INTELLIGENT FLUID SYSTEMS

BY

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ABSTRACT

Many critical types of equipment onboard a modern warship rely considerably on supporting fluid systems in order to function effectively. Weapons and sensors for example require the constant provision of chilled water to permit the maintenance of overall operational capability. History has illustrated the vulnerability of these supporting fluid systems to external damage due to their inherent distributed location throughout a platform. To date policy has attempted to mitigate this risk by pre-emptively isolating fluid systems into a number of sub ring mains in order to reduce the impact of any damage to the system. This method is both time consuming and is relatively inflexible at allowing rapid reconfiguration to supply specific equipments required by the command aim. The concept of an intelligent fluid system is to incorporate pressure transducers and simple controllers to each valve allowing them to make smart decisions about the state of the surrounding system and act accordingly within seconds to maintain the provision of fluid system to essential users.

Background

Fluid systems onboard warships represent a vital link within a complex assembly of platform sub systems responsible for transferring a varying array of fluid medium from the service provider to end user. The difficulty in maintaining the integrity of an inherently distributed system through both peace and war damage scenarios is well recognised as a key factor in the overall survivability performance of a platform. Chilled water is no exception, providing essential cooling to an ever increasing range of equipments including propulsion through to weapon systems and other core command functions. The reliance on chilled water continues to increase with modern equipment user groups becoming more complex and sensitive to fluctuations in supply conditions. Considering the criticality of the chilled water system, it continues to remain a surprisingly vulnerable system to damage resulting in a considerable reduction in a warships war fighting capability. Taking a typical frigate or destroyer employing a classical ring main chilled water design approach and imposing a 1m grid hit matrix over one side aspect, on average, in 75% of the hit nodes resulted in the total loss of the chilled water system and the subsequent end user equipments. In contrast, the analysis also shows that with the exception of chilled water, the loss of essential weapon systems to action damage reduces to approximately 30% due to other vulnerabilities within the system.

The key factor to chilled water vulnerability is the time taken to reconfigure the system post damage. Current practice attempts to undertake pre-emptive action by isolating the system into a number of sub systems in order to minimise the effects of damage as the risk increases. This is necessary as the time taken post damage to assess the system status, identify the breach location, locate the appropriate isolations and reconfigure accordingly can be considerable utilising the current manual techniques and resources, by which time the very limited additional capacity within the chilled water system afforded by the expansion tanks has longed been exhausted. As can be seen by Figure 1, the ability to manually reconfigure a fluid system post damage will continue to degrade as the ratio of compliment size against displacement continues to decrease.

Assuming that equipment users will have a continued reliance on the provision of chilled water in order to function and with the option of increasing reserve capacity within a chilled water system to the orders required to meet the limitations of manual system reconfiguration not feasible, the only other viable alternative is to investigate mechanisms for rapidly reconfiguring a system post damage.

Taken from an assessment of a typical DD/FF against established known weapon damage characteristics. This assumes no system sub sectioning and the loss of chilled water resulting in the loss of supplied equipment.

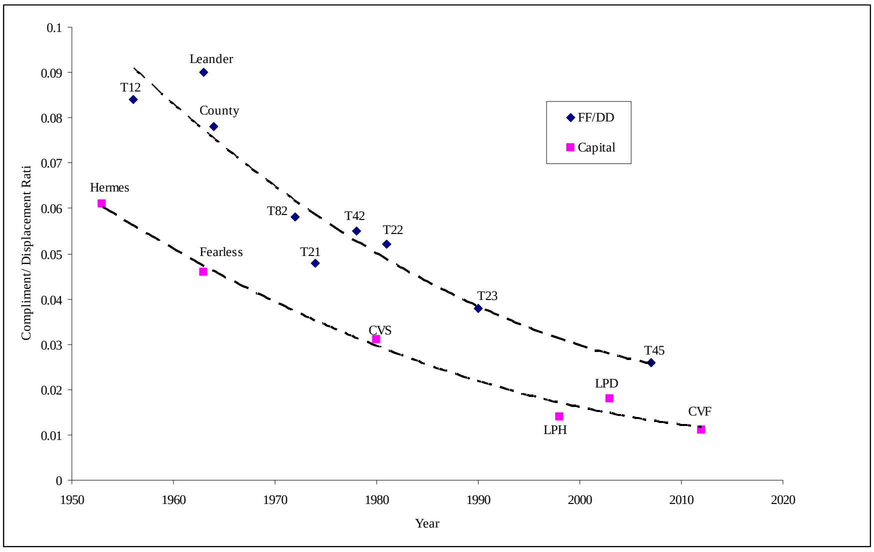


Fig. 1 Trends in Platform Tonnage Versus Complement Size

DEVELOPMENT PROGRAMME

In conjunction with the shortcomings highlighted previously, it was also apparent that various other industries and navies were beginning to investigate the possibility of smart valve technology in order to develop similar forms of automatic reconfiguration. In response, the Intelligent Fluid systems programme was established in early 2003 in the form of a feasibility study to investigate the potential gains available from embarking on a full scale development programme. The initial study also focused on identifying the potential capability benefits against indicative technology costs in parallel with assessing the potential outputs of a full scale development programme. This was vitally important in order to address issues of technology exploitation by ensuring the developed product had the potential to provide a sound cost effective solution with manageable risks as an attractive alternative to meet the needs of the prime contractor in meeting the MoD's requirements.

The feasibility study clearly illustrated the possible benefits of an intelligent fluid system, highlighting that many of the components such as valves, actuators and controllers are already well established technologies. It highlighted any future programme needing to focus on integration issues and optimisation. The study also concluded that whilst this technology has potential benefits to a wide range of distributed fluid systems, it would be appropriate to develop a small scale concept demonstrator focusing on the chilled water system. This system potentially offered the greatest benefit in terms of impacting on platform capability, but also represented the simplest system as it is closed in nature and does not experience relatively large pressure transients compared to high pressure firemain and fuel systems for example. The proposed concept demonstrator initially concentrated on investigating the integration of 4 main components to form a smart valve into a fluid system; valve body, actuator, controller and up/down stream pressure transducers. Once the characteristics of integrating smart valves operating solely on pressure variations within the system were firmly understood and modelled, phase 2 of the programme would investigate the benefits of linking the individual smart valves together into a higher intelligent network enabling the active reconfiguration of fluid systems to support specific requirements of the command aim as illustrated in Figure 2.

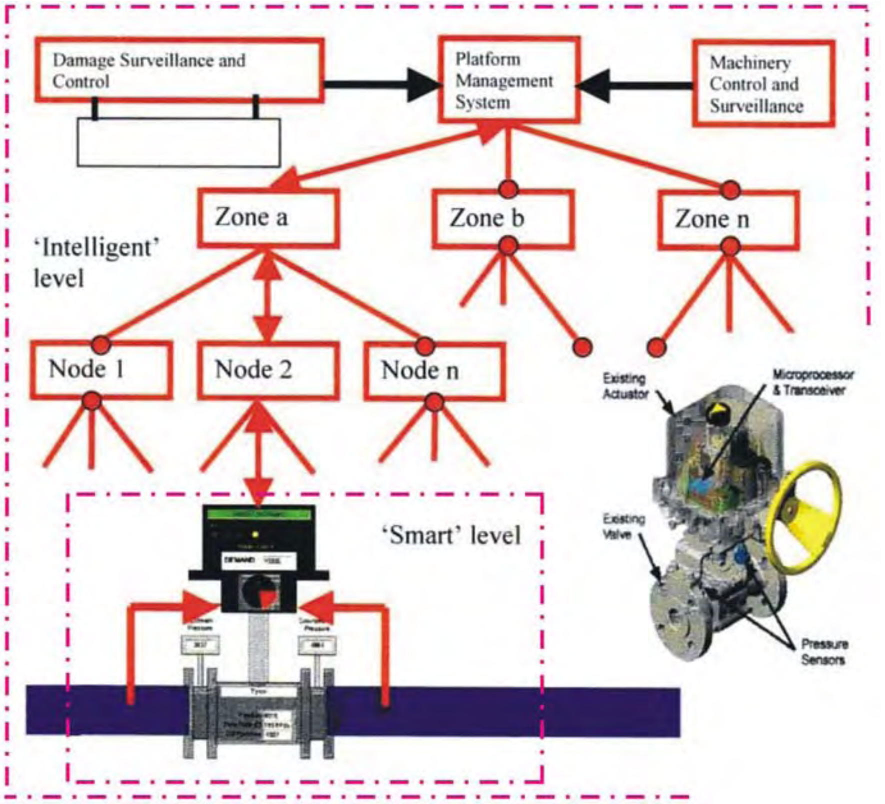


Fig. 2 Smart and Intelligent System Hierarchy

In Sep 03, phase 1 of the Intelligent Fluid System development programme commenced. This entailed the construction of a demonstration test rig to assess and confirm the suggested performance from the initial feasibility study whilst developing and validating a software modelling tool to enable the confident evaluation of future more complex fluid system designs without the need for further costly full scale practical testing. A broad selection of valve manufacturers were canvassed for interest in the programme, resulting in excellent support from wider industry and enabling the successful production of the test rig illustrated at Figure 3.

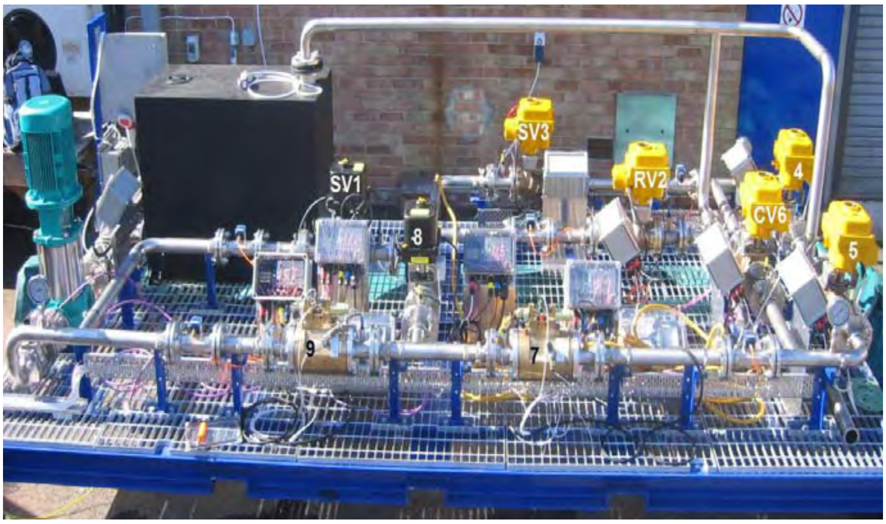


Fig. 3 Phase 1 Concept Demonstrator Test Rig

RESULTS

Simulation modelling results

In parallel with finalising the test rig details illustrated in Figure 3, a software model representation of the test rig was created using commercially available fluid dynamics modelling package as detailed at Figure 4. The layout was chosen to represent a simplified onboard chilled water system with a single pump providing flow to two legs; valves 1,3,4 and 9,7,5 with cross connections at valves 8 and 6. Valve 2 is positioned to simulate a rupture in the upper leg during testing and valves 4 and 5 are set partially closed to provide back pressure for the system to operate realistically.

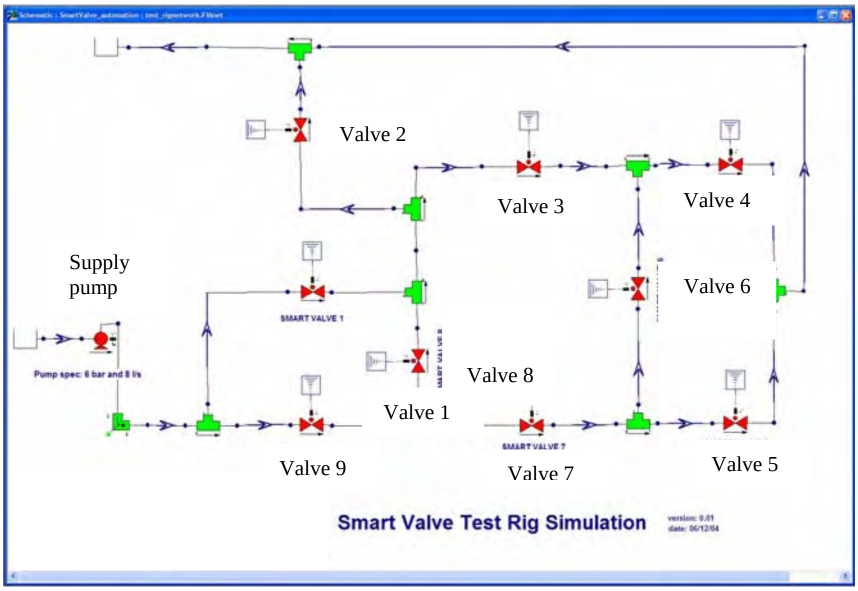
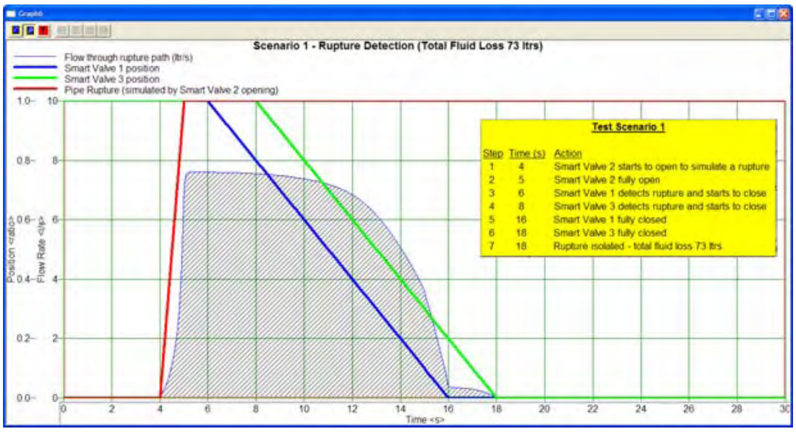


Fig. 4 Model Representation of Test Rig

The initial results from the model provided valuable indications of how the rig would perform, enabling a number of minor design refinements to be incorporated before commencing fabrication. A key prediction from the software model concerned the limited flow restrictions offered by the valve bodies. This is vital as the only method a smart valve has for determining the conditions in the surrounding pipe work and ultimately surmise of a potential local pipe rupture is through the information gathered from the two valve pressure transducers located either side of the valve mechanism. Therefore in principle, if both pressure transducers record an identical pressure value, even if considerably less than the nominal operating pressure, the controller will surmise that this is a system wide pressure drop such as a defective circulating pump and therefore take no action. However, if the controller sees a significant difference between the two values, at a pre-determined point it will surmise a rupture has occurred downstream and close accordingly. For this principle to work effectively, it relies on the valve construction providing a restriction in flow (equivalent to an orifice plate) to generate a pressure differential. Unfortunately it was clear from early model results that the valve bodies provided only a negligible restriction to flow and considerably short of the magnitude required to enable the controller to differentiate this from the inherent system noise.

Two options were consider in order to resolve this issue. Firstly the nominal diameter of the valve could be reduced to a size less than the surrounding system pipe work in order to provide a sufficient restriction to flow. This solution was considered unacceptable as it would produce an inefficient system resulting in larger pumping capacities required, the generation of excessive heat due to friction and potential increase wear of system components. This drove the development of a novel solution to resolve this issue by allowing the valve to partially close in certain situations, providing a temporary flow restriction and the generation of a larger differential pressure as a result of a rupture. This is achieved by allowing the valve to close by up to 40% following the detection of a significant pressure drop by the two transducers. Once the valve has partially closed, the controller pauses the actuation in the intermediate state for a predetermined period. During this period, if the differential pressure recorded by the transducers remains negligible, the controller surmises that this is a system wide pressure reduction and returns the valve to the fully open position. However, if whilst at the intermediate position the controller records a significant variation between the two transducers, it will now surmises a rupture exists downstream and signals the actuator to fully close the valve.

Based on these initial findings, the model was modified to incorporate appropriate restriction at the corresponding valve positions that effectively assumed the model to start from the partially closed valve position, ignoring the initial partial closing action. Figure 5 details the revised results from the fluid modelling software, providing further confidence in the intelligent fluid concept illustrating how smart valves 1 and 3 react to a simulated rupture by valve 2 in a simple scenario. Assuming a nominal actuator time of 10 seconds, a system pipe work diameter of 64mm (2.5 inch) and a pressure of 6 bar, the results estimate the total isolation of the rupture within 14 seconds with a best case estimated loss of only 73 litres of fluid.



Test Scenario 1

Step	Time (s)	Action
1	4	Smart Valve 2 starts to open to simulate a rupture
2	5	Smart Valve 2 fully open
3	6	Smart Valve 1 detects rupture and starts to close
4	8	Smart Valve 3 detects rupture and starts to close
5	16	Smart Valve 1 fully closed
6	18	Smart Valve 3 fully closed
7	18	Rupture isolated - total fluid loss 73 ltrs

Fig. 5 Modelling Predictions

Test rig results

Armed with the results from the software modelling, the necessary final revisions were made to the test rig design and construction commenced as shown in Figure 3. A PC user interface was also developed to enable each valve to be remotely controlled or designated to operate automatically in smart mode. The interface also enabled the gathering of valuable data and the close monitoring of the system state. Following successful commissioning of the test rig, the formal evaluation of the intelligent fluid concept together with validating the modelling results commenced.

To date, a relatively simple scenario has been successfully demonstrated where valves 1 and 3 are set to smart mode, valve 6 set to a smart cross connect mode and valve 2 used to simulate a rupture (Fig 4). Before the commencement of this typical scenario, the test rig is remotely preconfigured from the controlling PC as detailed in Table 1. Here steps 0-2 establish communication with all valves and baseline all valves to the fully open position. Step 3 remotely drives valves 4 and 5 to the 20% open position to provide sufficient back pressure in the rig. Valves 1,3 and 6 are then set to smart mode with valve 6 also being designated in a cross connect position. In this mode these valves are monitored by the PC but make decisions based purely on the locally positioned pressure transducers. Once the initial configuration is established, valve 2 is fully opened to simulate a system rupture and the rig is left to reconfigure accordingly.

Table 1 Pre-Scenario Configuration

Step	Elapsed time (sec)	Command	Valves	Value
0	0	valve - set remote	all	0
1	5	commutations - ignore	all	0
2	10	pos	all	100
3	10	pos	4,5	20
4	10	pos	2	0
5	10	pos	8,6	0
6	20	cross flow	6	0
7	20	smart	1,3,6	0
8	55	pos	2	100
9	60	pos	2	100
10	120	pos	2	100
End	150			

Table 2 below summarises the subsequent sequence of events recorded when starting from the scenario described above with reference to supporting figures.

Table 2 Sequence of Events

Time(sec)	Figure	Event
0-54	6	Pre test rig scenario configuration as detailed in Table 1. (Illustrated by dark pipe work shading upstream of partially closed valves 4 and 5.
		Nominal system pressure of 7 bar established.
55		Valve 2 (rupture valve) opens as detailed in Step 8 to Table 1.
62	7	Network pressure has dropped to atmospheric (presented as white pipe work). Valve 2 actuator position is showing 65 (0=closed, 90 fully open) with the differential pressure dropping from 7023mb to 110mb over valve 2.
63		Valve 1 detects low pressure and starts to close in order measure pressure differential.
65		Valve 3 also detects low pressure and starts to close to measure pressure differential.
71		Valves 1 and 3 are now both partially closed and holding position to measure differential pressure and surmise whether a complete system pressure reduction or pipe rupture has occurred.
76	8	Valve 1 surmises a rupture condition due to a high pressure differential (1338mb) and starts to fully close. Valve 3 records a relatively low differential pressure (22mb) across the valve and remains partially closed due to continued low system pressure detected by the transducers, 148mb and 126mb respectively.
80	9	Valve 1 reaches fully closed position (high differential pressure of 7771mb) - rupture path flow is virtually zero. Lower-leg network pressure is restored to nominal 7 bar. Upper-leg network pressure downstream of rupture is still at atmospheric (approximately 50mb).
88		Valve 6 (Smart cross-flow – denoted by an 'X' on the valve graphic) detects a system imbalance by virtual of the large pressure differential acting across the valve body (7780mb to Figure 9) and starts to open to re-establish flow to the upper isolated path.
97	10	Valve 6 achieves fully open position. Flow has been restored to upper-leg but the system pressure has dropped to 1 bar (1335mb entering valve 7) caused by a backflow through partially open valve 3 (differential pressure of 971mb) and out through valve 2 (i.e. re-establishes rupture flow). Note that Valve 6 has changed mode on opening from a Smart Cross-Flow valve to a standard Smart In-Flow valve ('X' on the valve graphic has gone).
101		Valve 3 now detects a rupture by the virtue of the backflow creating a differential pressure across the valve body and therefore starts to fully close.
105	11	Valve 3 is now fully closed and the flow through the rupture isolated as shown by the white pipe work between valves 1 and 3. The rest of the system is restored to normal operating pressure (7 bar) with flow re-established to both upper and lower legs.

The following figures illustrate the rupture isolation and system reconfiguration process with the segments on each valve actuator indicating valve position (Valve 7 was held manually open due to technical difficulties).

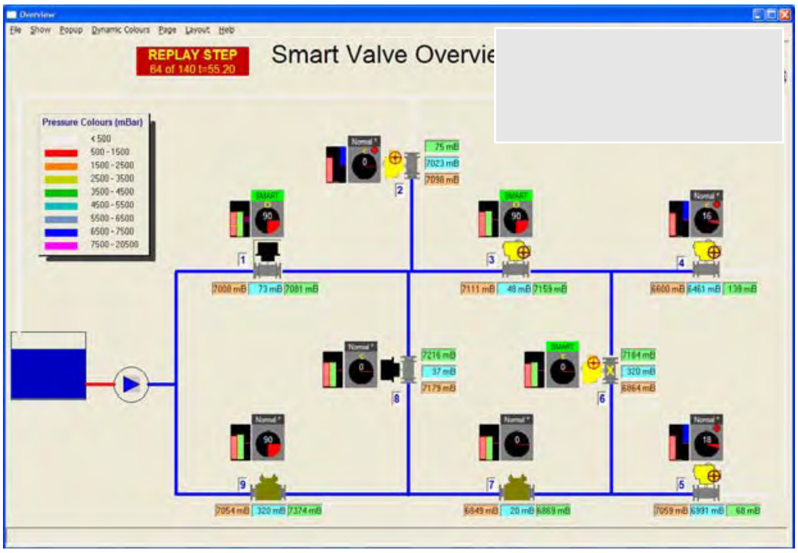


Fig. 6 Pre Rupture System Configuration

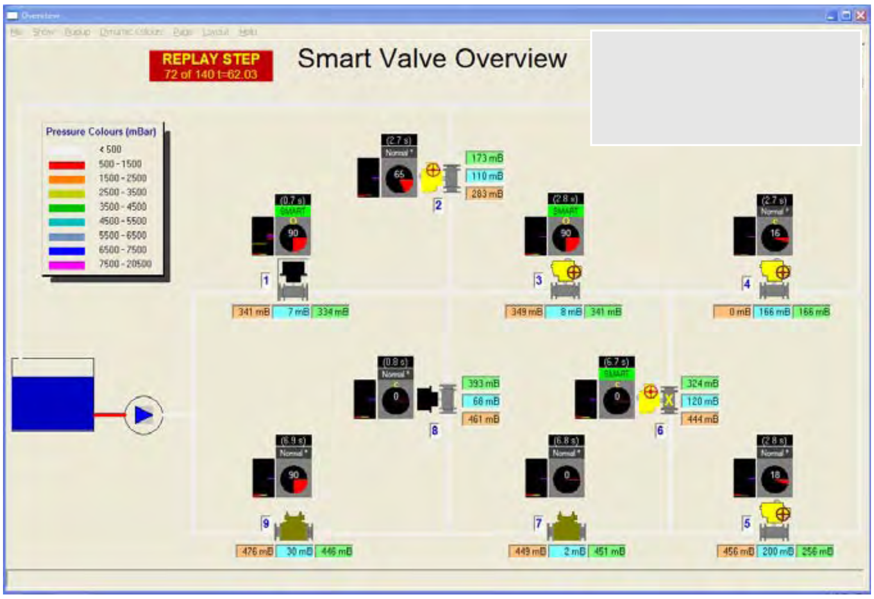


Fig. 7 Rupture in System (valve 2 fully open) – Loss of System Pressure

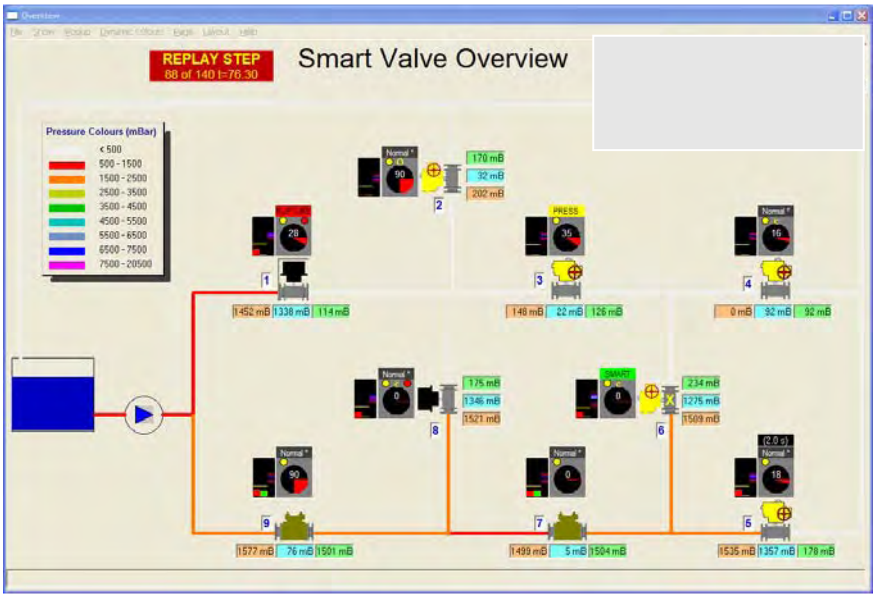


Fig. 8 Smart Valves 1 and 3 Partially Close to Ascertain System State

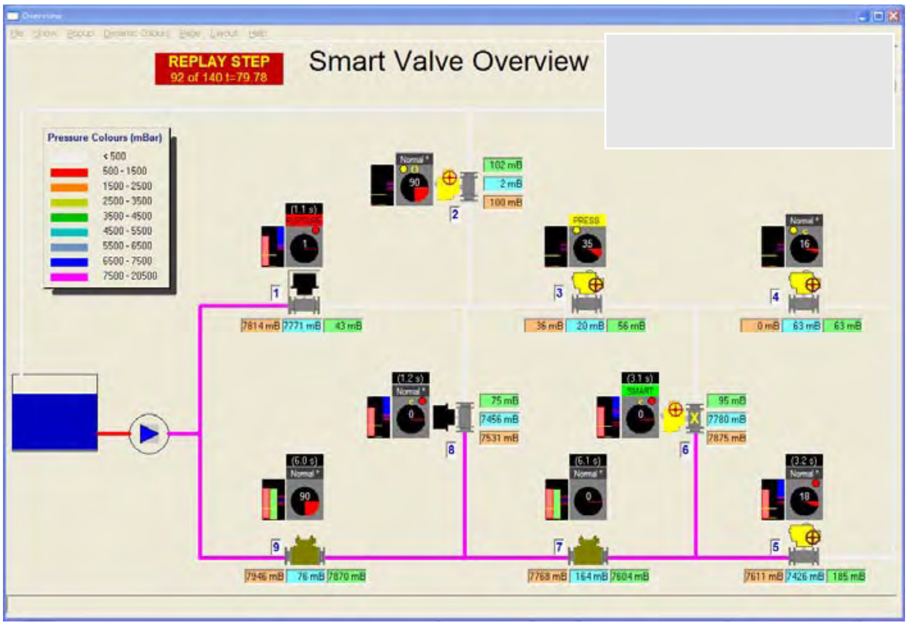


Fig. 9 Valve 1 Closed. Rupture Flow Almost Stemmed and Low Level Path of System Restored to Operating Conditions

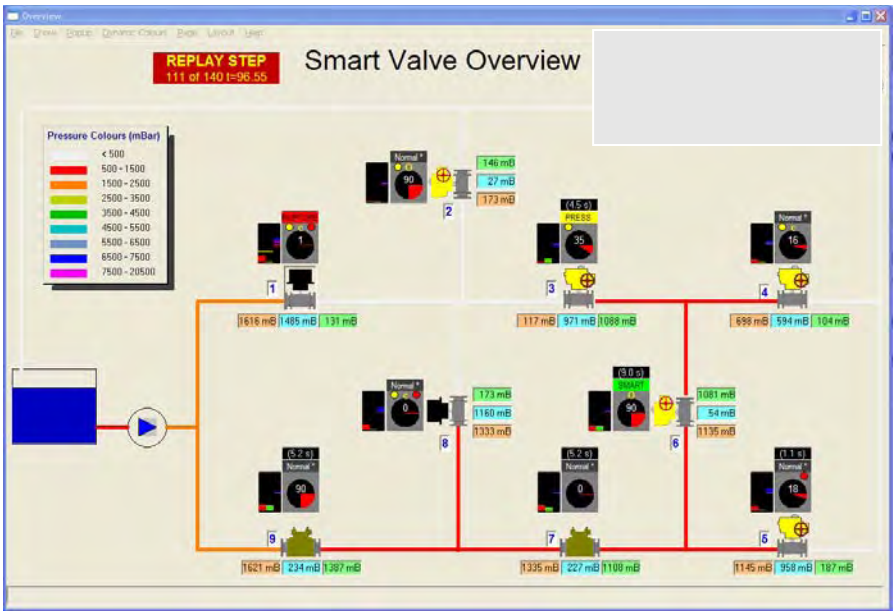


Fig. 10 Cross Flow Valve 6 Fully Open. Valve 3 Now Detects Large Pressure Differential.

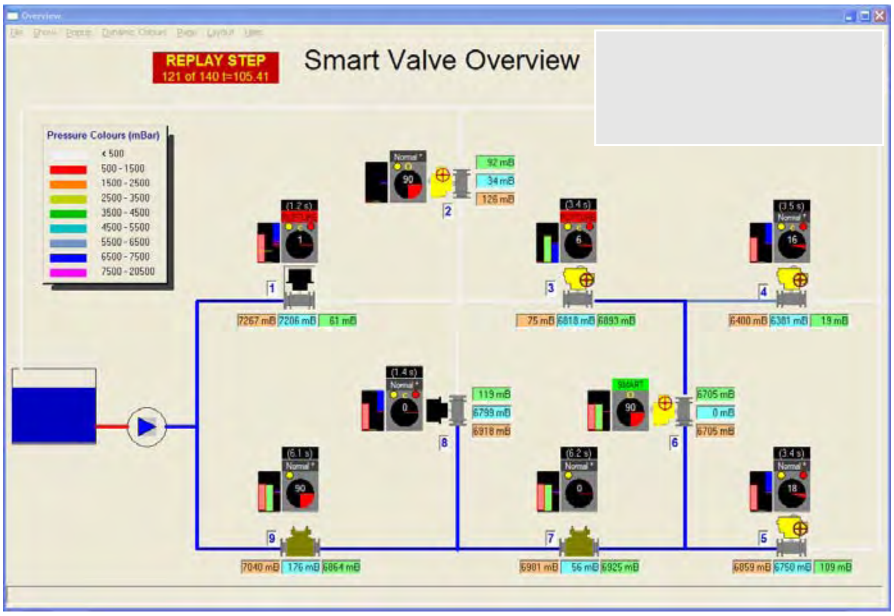


Fig. 11 Valve 3 Fully Closed. Supply Pressure Restored to Upper and Lower Legs.

Figure 12 below provides a graphical representation of key valve positions against time. It clearly illustrates the partially closed position maintained by both valves 1 and 3 whilst they ascertain the condition of the surrounding system. It is worth noting that whilst valve 3 sustained a relatively longer period at the partially closed position, this was a direct result of the system pressure dropping below a pre determined value. If during this intermediate period the system pressure was restored to 7 bar either side of the valve resulting in a negligible differential pressure across the valve, the valve would be restored automatically to the fully open position.

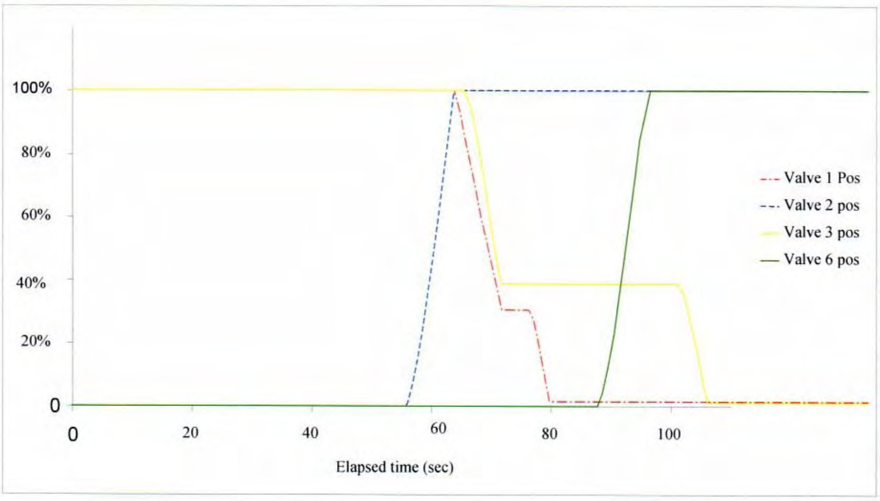


Fig. 12 Summary of Valve Positions Against Time

During the evaluation of the test rig, it was necessary to impose a restriction on the smart valves to prevent these from attempting to re-open once reaching the fully closed position. Early testing revealed that failure to impose this restriction resulted in system instability with valves continually hunting due to dynamic pressure fluctuations transmitting throughout the rig.

DISCUSSION

Model and test-rig comparison

Figures 13 and 14 below show a direct comparison of pressure and flow characteristics between the actual values measured on the test rig and those predicted by the model. While the fundamental shapes of the model are similar, there are some notable divergences.

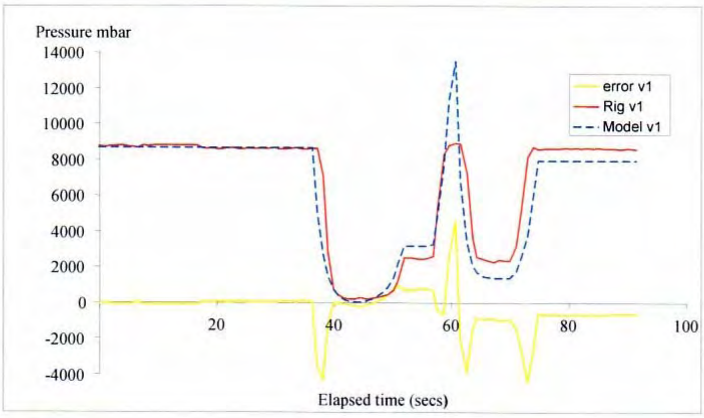


Fig. 13 Initial Rig/Model Pressure Comparison

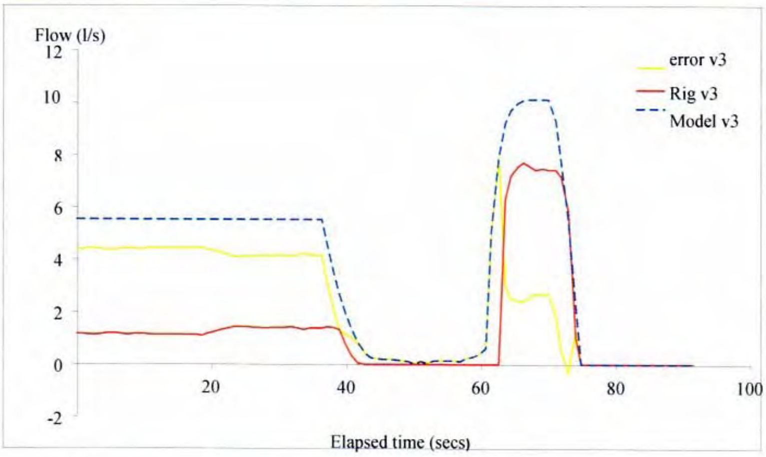


Fig. 14 Initial Rig/Model Flow Comparison

Note that valve 1 is used for the pressure comparison and valve 3 for the flow. This is because valve 1 has more pressure variations during the scenario, but its flow ceases as soon as it closes. Likewise valve 3 pressure is effectively zero once the rupture opens until valve 6 (cross flow) opens up to restore flow to the top leg.

The discrepancies between the actual and modelled results could be explained by two key problems. The first is the differences between the generic ball-valve model used within the modelling tool and the second is the variation in the response of identical valve/actuator pairs. Further investigation revealed that where the ideal generic model used allows flow as soon as the position is non-zero, the actual valve/actuator pair doesn't allow flow until the valve is approximately 20% open. Based on these findings, the generic ball valve model was modified with the new specific valve/actuator coefficient curve data. Using the modified parameters the model was re-run and the results compared to the data from the test-rig.

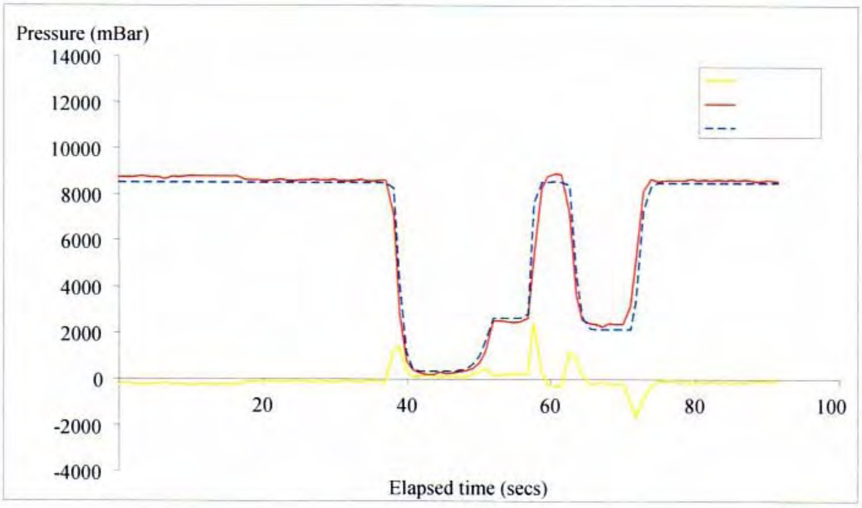


Fig. 15 Initial Rig/Modified Model Pressure Comparison

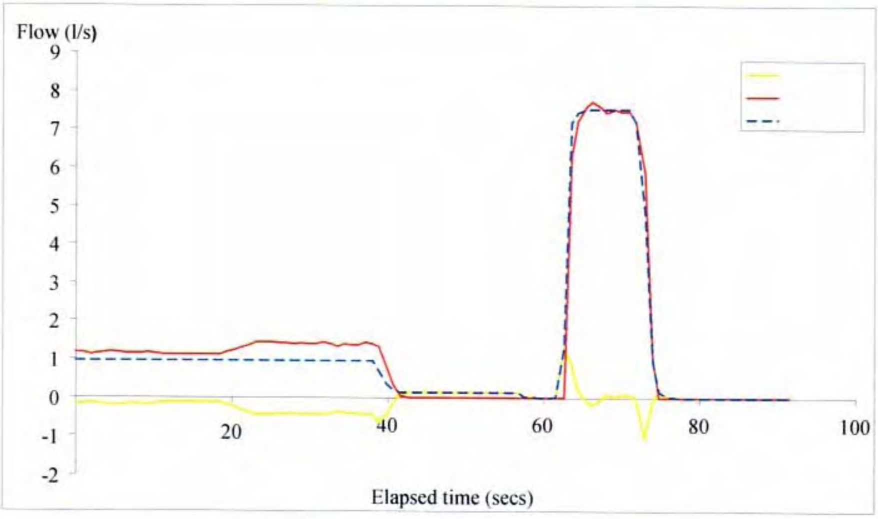


Fig. 16 Initial Rig/Modified Model Flow Comparison

The modified comparison results shown at Figures 15 and 16 show a much closer correlation between the model and the data taken from the test-rig. The remaining discrepancies are due to minor timing variations where a valve may start to operate either slightly earlier or later than in the model. This can result in large error spikes even though the curve matches quite closely.

Model limitations

These results show that while the gross characteristics and physical validity of a fluid network can be successfully modelled, its ability to resolve the fine detail, and order of operation of independently operating smart valves depends to a large extent on the quality of information available when modelling. Therefore the exact sequence of events of a smart valve network (where the valves are operating independently) cannot be determined due to variations in the physical characteristics of equipment and the exact operating conditions at that time. For example, in Table 2 at 101 seconds, smart valve 3 closes due to back-flow through the valve caused by smart valve 6 opening to re-establish the cross flow. Given accurate information, the model could successfully predict this sequence but if there were some minor discrepancy in the flow/position curve used in the model and the actual flow/position of the valve the model could see a lower flow through valve 3, delaying it closing. In the meantime, valve 6 has gone fully open and seeing a continual large pressure drop across it decides there is a rupture and re-closes. In one situation the rupture is isolated and flow is re-established in both legs. In the other situation the rupture is still isolated but there is only flow in the lower leg (due to the cross flow valve 6 having re-closed). Both of these results are valid (and could happen on the test-rig) but it only requires a small variation in one parameter (known as the 'Butterfly Effect') to switch between either. In a situation where many independently operating smart valves are involved in a cascading sequence of events there could be many possibly final configurations. With general fluid system network design, including chilled-water systems, the exact sequence of events is not required and it would be imprudent to base a design on the way software responds to a user-definable thresholds and timings. A generic set of system component characteristics is sufficient for system design and design guidance.

Smart valve performance

It is important to appreciate that the research presented in this paper represents the initial findings of the intelligent fluids programme. Not withstanding this fact, the results presented in Table 2 provide an encouraging start with the ability to stem the flow through the rupture achieved within 25 seconds, with the system actively reconfigured around the rupture point within a further 25 seconds (50 seconds in total). Considering that the threshold parameters for inferring decision points within the valve controllers have not been optimised, the time stated also including the valve first actuating to the partially closed position in order to make a decision and also the use of relatively slow standard industry valve actuators, provides confidence in the actual performance capabilities available in the future. The independent operation of the valves in smart mode will ultimately only be tested onboard a platform following the loss of the higher level collective function as illustrated in Figure 2, and therefore represents the worse case functionality available. The inclusion of smart valves into a networked system driven from the PMS offers a wide range of advantages including:

- The ability to actively reconfigure the system in line with the command aim ensuring priority is placed against supplying mission essential equipments.

- The potential rapid reconfiguration of a fluid system moments before receiving weapon damage when the threat axis is known to minimise system disruption and achieve the optimum configuration to maximise the survivability of the system.
- Routine cycling of the valves within the system as part of a maintenance routine to provide valuable data on system performance and identify defects within the system.
- Remove the requirement to manually reconfigure a fluid system into sub system pre action (state 1 preparations) as the system will have the speed of response required to reconfigure to meet a given situation.
- By arranging the valves into a hierarchical structure will ensure system resilience to damage.

Further evaluation of the applicability of this system using an established vulnerability assessment modelling tool has also highlighted considerable benefits. Again based on a mainstream frigate/destroyer utilising a classic ring main chilled water system, the retro fitting of a typical intelligent fluid system is predicted to increase the survivability of chilled water reliant equipments from approximately 25% to 75% therefore maintaining war fighting capability post damage.

The programme is continuing over the forthcoming months to investigate issues surrounding alternative pipe construction material, effects of fluid head, operating a part intelligent/part smart valve system (when valves become individually detached from the network), battery backup systems and the applicability to other fluid systems.

Conclusions

Today’s modern warships have a considerable reliance on chilled water in order to conduct war fighting functions. Unfortunately fluid systems, particularly chilled water, are inherently vulnerable to damage by nature of being distributed throughout a platform and having very limited ability to rapidly reconfigure post damage.

The integration of two pressure transducers either side of the valve mechanism together with a simple controller forming a ‘smart valve’, have the potential to allow a valve to surmise possible ruptures within the immediate vicinity and undertake safeguard action as appropriate.

Software modelling of a simple scenario has predicted the ability of a smart valve to detect and close accordingly within approximately 14 seconds thus stemming fluid flow through the rupture point and thus maintaining chilled water supplies to the majority of end users.

Construction of a full scale test rig has confirmed the modelling findings, but also the ability to use ‘smart cross connection valves’ to reconfigure supplies to otherwise isolated areas.

Vulnerability assessment studies based on typical frigate/destroyers with classic chilled water ring main systems have predicted a reduction in vulnerability of key end user weapon systems from approximately 75% to 25% when implementing a intelligent fluid system.

The programme is continuing to develop higher level intelligent functions together with factors including alternative pipe material, optimising valve number and positions and effects of damage of valve communications network.

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