.35-15.10 **METHOD FOR THE SIMULATION OF THE SWIM OUT OF A WEAPON FROM A LAUNCHING TUBE, Fabian Pecot, DCNS Research / SIREHNA, France.** Among miscellaneous missions expected from a submarine, launching weapons from a tube, either by pulse or swim out system, is of major importance. To secure these launchings and to determine the safe operating envelope, the use of a numerical approach could constitute an interesting alternative to expensive small or full-scale trials. Indeed, this type of code is able to predict trajectory and hydrodynamic behaviour of a weapon. This paper focuses on the development of a numerical methodology based on a CFD code simulating swim out torpedoes launching from a tube. This methodology relies on overset grid approach. The main advantage of this method is to avoid the remeshing of the evolving fluid calculation domain due to the weapon displacement with or without rotation of the counter-rotating propellers. The code solves the strongly coupled URANS and 1-dof weapon dynamics equations, with given propellers rotating velocities. To validate this numerical methodology, full-scale trials of swim out launchings from a monodiameter tube immerged inside sea water at rest were carried out with a torpedo-like drone. A satisfying correlation was obtained between numerical and experimental results in terms of both weapon velocity and pressures inside the tube.

15.10-15.45 **THE OPERATIONAL BENEFITS OF COVERTLY REFU ELLING A CONVENTIONAL SUBMARINE WHILST AT SEA, Simon Harrison, Karl Slater, Hamid Diab, Defence Science and Technology Group, Australia, Martin Renilson, University of Tasmania, Australia.** Conventional submarines are significantly cheaper to own and operate than nuclear powered submarines; however their capabilities can be constrained by the available diesel fuel quantity in some types of mission. In order to assess the constraints and sensitivities of design parameters on the operational performance of submarines, the Defence Science and Technology (DST) Group has developed the Integrated Performance System Model (IPSM). This tool is capable of conducting platform level performance assessments of submarines, and can be used to assess the effect of design changes on operational capability. An analysis of the performance impacts at the operational level that the novel concept for covertly refuelling conventional submarines whilst at sea is presented. The intention of the capability to refuel at sea is to increase the level of capability achievable by existing conventional submarine designs without significantly compromising the stealthy nature of their operations. The analysis presents methods for determining the maximum achievable speed, of advance in transit portions, of a number of different missions. Following this an analysis of the different missions will demonstrate the impacts of refuelling at sea and highlight how conventional submarines may be constrained by overall endurance or by diesel fuel quantity depending on the design of the mission.

15.45-16.15 **COFFEE**

16.15-16.50 **SYSTEM OF SYSTEMS DEVELOPMENT FOR THE UNDERWATER BATTLESPACE, Phil Atkinson, BAE Systems Maritime - Submarines, UK.** he advancing capability of Autonomous Underwater Vehicles proposes a new way of delivering improved capability in the Underwater Battlespace through the systems integration of manned and unmanned assets both below and above water. There are however numerous engineering challenges to providing a fully capability in the underwater environment due to a number of disruptive technology developments. Many, but not all, of these challenges are already within our grasp; however a holistic systems approach is required to determine how each of these is required to work in tandem to provide an optimal design.The paper will demonstrate how the required technologies can be used to realise an optimal design for an effective underwater battleforce and how this emerges from a number mission operational requirements. An optimal, but configurable, system design is required that adequately defines the functional capability of its assets while the successful development of new System of Systems using manned & unmanned assets offers an enhanced flexible battleforce capability and one which is affordable and more resilient.

16.50-17.25 **LR CODE FOR UNMANNED MARINE SYSTEMS, Matthew Palmer, Lloyd's Register, UK.** Lloyd's Register has created a goal-based code for the certification of Unmanned Marine Systems (UMS) – including Unmanned Underwater Vehicles (UUVs). This has come about through Lloyd's Registers work with the marine industry to assess the applicability of existing regulatory regimes to unmanned vessels and to determine appropriate alternatives. As a result this Code was created to provide a safety framework to capture the novel design aspects of these vessels, in a goal based format.

17.25- **GENERAL DISCUSSION & EVENING DRINKS RECEPTION**

08.30-09.00 COFFEE AND REGISTRATION

09.00-09.35 SAILING AT PERISCOPE DEPTH UNDER WAVES, Frans Quadvlieg, MARIN, the Netherlands. Waves are one of the limiting factors for operations at periscope depth. It is desired to have a good insight in the performance of the submarine to remain submerged in various seastates and various wave directions. In order to answer to the question "what is the performance" in a statistically meaningful way, a significantly long amount of sailing time needs to be analysed. This is achieved by combining simulations and model tests. This paper describes an early study that is based on model test are carried out using a generic submarine model (BB2). With this model, free running tests are carried out with the submarine sailing under various wave conditions. The model tests are "sniffing" tests that give an insight in the capabilities of the submarine, when controlled using a generic autopilot. Results will be compared to simulations.

09.35-10.10 PAST, PRESENT AND FUTURE IN SUBMARINE MANOEUVRING CONTROL, David Ritchie, Naval Architecture Manager, BAE Systems Maritime - Submarines, Barrow-in-Furness, UK. Since the end of the Second World War the aircraft industry has largely been seen as the 'early adopter' of complex vehicle control systems driven by its own needs to drive for performance, safety and the necessity of automation to increase safety and reliability whilst reducing crew numbers and operating cost. Submarines have typically lagged the aircraft industry in their adoption of new technologies in this area, and so the aircraft industry therefore provides an interesting portal into the future. This paper aims to examine the trends of functionality of UK submarine vehicle control systems in terms of performance, safety and cost, by looking back at legacy mechanical systems, the progression into digital control and its evolution to the current 'state of the art'. It will conclude by presenting a vision for an idealised future Submarine Manoeuvring Control System and outline the technological enablers and challenges required to realise it.

10.10-10.45 THE DYNAMIC STABILITY OF SUBMARINES ON THE SURFACE C Pope, P Crossland, S Machin, QintetiQ, UK. In the UK, the stability of a submarine on the surface continues to be evaluated according to hydrostatic stability criteria that, for a surfaced submarine, are based on the examination of the metacentric height and the righting lever. The aims of these criteria are to provide sufficient stability to prevent capsize and to limit submarine motions to reasonable levels whilst on the surface. However, the methodology, based on the work of Sarchin and Goldberg (1962), was developed over a period of time to provide guidance in the design and operation of naval ships; the methodology is empirical in nature derived from data obtained from USN destroyers whose hull forms are quite unlike submarines. Furthermore, there has been significant amount of research undertaken to investigate suitable alternative measures of stability that incorporate the hydrodynamic response of the vessel to the environment and in the use of performance based measures rather than the traditional static stability criteria. This paper describes a programme of work aimed at applying some of the tools and techniques developed for surface ships to quantify the feasibility of using such techniques for the dynamic stability of submarines on the surface, primarily at zero speed. The tools have been validated using a series of model experiments and a proposal for a potential amendment to the current static stability criteria is proposed.

10.45-11.15 COFFEE

11.15-11.50 EFFICIENT MODELLING OF THE STRUCTURAL RESPONSE OF SUBMARINE PRESSURE HULLS TO UNDERWATER EXPLOSIONS, D Graham, J Hobson, P Murphy, C Toole, S Cross & J Farnworth, QinetiQ Rosyth, UK. The effects of underwater explosions on the equipment aboard ships and submarines have been well studied. Damage to equipment is usually accepted as critical for ships and submarines near the surface and the effects can be mitigated by shock mounts. Major structural damage can also be caused by whipping. Hydrostatic pressure makes submarine pressure hulls more susceptible to structural damage with increasing depth and current assessment methods rely on empirical relations based on historical data. This paper will compare two approaches to modelling underwater explosions and the subsequent response of the pressure hull structure. A 'hydrocode' (ls-dyna) uses equations of state to model the behaviour of the gaseous explosion products and the surrounding water, and models the evolution of the gas bubble, and any interactions with the structure, explicitly. A simpler approach is to model the water as an acoustic medium and impose the pressure loading from an explosion. Interaction between the fluid and structure is captured but will not be valid if there is bubble impingement. The latter approach delivers reduced run times allowing parametric studies and the analysis of larger structures over longer time periods to be carried out.

11.50-12.25 ALTERNATIVES TO DOMES AS PRESSURE HULL END CLOSURES Kevin Heaney, Hickson H J, Buckton E P, Underwood J M, BMT Defence Services Ltd., UK, B Blum, P Gough, Naval Authority Group UK MoD, UK. This paper presents research undertaken examining a number of alternative pressure hull end closure geometries which do not require double curvature two of which are presented here; faceted domes and flat bulkheads. Finite Element Analysis (FEA) has been used to examine the structural response and viability of the potential alternative end closures. This paper discusses the advantages and disadvantages of the different end closure options, including the weight and volume changes compared to a traditional dome, the potential manufacturing issues, and overall viability of the concepts.

12.25-13.25 LUNCH

13.25-14.00 PERFORMANCE VERIFICATION OF A SUBMARINE AIR CONDITIONING SYSTEM, Jan D. Wilgenhof, MecDes, the Netherlands., Jesús Molina Toledo, Navantia, Spain. One of the large energy consumers in a conventional submarine is the air-conditioning system. The system removes a large part of equipment waste heat as well as metabolic heat and water vapor produced by the crew. It also reduces the humidity of intake air during and after snorting in tropical waters. Air temperatures and humidity in the compartments are important in view of crew endurance and equipment limits (e.g. humid air in electronics). A conventional heat balance cannot provide this because it assumes fixed (maximum allowable) space temperatures and it is performed only for steady state. Therefore a dynamic air energy balance has been developed, which simulates the heat transfer with the environment and the heat transfer between the spaces in the submarine as well as the thermal contribution of the ventilation flow, based on variable space temperature. Equipment and crew are included as heat sources. This software tool contains also a ventilation network model for the air flow rates, a water vapor concentration model for the humidity and an air cooling model.

14.00-14.35 MANAGEMENT OF FLOW GENERATED NOISE ON NAVAL PLATFORMS, Chris Carter, Frazer-Nash Consultancy Ltd, UK. This paper describes a programme of work to quantify signature performance during the design process and develop new tools to support decision making. This new capability enables flow generated noise performance to be progressively assured against requirements and the performance to be balanced against programme, cost and risk considerations. A range of tools and techniques are now available, which are applicable across the design process. This comprises scoping calculations for application during concept design where the quality and availability of information is low and there is a need to rapidly explore the design space. During the preliminary or FEED stage, more sophisticated techniques are employed to make use of the greater quality of information. At this stage analytical methods are fused with empirical relationships to provide a hybrid approach which is sensitive to design changes, but still rapid enough to enable design exploration and sensitivity studies. During detailed design, high fidelity numerical methods are used to capture design details and produce high resolution predictions. New flow noise mitigation strategies are also discussed, including avoidance of cavitation and the application of silencing devices for fluid systems.

14.35-15.10 ON THE ADDED RESISTANCE OF UNDERWATER VEHICLES IN CLOSE PROXIMITY TO REGULAR WAVES,, Renato Skejic, SINTEF Ocean, Trondheim, Norway, Martin Greve, Stefan Daum, Thyssenkrupp Marine Systems, Kiel, Germany. The present study is focused on the added resistance of UV's near the free-surface in regular deep water waves by addressing hydrodynamic design aspects such as speed loss or effective power increase, respectively. It has been assumed that the vehicle is operating in a range of small to moderate Froude numbers. By moving forward in a straight flight at constant depth different encounter angles of incident regular waves are investigated. A modified version of the (Doctors and Days, 1997) method as presented in (Skejic and Jullumstrø, 2012) is used for the determination of the total resistance and consequently the effective power. In particular, the wave resistance in calm water is estimated by using different approaches covering simplified methods, i.e. Michell's thin ship theory with the inclusion of viscosity effects (Tuck, 1974) and (Lazauskas, 2009) or Boundary Element Methods (BEM), i.e. 3D Rankine source calculations (Hess and Smith, 1964). These potential flow approaches are compared to fully viscous Finite Volume Method (FVM) results for selected cases.

15.10-15.40 COFFEE

15.40-16.15 PROBABILISTIC SUBMARINE FLOOD RECOVERY ANALYSIS, Neil Horn, MoD, UK. A review of UK MoD's existing deterministic methodology for submarine flood hazard assessment is presented, along with recommendations as to how an alternative, probabilistic approach could be implemented. The work builds upon an investigation carried out by UK MoD between 2013 and 2015, and takes cognisance of current probabilistic safety analysis techniques that are applied in other fields, notably nuclear engineering. An illustrative example of a holistic flood risk estimation process is presented, with particular emphasis on the estimation and handling of significant sources of uncertainty. An example set of deliverables illustrates how a distillation of the resulting data could be conveyed to key stakeholders, including Duty Holders and Operators, in order to support informed decision-making on matters such as the tolerability of major defects, or the suitability of newly-proposed emergency procedures. A gap analysis identifies areas of modelling software capability and technical knowledge that would need to be developed further in order to implement and support the proposed methodology.

16.15-16.50 LOCATION, LOCATION, LOCATION: DOES IT MATTER IN SUBMARINE FLOODING? Malcolm James Cook et al., BAE Systems Maritime. In preparing a response to flooding in submarines one normally considers whether the flood will compromise propulsive functions. In a number of flooding scenarios it is likely that flooding will overwhelm the functional capacity of the hydrostatic (ballasting functions) and require hydrodynamic lift, based on forward propulsion. Lift is proportional to forward momentum and as such a submarine experiencing a flooding event may need to increase forward momentum to increase lift, making demands on propulsive power. Implicit in the response to flooding is the coordination of two control teams, one within manoeuvring providing the responses to demands for propulsive power and another in the forward control team managing ballasting functions, especially emergency ballasting functions. Coordination of both control teams under time pressure implies either explicit or implicit communication to rapidly achieve the desired responses. This paper considers the time costs of verbal communication and the potential for modifying emergency operational procedures to acknowledge the availability of implicit platform management systems information to expedite the response to floods in situations where propulsion may be compromised. This paper discusses the alignment of physical models of flooding and human response to flooding to ensure that performance failure on demand meets acceptable criteria.

16.50- GENERAL DISCUSSION

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