THE DEVELOPMENT AND TESTING OF AN OPTIMISED RIDE CONTROL SYSTEM FOR A 102-METRE TRIMARAN FERRY

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SUMMARY

A substantial amount has been learned from the design, manufacture and operation of a 127-metre length Trimaran RoPax vessel as well as a similar hull configured as a warship now in service with the US Navy. The trimaran hull shape and layout are carefully designed to work in conjunction with underwater foils in order to maximise passenger and crew comfort, and for the design of the next generation of high-speed trimaran it was decided to develop a new ride control system specifically to suit the characteristics of trimaran motions, which were found to be generally longer and slower than catamarans. Various systems and controlling software were analysed in a numerical simulator, and fully-articulated T-foils were developed to best suit the new design. These were designed and manufactured in-house at the same time as a 40-knot 102-metre length trimaran was being constructed. New controlling software was also developed to suit the long-period motions of the vessel. Extensive trials have proven the success of the system with some noticeable improvements over the performance of the first vessel.

NOMENCLATURE

GM_T	Transverse Metacentric Height
LCS	Littoral Combat Ship (US Navy)
KG	Vertical Centre of Gravity above base
MSI	Motion Sickness Index [3]

1. INTRODUCTION

A simple and effective approach to the design of a high-speed craft is to make the hull as long and as thin as practical. This provides low wave-making resistance and superior ship motions, but regulatory stability can then be problematical.

A common solution to the stability issue is to duplicate the long and thin hull and to create the catamaran, but there is an alternative which is to add to the long and thin single hull two small outer hulls or amahs to provide the necessary stability, resulting in a layout called a stabilised monohull or trimaran.

The widely separated hulls of a catamaran provide plenty of stability, sometimes too much, and catamarans can be very uncomfortable in beam seas because of the high levels of acceleration resulting from the excessive metacentric height GM_T.

The stabilised monohull arrangement, with its long and thin hulls, only requires relatively small forces to change the attitude of the craft, and therefore it obviously fits very well with the idea of underwater fins to provide hydrodynamic forces in order to control the attitude and accelerations of the craft to the desired level.

2. BACKGROUND

The first large trimaran ferry was the 127-metre long *mv Benchijigua Express*, completed in 2005 and operated since that date on a regular daily service between the various islands in the Canary Islands in the North Atlantic Ocean. Details of this craft and its development are given in References [1] and [2].

As this boat was the first of its type, it was subjected to many trials, and instrumentation remained on board for the first year of operation. The results of these measurements were used to identify areas where the performance of the concept could be improved.

As a result of the development of this large trimaran trimaran, and its subsequent successful operation, the hull form was used as the basis for a 127-metre long warship for the US Navy developed as a Littoral Combat Ship (LCS2), as illustrated in Figure 1. Several of these craft have now been ordered, and trials on the first craft have confirmed the superior behaviour of the trimaran concept, particularly when compared against alternative craft designed for the same tasks.

Figure 1: USS Independence, a 40-knot 126-metre trimaran designed and built by Austal

3. A NEW GENERATION OF TRIMARAN

3.1 SELECTION OF FORCE GENERATORS

Taking advantage of the unusual capabilities of trimaran shapes, *Benchijigua Express* had been deliberately designed with a low metacentric height GM_T in order to provide a slow roll characteristic and thereby enhance passenger comfort. However for the next stage of development it was decided to increase the GM_T value in order to reduce the magnitude of the roll, whilst maintaining the slow rolling period and hence a low acceleration. The new Ride Control system was also to be designed specifically to exploit the trimaran layout, In plan view, the trimaran is approximately triangular in shape, so fitting force generators at the three apexes of the triangular plan form would provide the maximum lever for the force generators and hence the largest correcting moments. The most effective force generators for a high-speed craft are unquestionably hydrodynamic foils, and so it was decided to explore the idea of fitting one foil at the bow of the main hull and one foil at the after end of each of the two amahs. All of these foils were to be actively controlled such as to have a variable angle of attack, capable of generating forces in both the up and down direction in a rapid time frame.

Foils generally generate a maximum lift perpendicular to the plain in which they are oriented. With the foils located at the forward and aft extremities of the vessel it was obvious that the foils should be horizontal to generate the maximum pitch reduction. For maximum roll reduction, the foils were initially investigated with an anhedral angle, as illustrated in Figure 2, with the axis of the foil passing through the apparent roll centre. However this would require the foils to be handed, and for commonality of spare parts it was decided to make the foils horizontal and identical on either side. The resultant loss in maximum force moment was approximately 8%. The foils were offset inboard from the centreline of the demihull in order to remain fully within the beam of the ship which would allow the vessel to lie alongside a wharf.

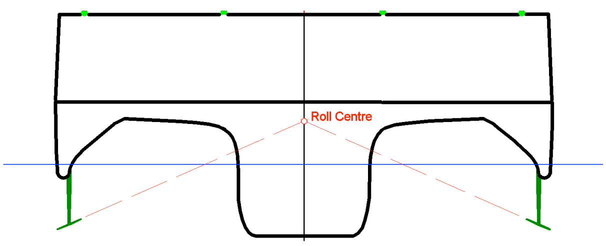

Figure 2: Illustration of possible foil anhedral to generate maximum anti-rolling moment

3.2 THE TRIMARAN SPECIFICATION

The specification for the craft was based on our analysis of likely trade on the selected route, the most efficient operating speed and the minimum vessel size necessary to provide a comfortable ride in the target operating area. The vessel was primarily sized to suit an economical purchase price whilst offering a substantial carrying capability. The capability requirements were as follows:

Passenger Numbers	>1000
Vehicle Numbers	>245
Truck capacity	190 lane metres
Design Speed at 450t dwt	39 knots
Maximum deadweight	700 t

The car capacity dictated the overall ship beam (26.8m) which is related to the standard car size of 4.5m x 2.35m . The vehicle numbers also dictated the minimum ship length (102m).

The required speed and outline ship dimensions indicated the necessary propulsive power (3 x 9100 kW), and the dimensions of the most likely engines with the required power and their associated waterjets determined the minimum width of the main hull.

The main dimensions were thus identified, and the initial General Arrangement drawn up, permitting an estimate to be made of the *LCG* and *KG* values.

A hull form having the necessary general characteristics outlined above was then developed, with a GM_T value that had previously been identified as a starting point based on that of *Benchijigua Express*.

3.3 SELECTION OF METACENTRIC HEIGHT

The hull form and preliminary ride control arrangement were modelled in a seakeeping simulation in a variety of sea conditions and wave headings using the software *VERES* from Marintek. The underwater shape of the amahs were varied to give a variety of hull shapes with different GM_T values, and from this data, reproduced in Figure 3, a choice was made of the design GM_T, based on the metacentric height at which the amount of roll started to increase rapidly with reducing GM_T in stern quartering seas. A design GM_T of about 6 metres was selected.

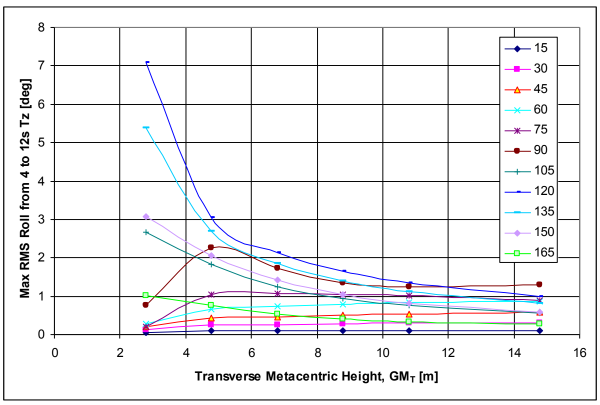

Figure 3: Roll angle resulting from varying GM_T values at various wave headings (Head Seas = 0°)

3.4 SHIP MOTIONS AND SELECTION OF RIDE CONTROL SIZES AND ACTUATION

3.4 (a) Foil Selection

Having selected the GM_T and the associated hull shape, together with the locations for the three force generators, *VERES* was then used to investigate the ship motions with a variety of types and sizes of force generators, and with different actuation methods. A number of standard sizes were available, having been developed for previous vessels, and there was potential for substantial cost savings if an existing design was suitable. However there were a number of other factors that influenced our decision, based on the unique nature of the trimaran.

Firstly it was recognised that a vessel with a wide hull such as the trimaran will lift the amah by a significant amount when the vessel rolled. It was obviously desirable for the aft force generator to remain immersed; however the draft of the amah at the transom was only about 800mm. This implied a long strut in order to immerse the aft foil as much as possible.

Secondly, with the aft foil located at the extreme aft end, it was thought possible to make the foil retractable for maintenance and cleaning by hinging it aft and up behind the transom.

With the need for a hinged long strut came the realisation that this would suit a fully actuated foil, as opposed to a foil with an active flap, as illustrated in Figure 4.

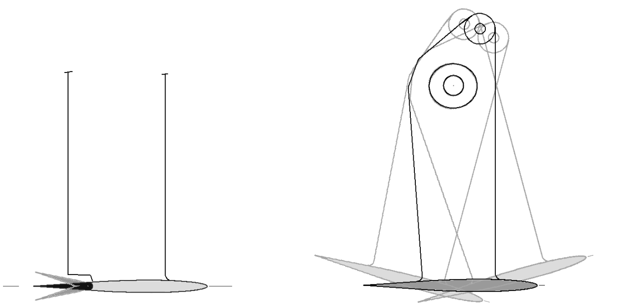

Figure 4: Sketch of T-Foil options, with active flap (left) and a fully-actuated or swinging foil (right)

Recognising that a long strut would require new patterns for casting the unit, the size of the aft foil was no longer constrained by the need to use an existing design, and a variety of new section shapes and sizes was also investigated using *VERES*. These were compared with the simulated performance of several other Ride Control alternatives in a Mediterranean wave environment on the basis of operability within certain constraints, including Motion Sickness Indices (MSI 20% in 2-hr period, in accordance with Reference [3]), Lateral acceleration values (<0.05g) and Roll angle (<4°)

It was found that:

- a vessel with a 2.63m^2 area T-foil on each amah had the same operability factor as the same vessel fitted with two 5.2m^2 fins on the main hull (both 97% operable, assuming all headings had equal weighting).
- Increasing the size of the T-foil on the amah made only a small difference to the overall operability. Increasing from 2.5 m^2 to 3.5m^2 area on each T-foil increased the overall operability from 90% to 91%, assuming all headings had equal weighting, and in stern quartering seas the operability increased from 86% to 90%. These small increases were not felt sufficient to warrant the expense of the larger size of T-foil.
- Increasing the size of the T-foil on the bow of the main hull from 7m^2 to 13.5m^2 did not appear to warrant the expense involved, as the vertical acceleration at the centre of the passenger cabin was only decreased by approximately 5%
- The effect on ship motion by changing the GM_T value by modifying the waterplane area in way of the amahs was investigated for GM_T values of between 4 and 8 metres. This resulted in a maximum change of about 18% to the Roll angle. The selected GM_T value of 6.0 metres was determined to be adequate, as GM_T was selected on the basis of a slow roll for comfort rather than on a limit for operability.

As a result of this numerical analysis, the bow T-foil with an active flap was sized at 10 m^2 and the two aft fully-actuated T-foils were each sized at 2.5 m^2.

3.4 (b) Manoeuvering

Three auxiliary steering options for course keeping were considered for this trimaran;

- No auxiliary steering fitted
- A pair of steering interceptors fitted to the vessel's main hull transom with deployable surface area of approximately 670mm x 160mm.
- A single Austal Ride Control T-Max System, effectively a 3.25m^2 rudder.

Based on information collected on *Benchijigua Express* a mathematical model was developed in Simulink and MATLAB to analyse the variance between the three options. A representation of the typical course keeping simulation is shown in Figure 5.

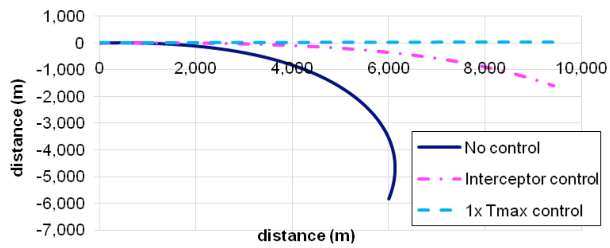

Figure 5: Typical result comparing the course keeping ability of the three options. The conditions in this scenario; Ship speed = 25m/s, wind speed = 5m/s at 30° to Port (from bow).

The T-Max system undoubtedly provided the best course keeping although it suffered from higher drag. This penalty was weighed up against the loss of forward thrust by using the main water jets to maintain course and it was concluded that the T-Max system was the preferred option.

Experiences with *Benchijigua Express* demonstrated a relationship between the vessel's roll and yaw motions – roll-yaw coupling. This was investigated during tank testing with the results indicating that roll-yaw coupling could be reduced compared to *Benchijigua Express* due to the modified hull form and position of the T-Foils.

3.5 DETAILED DESIGN OF THE SWINGING T-FOILS

The swinging T-Foil is a hollow, cast, nickel aluminium bronze, swinging hydrofoil, as shown in Figure 6. The T-Foil actuation mechanism can be considered to be located centrally at the top of the strut.

Figure 6: Transom-mounted T-foils, port and starboard, prior to trials.

3.5 (a) Design Loads and Mechanical Design

The range of actuation was chosen as +/- 10°, however for the purposes of design it was considered to be +/-20° due to possible inflow angles. The foil section was designed as thin as possible consistent with strength to reduce the onset of cavitation. A fence was also added to the strut to prevent ventilation. The dynamic waterline was estimated to range from approximately 2.7m to 3.6m above the baseline of the foil.

The T-Foil was designed to provide an operational lift force of 400 kN at the operating speed and be able to withstand slam pressures of 200 kPa. The design life span was set at 20 years, and fatigue loads were estimated for a projected operational area and schedule.

Finite Element Analysis (FEA) was conducted in ANSYS using 3-D models generated in Inventor. The hydrofoil's skin thickness and webbing details were analysed and modified as required to provide a lightweight yet mechanically sound foil suitable for operation in the desired conditions.

In the event of a failure, the T-Foil was designed to be manually actuated to a neutral position to minimise any influence on the vessel's motion. To simplify the maintenance, the T-Foil was been designed to be removable without needing to slip the vessel.

3.5 (b) Dynamics

The T-Foil's unusually long strut raised concerns relating to vibration induced loads. Consultants were sought to aid in the analysis, focusing on two key sources of potentially destructive unstable vibration modes – high-speed flutter instability and low-frequency resonance.

To assess the likelihood of vibration, a 3-D finite element model was created using lumped-mass approximation with six Degrees of Freedom (DOF) at each node. The structure of the model was validated by comparing the unloaded results for deflection and oscillation frequency against well established data for the vibration of cantilevered beams. The hydrodynamic loading was validated by comparison against known lift curves for NACA foils.

Comparison of the results from the in-vacuo case against the fully loaded case (with speeds of 0-40 m/s) indicated that all modes tend to experience increased hydrodynamic damping with increasing flow rates. At operational speeds it was unlikely that the foil would experience high-speed flutter.

Results of the frequency response curves for harmonic forcing indicated that the foil may be susceptible to some resonance from periodic low-frequency transverse forcing when the vessel was operating at approximately 10-20 knots, with excitation frequencies of approximately 10-25 Hz. In addition the foil was also indicated to be at risk to low-to-moderate frequency vibration in the torsional direction. Upon further consideration of the operating conditions, structural damping and hydrodynamic damping (which was not considered in this model) it was concluded that damage to the foil or hinge block was unlikely.

Post manufacturing resonance testing was performed on the T-Foil with the results validating the analysis.

3.5 (c) Hydraulics

A single custom-designed and built hydraulic cylinder was designed to actuate each T-Foil. The size of the cylinder was governed by the mounting arrangement and maximum swinging angle of the T-Foil, and the forces required to actuate the surface under maximum loading conditions with respect to the designed hydraulic pressure. Due to the location of the T-Foils (externally mounted on the amah transom) it was also necessary to consider buckling of the cylinder under slam load and selecting materials capable of withstanding the harsh environment. The result was a 6.5" bore x 470mm stroke cylinder constructed entirely from 2205 stainless steel.

Based on a designed movement speed of six seconds per period, each swinging T-Foil actuator was supplied with approximately 200 ℓ/min @ 180 bar of constant hydraulic power. In order to respond to instantaneous motions greater than the designed speed, hydraulic accumulators were installed in the system local to each surface that allowed additional short term power.

3.6 CONTROL HARDWARE AND SOFTWARE

A new motion control system was developed simultaneously with the T-Foils providing enhanced features and allowing the controller to be optimised for the slow roll characteristics of the craft.

3.6 (a) Hardware Selection

Several types of hardware were considered for the new Austal control system platform, however this was quickly reduced to a choice of two – National Instruments' CompactRIO Programmable Automation Controller (PAC) utilising LabVIEW software, and Schneider Electric's Modicon Premium Programmable Logic Controller (PLC) utilising Unity Pro software.

Simulation programs representative of functionality typical of the Austal control system were specifically developed to test each platform's ability to process complex algorithms and functions within acceptable timeframes. Both platforms successfully passed all technical requirements with the largest difference between the two platforms being the programming languages.

The National Instruments' LabVIEW software uses a high level graphical programming language that allows for complex mathematical functions, signal processing and control loops to be implemented quickly via in-built function blocks whereas complex functions typically need to be broken down into smaller parts for Schneider Electric's Unity Pro software. Unity Pro however follows IEC 61131 standards and can be more commonly supported by control systems engineers.

Both platforms were suitable for the task but the PLC was selected as Austal Ships has a long standing commercial relationship with Schneider-Electric and already has significant in-house expertise with their Unity Pro software.

3.6 (b) Software Development

The "soft ride" is a major characteristic of trimaran hullforms. To augment this, the controller was designed to slow the vessel motion, both as the vessel heals over and as it comes back upright. The new controller was automated to reduce the amount of human input required, improving performance by reducing the potential for human error in selecting the appropriate settings.

To optimise the reduction of vessel motions a concept was developed that automatically changed the algorithm inputs depending on the roll and pitch angle of the vessel. This allowed the controller to reduce ship motion as deck angles increased and to slow down motions as the natural buoyancy forces right the vessel. At large angles of roll or pitch on the previous trimaran, the main cause of passenger concern was the vessel angle, not acceleration, so at large angles the controller was focused on bringing the vessel upright. As the deck angle reduced, the controller focus was shifted to reducing accelerations, as illustrated in Figure 6.

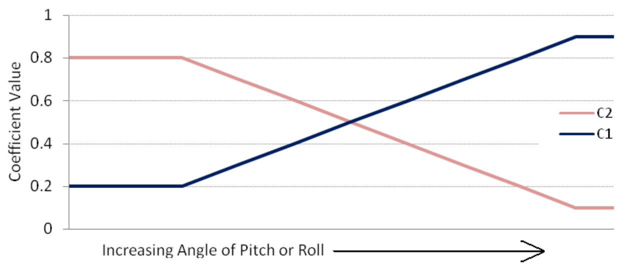

Figure 6: Illustration of bias between Angles (C1) and Rates (C2). Values are indicative only.

The controller was organised such that the values used to define the two functions in Figure 6 of the graph could be easily changed so that the ride control algorithm could be tuned to a particular vessel and the normal operating sea environment.

An additional area of automation of the ride control system was to allow the system to self-determine what motions the system should focus on, either pitch or roll. This automation was achieved by observing the vessel motions, both angles and rates, to determine which mode of motion was causing the most discomfort based on known inherent vessel properties.

During testing this feature proved very successful with the controller quickly and smoothly changing its focus between pitch to roll as the vessel's heading was changed. Further detail is given in Section 3.5 (d).

4 PERFORMANCE ON TRIALS

4.1 TURNING CIRCLES

Turning circles were carried out to both port and starboard and with the ride control in passive mode and also in active mode. The diameters of all of the turns were very similar in all cases, being close to 1000 metres. The aft T-foils acted to keep the vessel close to upright throughout the turn, as illustrated in Figure 8, where the turns with a passive foil resulted in a heel of approximately 4½° and with an active foil the heel reduced to approximately 1½°. The speed in the turns was on average about 2 knots higher for the vessel with an active T-foil compared to the passive mode.

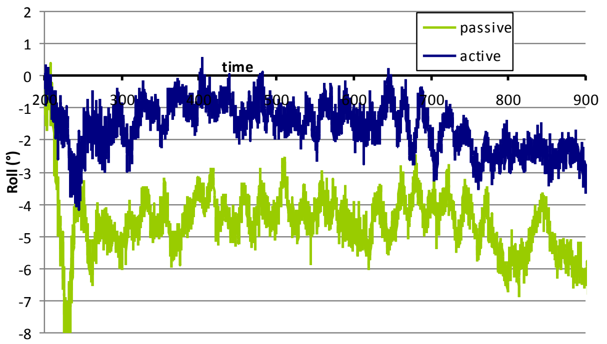

Figure 8a: Heel resulting from a constant rate turn, with aft T-foils passive and active

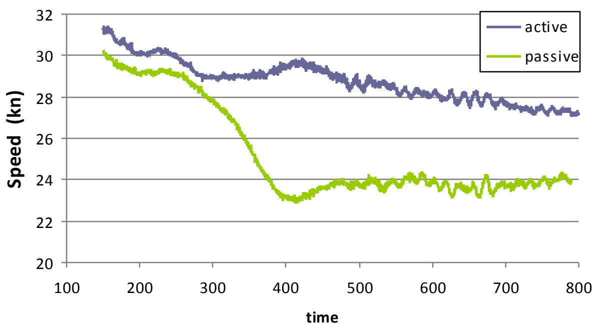

Figure 8b: Speed through a constant rate turn, with aft T-foils passive and active

4.2 COURSE-KEEPING ABILITY

The course keeping ability at high-speeds proved to be excellent, no doubt assisted by the struts associated with the aft-T-foils on the amahs.

4.3 SHIP MOTIONS

The ship motions were analysed in *VERES*, as previously described: further detail is given in Reference [4]. The conditions during Day 16 of trials were:

- Wind generated waves H_S =1.51m
- Swell H_S = 3.32m
- Swell T_1 = 12.4s
- Swell direction 0° to waves
- Short crested seas (assumed spreading 90°)

The accelerations and motions were recorded throughout the trials using a Seatex MRU6 device, supplemented by a Racelogic triaxial GPS system. A comparison of the roll angle measured during trials against the predictions from numerical simulation using *VERES* is illustrated in Figures 9, where the MRU measurement is located at a period of 5.4s and a roll of about 1.2°. Although the values appear to match extremely well it should be noted that the exact wave spectrum during trials was not known, the wave direction could not be ascertained with an accuracy of greater than about 5°, and the amount of wave spreading was not known.

Trials at a later date were also conducted over a range of 30° headings and the roll and pitch angles compared with numerical simulations. These results are illustrated in Figure 10 and demonstrate a close correlation.

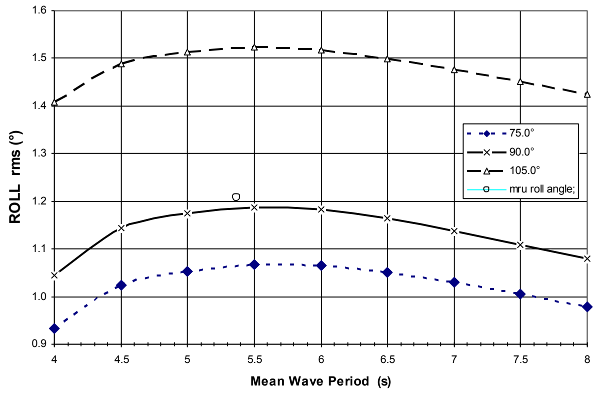

Figure 9: Trials result for Roll in beam seas, H_S = 1.51m with 3.32m Swell, in short crested seas with 90° wave spreading, compared with Veres predictions at three different principal wave directions

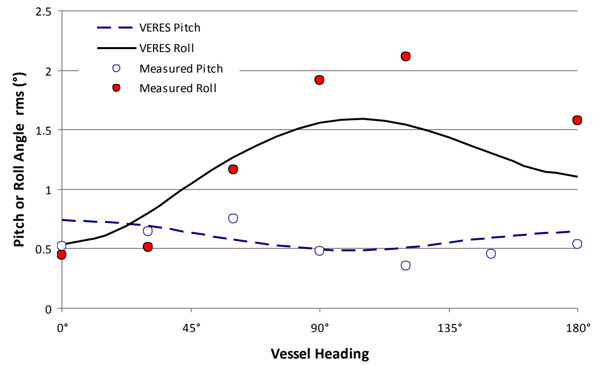

Figure 10: A comparison of roll and pitch angles measured on trials over a range of headings, compared with numerical predictions

Trials were carried out to determine the maximum permitted wave height to ensure compliance with the safety levels described in Annex 3 of the HSC Code, using the procedure outlined in Annex 9. The mandatory two sets of measurements of lateral accelerations were carried out in 0.9 m and 3.8 m significant wave heights, which under the regulation permitted extrapolation to a wave height of 5.7 metres, which equated to an anticipated maximum transverse acceleration of 0.14 g. This value was well below the Safety level 1 value of 0.2 g and far below the maximum permitted safety level 2 value of 0.35 g, indicating that the vessel would have a slow and comfortable motion even in the worst intended conditions.

4.4 CONTROLLER FOR THE RIDE CONTROL SYSTEM

In order to calibrate the automatic pitch-roll weighting equations which formed the basis of the revised ride control, the vessel was trialled over a number of days with different sea conditions. These trials were carried out in two parts, with initially the ship's crew trying various settings for pitch and roll in order to determine what they felt to be the most comfortable ride in those seas, and the values recorded. The automated system was then selected and a comparison made between the two, as reproduced in Figure 11. It was apparent that the automated selection was very effective at determining the "best" weightings, although it should be noted that the results and comparisons are only for a limited set of sea conditions available on the days of trial. Similar trials could easily be carried out in the area of intended operation such as to optimise the weighting coefficients for the wave characteristics for the operational area.

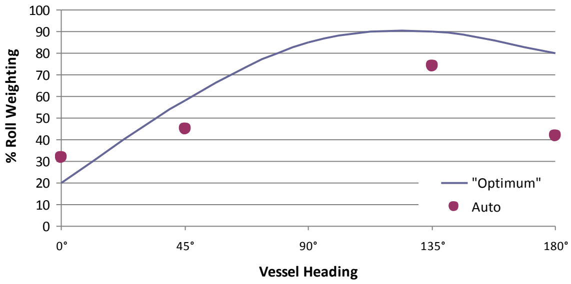

Figure 11: A comparison of manual "optimum performance" settings for roll weighting and the automated selection of settings

5. CONCLUSION

Trimarans provide a long and thin hull solution to achieve low resistance and also provide a platform that is easy to control with underwater foils.

Two large trimarans are successfully operating in service. One as a commercial ferry has been in operation since 2005, and the other as a warship with the US Navy since 2009. Two other warships are also currently under construction. The next generation of design has been evolved from the two previous designs in order to optimize the vessel motion and to provide a controlled slow roll and to reduce pitching.

The approach to the design of this novel craft, outlined at the beginning of this paper, has been validated by the performance of the craft as recently measured during ship trials. The motions of the ship are immediately obvious as being different to other high-speed craft, with low levels of acceleration being evident and as predicted by the use of numerical simulation.

Measurements during ship trials have also justified the methodology by which the swinging T-foils were developed and designed, as well as the selection of foil size. The T-foil has proven to be simple to operate and is rapidly deployed, and provides a considerable amount of force as demonstrated by a reduction in heel angle in a turn by a factor of 4.

The associated software has also demonstrated that control of pitch and roll can be automated with appropriate weighting given such that the maximum reduction in ship motion is selected at all headings, no matter what the wave period.

The ship motion simulation, using Veres software, has been demonstrated to provide excellent prediction of the vessel motion in trials.

Ideas for development of the ride control system for the future include a hinged fully actuated T-foil mounted on the transom of the amahs and having an integral steering capability, permitting the deletion of the T-max rudder and associated reduction in resistance.

6. REFERENCES

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AUTHORS BIOGRAPHY

Tobias Clarke works in the Research and Development department at Austal Ships. He is responsible for the development and testing of new hull forms as well as the trialling of vessels once constructed. He also works on developing and testing the ride control systems and hardware installed on the vessels built. Since the introduction of CFD capabilities into Austal he has been one of the main users of the software.

Tony Armstrong has held the position of Manager of Research & Development at Austal Ships since 1998. He is responsible for new hull concepts and is the pioneer behind the development of the trimaran platform,

having model tested over 30 trimaran concepts since 2002, as well as optimisation of the catamaran platform for minimum resistance. His previous experience includes the position of Director of Design at International Catamaran Designs (Incat Designs) during the development of the first large wavepiercing catamarans (1989-1995). He obtained his Doctorate from the University of New South Wales on the subject of the viscous resistance of catamarans in 2000.

Jonathan Lee holds the position of Motion Control Systems Engineer and is the projects leader for Austal Ride Control's Electrical and Control division. He is one of the original developers of the new Austal ride control system. He joined Austal Ride Control in 2006 shortly after graduating from The University of Western Australia with honours in Mechatronics Engineering.