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Hydraulic Direct Actuator Drives Conventional Submarine Energy Management

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Abstract—

Conventional submarine designs often use a fixed pressure hydraulic system with fluid stored in accumulators at the maximum system pressure. This is often referred to as a ring main system. The required pressure for moving the hydraulic actuators is generally very much lower than this maximum system pressure therefore the difference is wasted as heat and noise in the throttling control valves and the fluid coolers. Further, the hydraulic supplies are often pumped through long pipework routes through the submarine before they reach the location of the actuator. This involves more pressure losses and inefficiency creating additional heat and noise.

The actuator system and the hydraulic supply system are each designed to cope with the maximum pressure and the maximum flow. The maximum power is taken as the maximum pressure multiplied by the maximum flow, even though these two extreme conditions will seldom occur in the operation of most equipment particularly control surfaces. Depending on the operating requirement and maneuvering scenario the overall efficiency may be as low as 5%. Hence there is large scope for improvement in overall efficiency.

MacTaggart Scott have produced direct hydraulic drives for many applications on surface ships that use dedicated supplies, and pumps that vary the flow and pressure to exactly match the required forces and positions. Examples of these direct variable pressure hydraulic systems include aircraft elevators, ammunition lifts and helicopter traversing systems. The flow and pressure are adjusted by the dedicated control system to suit the load demand with a significantly improved overall efficiency of around 75%. Alongside this, other benefits include a lower noise signature and much less wasted heat to be managed by the cooling system.

The dedicated hydraulic drive does not need to store oil in high pressure accumulators and there can be significant savings in the space and weight that these and their associated nitrogen pressure vessels occupy. The dedicated variable pressure hydraulic drive can use a variable displacement pump and a variable speed electric drive motor to precisely match load demand, and even to regenerate electrical power during braking or over-run conditions. This regeneration option would further improve the overall efficiency of the actuator system.

MacTaggart Scott has completed computer simulations and recently built a full-scale technology demonstrator for the control of a steering actuator. The demonstrator has proven the technology for power-limited, independent hydraulic control of an actuator. The demonstrator system has demonstrated that it can accurately position the control surface actuator with the full resistive or over-running loads applied by a computer-managed test rig in accordance with specified loading criteria.

I. Introduction

This paper has been prepared to give a general overview as to the benefits of selecting Variable Pressure Hydraulics to control the Rudder and Hydroplane actuators within a submarine.

II. Variable Pressure Hydraulics versus Conventional Submarine Systems

A. System Architecture

Broadly, there are two types of hydraulic system used within submarines. The first system is a ring-mains system which runs at constant pressure, based on the maximum demand of the system. The second form of system comprises of smaller hydraulic systems distributed locally where needed. This system would operate when needed, remaining in an off state until this time. Often, combinations of these two are used to increase the overall efficiency of the system, as certain equipment can be switched off when not in use. However, not all aspects of submarine hydraulics are best suited to either a continuously on, high power system, or a system which is either on or off. It is the purpose of an adaptive system to bridge this gap, and provide hydraulic power which matches the demands of the system, maximising system efficiency. This is particularly the case in control surface actuation, which requires a broad capability to meet the varying demands for position and rate of travel while experiencing complex hydrodynamic loading.

B. Conventional – Constant Pressure System

For a conventional hydraulic system used in submarine applications, hydraulic equipment is driven by using large numbers of accumulators maintained at high pressure. In this case a fixed displacement pump is driven at constant speed. This pump charges an accumulator bank until the required pressure is met, at which point a check valve closes to prevent further pressurising of the accumulators. With the pump still running, the excess hydraulic fluid is passed through a, now open, unloader valve and dumped to the system reservoir, while hydraulic power is provided to the rest of the system via the accumulators gradually discharging. During discharge, the accumulators will eventually drop below a set pressure, causing the unloader valve to close, and allow fluid to re-charge the accumulators via the check valve. Hydraulic fluid is pumped into the accumulators until the system reaches the set pressure, at which point the unloading valve opens to divert the flow back to tank. This cycle continues at a rate determined by the required demand and/or operating conditions.

C. Conventional – Hydrostatic Transmission

A hydrostatic transmission system uses a variable displacement pump to drive an associated hydraulic motor or motors. In marine and industrial applications the pump is typically driven by a constant speed electric motor. Flowrate can be adjusted by varying the pump displacement, to meet the required flowrate for the system. However as the electric motor runs at constant speed, while the load due to the pump may change, the motor does not always operate at the best efficiency point for those conditions. To operate with greater efficiency under a varying load, the motor would be required to change its speed. This is the basis of the adaptive Variable Pressure Hydraulics (VPH) method.

D. Adaptive VPH

The reasoning behind the use of adaptive VPH actuation is that submarine maneuvering can be delivered through high flow rate (high control surface rate of travel), and high pressure (control surface torque), although not necessarily at the same time. Thus the operating conditions the system must achieve are; high pressure at low flowrate, and low pressure at high flowrate. Hence the theoretical maximum power (at maximum flowrate and maximum force) is not required to deliver whole boat maneuvering performance.

This performance is achieved by using a variable displacement pump driven by a motor. When the load force is low, the system can deliver high flowrate by setting the pump displacement to a maximum. Alternatively, when the load force is high, the pump displacement is reduced to satisfy the power and torque envelope of the driving motor.

The circuit would consist of a variable displacement piston pump coupled to an electric motor, with all components available as commercial off the shelf (COTS). The variable speed electric motor would typically run at speeds in the range 500-1800rpm or more, with the pump at full displacement. By running with the pump at maximum displacement, its mechanical efficiency will be maximised. Below 500rpm pumps can suffer from negative effects such as pressure pulsation, and variable speed electric drives can generate excessive heat. For this reason, 500rpm would be selected as the minimum speed, so that when lower flows are required the displacement of the hydraulic pump can be reduced accordingly.

Describing the system in conventional hydraulic terminology, the adaptive VPH system is a hydrostatic transmission optimised for driving a cylinder. In its most efficient form, it is a closed-loop circuit, with fluid returning to the pump rather than to tank. This permits hydrostatic braking and electrical energy regeneration. The recovered energy can either be dumped across a load resistor, or used for other purposes. Power-limiting control is applied to the pump so the displacement is limited according to the rotational speed and pressure difference. A variable speed drive is used to control the electric motor.

E. Load Cases

Three possible system demand types can be considered, in order to evaluate the suitability of each hydraulic system to different applications within a submarine. The first possible demand is a continuously operating system, with little variation in loading, such as a communications buoy tow. There are, in fact, very few hydraulic systems within a submarine which operate constantly. In this case the most applicable possibility is the conventional hydraulic layout with a motor sized to meet the demand, as it is able to provide continuous power with an efficiency of around 85%. However, if a seldom used piece of equipment were to be added to this system, such as mast raising equipment (MRE), there would be a detrimental effect on the overall efficiency.

The second type refers to seldom used equipment. A conventional system and related electric motor would have to be sized based on the continuous load demand as well as the maximum demand of the infrequently used actuator. When the MRE was not being used, a conventional system would be unloaded and remain idle for long periods of time. In this respect, it would be inefficient as a large fraction of installed power capacity is seldom used. Overall, the system efficiency would drop from approximately 85% under maximum load, to less than 10% when the load is reduced.

A smaller, dedicated system would be much more suitable in terms of efficiency for this scenario. This type of application would have little variation in loading, as external forces on mast equipment are typically stable and predictable. So the motor operating condition could be chosen in order to maximise efficiency throughout normal use while still having variable flow capabilities.

The third demand type refers to other equipment with varying requirements, such as control surface actuators. The loads and demands of the actuators vary across a large range of forces, displacements and rates of travel. As a result, a dedicated conventional hydrostatic system is not the most efficient solution as it is limited by the speed at which the pump motor operates, nor is a conventional system the optimum solution.

Control surfaces have a varying torque profile across a range of positions (angles of attack) and boat speeds, necessitating a higher degree of system adaption if efficiency is to be maximised. Including motor speed variation in conjunction with pump displacement variation, as part of an adaptive hydraulic system, makes this possible. The motor cannot be operated at the best efficiency point of around 85% at all times, due to possible issues at low speeds, however the efficiency would be much improved over the range of demands when compared to the two other demand types discussed used in the same application.

The importance of selecting a pump to operate as closely as possible to its best operating point cannot be overemphasised. Not only should this save on energy costs, it will have several other benefits. The pump should run smoothly at the best operating point with minimum internal disturbing forces, thereby saving on maintenance costs due to premature failure of components such as bearings, wear rings, bushes, couplings and seals. The risk of damage to pump components due to cavitation should be reduced. Vibration should be minimised, benefiting other equipment and contributions to noise signature. Noise should be minimised, improving the operating environment and signature. Pressure pulsations should also be minimised, reducing the risk of problems in the pumping system as a whole.

III. COMMONPLACE USE OF VPH

VPH and variable displacement pumps are a well-established technology which is used throughout industry for varying applications. As such, the components of a VPH system are individually mature and have been proven in applications such as flight control systems and on frigate and commercial shipping stabilisers, among others.

Since the late 1970s, the aviation industry has been investigating the use of electro-hydrostatic actuators (EHAs) for aircraft control systems as part of ‘Power-by-Wire’ technology. The aim of this technology is to eliminate use of bulky and heavy hydraulic circuits through using electrical power circuits as an alternative, the benefits of which include reducing system weight and maintenance costs. EHAs form part of this technology as they are electrically powered, but use small hydraulic pumps and reservoirs to transform electrical power into hydraulic power.

Airbus has been working with EHA flight control systems for over twenty years, initially with the A320 and A340, but now extending to the A380 and A350. The use of EHA on the A380 has been particularly effective due to the large size of the A380 itself.

Inherent to large aircraft are large control surfaces, which require much more hydraulic power and larger distribution networks to actuate the surfaces, when compared to more conventional aircraft with a ring-mains layout. This adds weight and complexity to the system. Use of EHAs on the A380 has allowed for a reduction in component size, generation equipment, pipework and amount of hydraulic fluid. Further, the installation is easier as simple electrical connections can be made in place of lengthy and potentially complex pipework.

Overall the benefits of EHA use on the A380 have been improved reliability and maintainability, reduced weight and costs, and increased safety margin due to the redundancies introduced through using dissimilar power sources.

Variable displacement pumps are also used extensively within drive hydraulics for lifting equipment such as cranes and elevators. MacTaggart Scott has a wide range of experience using variable displacement pumps in these applications, as previously mentioned. The main benefits of their use are particularly apparent when operating through cycles with varying loading. Using variable displacement pumps in these applications allows for extension of hydraulic component life and improved controllability, and as a result greater safety.

The use of variable displacement pumps has also been addressed for use in vehicles. Known as ‘steer-by-wire’, drive-by-wire’ or similar, they function with the same aim as the VPH system described herein, whereby smaller, local actuators are used in place of a large centralised system. The intended result being an increase in efficiency as the system power is varied to match the demand of each actuator, rather than operating continuously at full power.

Recent research at Purdue University [1] also demonstrated the applicability of variable displacement pumps within steering systems for heavy construction equipment. Rather than using a central variable displacement pump, each actuator used a dedicated pump controlled electronically, eliminating the need for valves. Testing of the ‘steer-by-wire’ electro-hydraulic steering system on a front-loader showed 15% fuel savings and 23% increased machine productivity, resulting in a total fuel efficiency increase of 43% during steering manoeuvres.

IV. BENEFITS OF VPH ON SUBMARINE SYSTEMS

Traditionally, submarine control surface positioning has been achieved by actuators powered through the main hydraulic system, operating at maximum power, which also provides hydraulic power to other components of the ship. As a result, hydraulic fluid is carried through piping to reach connected hydraulic components, incurring energy losses on-route. Even greater losses can occur in proportional directional control valves, due to flow throttling. The VPH design is based on mitigating these losses through use of local pump and control assemblies, the performance of which varies to meet the actuator demand. There are also further benefits with the VPH system, over the traditional ring-mains setup.

A. Noise Signature Reduction

Reducing the amount of pipework needed (in terms of both length and diameter) offers opportunities for reduction in noise signature through minimising bulkhead penetration as well as, of course, minimising flow throttling and associated issues. Signature performance can also be modelled and tested much more representatively and tractably with VPH due to the compact size. This helps to eliminate the influence of ship-based contributors such as extended piping, mounting and bulkhead penetration to make it possible to obtain a representative noise signature with greater confidence.

B. *Weight savings*

The autonomy provided by independent hydraulic circuits with pneumatic motor backup removes the need for many hydraulic accumulators and nitrogen pre-charge bottles, as well as associated manifolds and control valves. A theoretical comparison of weight differences between a traditional system and VPH, for major items of equipment within an ongoing project, gave significant weight reductions of 57% across the whole boat.

The improved energy efficiency of a VPH system also has a big effect on the size of engines required, a particular concern for diesel powered craft. The rudder and hydroplanes can be working hard under autopilot control, which can give poor efficiency in constant-pressure systems. The improved efficiency of adaptive hydraulic control will lead to lower demand on the engines. As a consequence smaller, lighter engines can be used. Less heat requires less cooling hence further savings in weight and noise.

C. *Safety/Redundancy*

Centralised oil distribution systems, such as current in service systems, pose the risk of contamination of all oil consuming components in the event of component failure. Due to this, acceptable damage tolerance requires many costly filters to be introduced in to the system, to reduce the possibility of cross contamination. With the VPH design this necessity is removed, again providing opportunities to reduce cost and weight.

Redundancy is also improved with the VPH design. In the case of hydraulic burst, emergency operating procedure requires that all hydraulic plants are shut off and accumulators depressurised. In the case of current ring-mains systems this would leave boat performance severely impaired, due to loss of control surfaces.

If this scenario were to occur with the VPH design, impact on control would be much less severe. Each VPH plant is local to the actuator and hence the probability of losing control of all control surfaces is reduced significantly, as it is unlikely that failure would occur simultaneously at several locations. Further, hose failure of a single VPH system would result in loss of control for the associated control surface, during the time taken to locate and remedy the failure. During this time, however, control would still be maintained by the remaining control surfaces, albeit with hampered manoeuvrability. The use of pneumatic motors and high pressure accumulators as safety backups also provides increased control in the event of an emergency scenario.

Pressures produced by the VPH system during normal operations are significantly reduced when compared to existing systems. As a result pipe cyclic stress levels are reduced, as is the risk to crewmen, during the event of a hydraulic burst. The system volume is also significantly less (the volume which could be released during a burst) which also allows for more effective monitoring of small leaks. Small losses of hydraulic fluid would be more evident in the smaller, VPH systems as a small loss would represent a larger percentage change compared to the same leak in a ring-mains system.

Further, given that VPH itself is a well-established technology, there is a large background of commercial use of the components. With this come associated knowledge and design methodologies which can be drawn on to enhance the service life and deployment of VPH in this new application.

A possible drawback of the adaptive VPH system, in terms of redundancy, is that separate dedicated units would not be connected to the ring-mains. Although a backup pneumatic motor would be used, conventional control surface actuator systems could be connected to several ring-mains systems (as there may be multiple on the boat). Using this method would make it possible to increase redundancy through simple connection to existing equipment. However, capacity would be have to be added to the ring-mains, negating the benefits of using an adaptive system.

Of course, the VPH emergency solution would have limited performance when compared to the current actuator systems, as it is unable to provide both maximum pressure and maximum flow simultaneously. However, given that during the large majority of submarine operating scenarios this simultaneous condition is not needed, large improvements in efficiency, weight and safety come at minimal performance cost.

V. MACTAGGART SCOTT VPH PROGRESS

A. *Concepts*

Three VPH concepts were created for submarine use, in parallel with the simulation process. The initial concept used an open hydraulic circuit and unbalanced actuator. The circuit comprised a variable displacement pump, a directional control valve, the actuator and a pair of counterbalance valves. Filters and a cooler were used to maintain oil cleanliness and the correct temperature. The variable displacement pump was driven by a variable speed electric motor, with an emergency pneumatic motor also coupled as a backup.

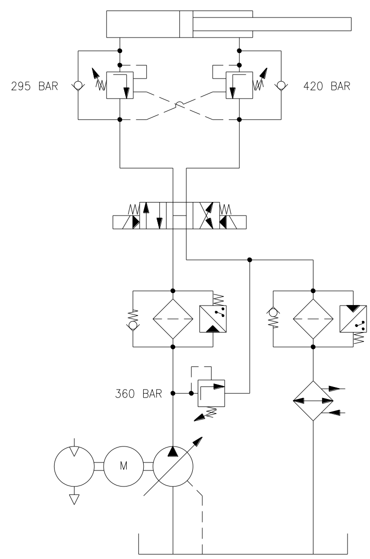

Figure 1. VPH Concept 1

A second concept was designed based on a closed hydraulic circuit and bidirectional pump. This step was taken after simulation of the initial circuit, which showed inefficiencies for some valves at low loads (loads as specified by customer requirements). Figure 2 shows a simplified circuit diagram including the main features of the system. Although some complexity was added through additional components (such as a flow combiner/divide to make up for unequal actuator areas), overall efficiency was improved due to reducing sources of flow throttling. This result was found from computer simulation.

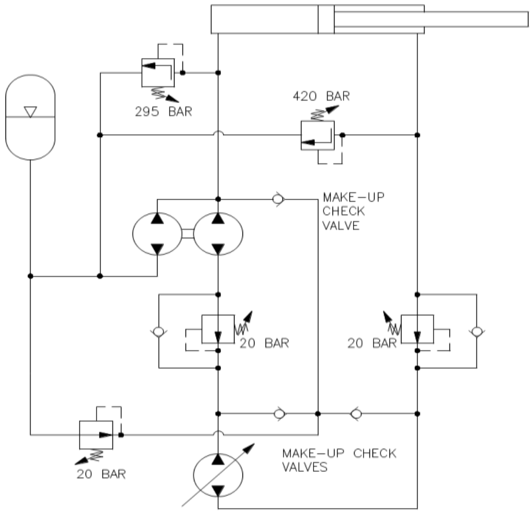

Figure 2. VPH Concept 2

The third concept was further developed to include a balanced actuator. Using a balanced actuator resulted in a simplified circuit as flow combiner/dividers and large accumulators were not necessary to make up for actuator area differences.

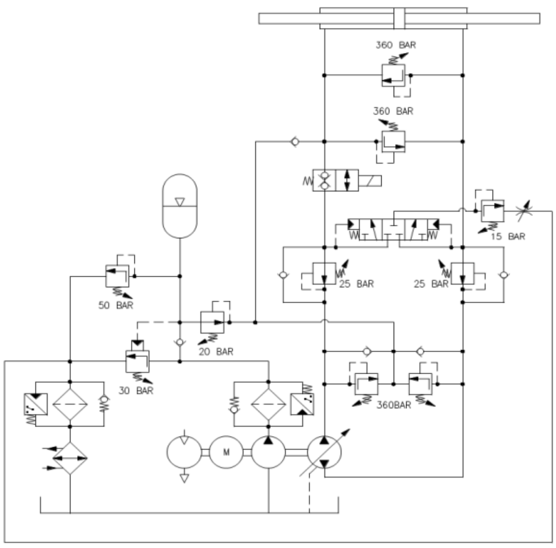

Figure 3. Modified Circuit for Concept 3 with Balanced Actuator

The hydraulic circuit in each concept was controlled using a closed-loop (feedback) control system where the cylinder rod extension is compared against a demand value. The error was fed into a proportional, integral and differential (PID) controller to determine the flow required from the pump to move the actuator into the correct position. The controller used the flow demand to calculate the required pump displacement and electric motor speed, as well as the position of the directional control valve.

B. Simulation

Each concept was modelled using VisSim dynamic simulation software. This allowed evaluation of actuator performance, such as displacements and velocities, pressures and flow rates throughout the circuit, power consumption, among other properties.

Loading profiles were created to emulate the complex hydrodynamic loads experienced by hydroplanes and rudders, and were applied to the circuit accordingly.

Simulation results were analysed to find the most efficient concept for the load criteria specified by the client, as well as possibly sources of optimisation. In this case the second concept using an unbalanced actuator was taken forward for testing using a dedicated test rig.

Examples of simulation results are shown in the figures below. These figures indicate the performance of the second concept including an unbalanced actuator, under several different demands. The first simulation trace illustrates the steady state response and initial small overshoot of the system (in blue) in response to a step displacement demand (red). The second figure shows actuator displacement for a triangular position demand under loading. Again, the demand is in red, and system response in blue.

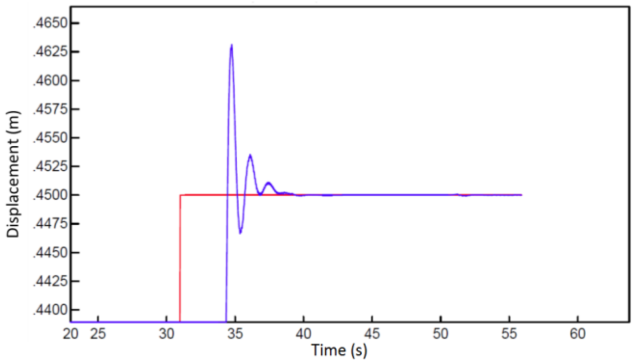

Figure 4. Step Response for Concept 2

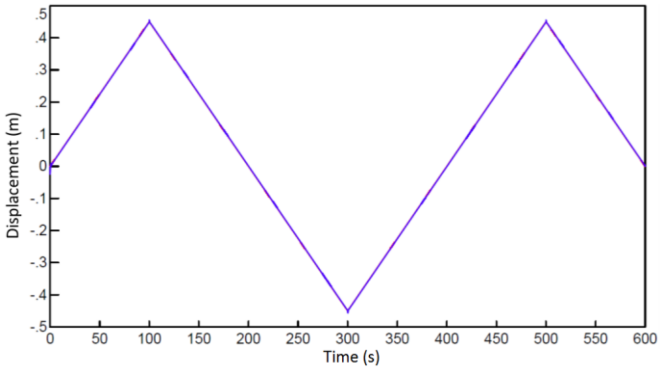

Figure 5. Response of Concept 2 for Triangular Position Demand under Loading

Simulation also yields pressure results at different point across the circuit, which can be used for in-depth analysis and optimisation. Figure 6 shows system pressures at specified locations for a certain loading condition and actuator displacement.

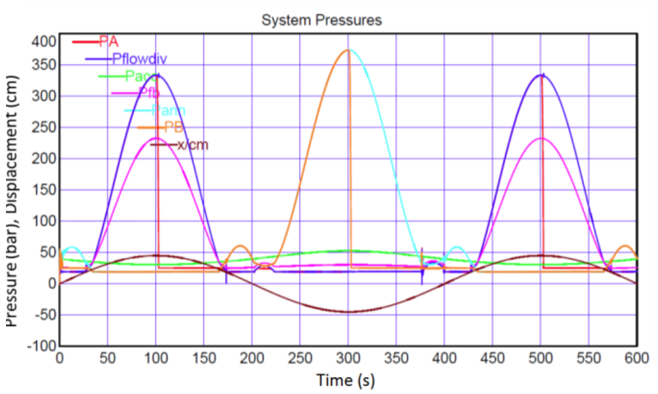

Figure 6. System Pressures for Concept 2 under Loading

C. *Physical Testing*

A demonstrator was constructed to enable physical testing of the VPH system. Alongside the VPH circuit a load emulation plant was also built to apply the required test loads to the actuator.

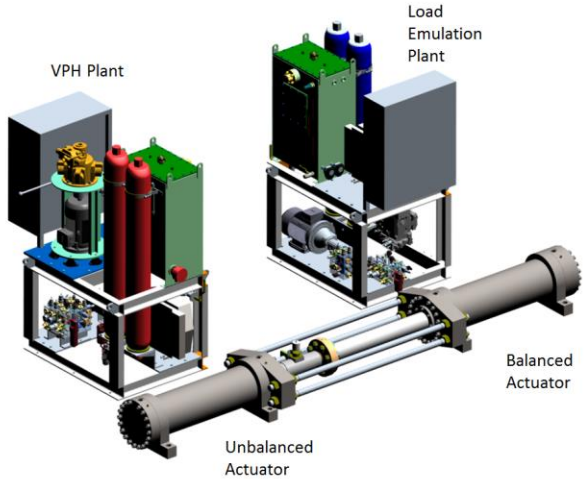

Figure 7. Model of VPH Demonstrator

Initial testing carried out on the VPH demonstrator was deemed to be partially successful. Scope for improvement was highlighted, with the intent of further reducing power losses within the VPH circuit, and improving the performance of the load emulation circuit. These changes were implemented and the physical plant attained the efficiency levels predicted by simulation.

VI. SUMMARY

Demonstrator testing effectively showed the ability of an adaptive VPH system to meet the technical requirements demanded of conventional control surface systems. These results were in-line with simulation results which had been used to verify the feasibility of the concept. This highlighted the energy reduction obtainable, as the power limited system could meet these requirements while using much less energy.

Testing the VPH demonstrator against the performance requirements showed that it is effective as a load positioning system. Alongside efficiency there are several other benefits in areas such as weight, heat, safety and noise improvement with VPH. To deliver these improvements there are some performance aspects which are impacted detrimentally. Of course, as the adaptive VPH system cannot provide both maximum pressure and maximum flowrate simultaneously, there is some decrease in the performance range available. Given that the probability of this demand being required is known and is extremely small it is believed this penalty is acceptable in order to achieve large energy benefits.

The next step in the development of the VPH system is design and testing of ship-fit equipment, for which MacTaggart Scott will soon be under contract.

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[1] N. Dahler, C. Wang, and M. Ivantysynova "Novel energy-saving steer-by-wire system for articulated steering vehicles: A compact wheel loader case study" *Proceedings of the 13th Scandanavian International Conference on Fluid Power SICFP2013.* Linköping Sweden