PROACTIVE SHOCK MITIGATION: REDUCING INJURY AND IMPROVING PERFORMANCE OF CRAFT AND CREW.

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SUMMARY

Dynamic ballast systems have been used for decades by Search and Rescue (SAR) organisations such as the Royal National Lifeboat Association (RNLI), and are proven to reduce vertical acceleration levels. Dynamic ballast can therefore be utilised to reduce the risk of injury onboard High-Speed Craft (HSC), and to improve the effectiveness of crews in performing their assigned tasks.

However, unlike external trim-control systems such as tabs or fins, ballast systems are inherently complicated to retrofit into existing craft, and should therefore be considered from the onset of the design stage. This simulation model has been developed to assist naval architects who may be unfamiliar with the technology. Here the effect of dynamic ballast upon a 13m Rigid Inflatable Boat (RIB) is studied, noting the relation between pure trim adjustment versus the addition of mass, the speed of travel, as well as comparing effects at different hull deadrise angles.

1. INTRODUCTION

Many professional boat crews must, by necessity, operate in rough seas. Rescue services are inherently likely to be called upon when conditions are poor, whilst time-critical military operations cannot be postponed for calmer seas. However, high-speed transit in rough seas can result in significant impact events [1], where the vessel is slammed against the water surface. The nature of the vertical acceleration may change depending on the design of the craft and the shape, size, and frequency of waves [2], but is typically in the form of an angular motion, with the bow of the craft being raised prior to impact. This shock travels throughout the craft, reaching the passengers and crews onboard and subjecting them to pain, potential injury, and fatigue [3]. As well as the risk to humans onboard, extreme levels of impact can put the entire craft at risk of structural failure [4].

1.1 EFFECTS OF IMPACT

The most commonly reported injuries are to the neck, lower back, shoulders, and knees [1], and there is also evidence for neurological damage caused by frequent high-level impacts. Crews also report that these conditions are detrimental to mental acuity and physical capability [5]; in a retroactive study [6] of combat crewmen, 70% felt that they had experienced an impaired capacity to perform their assigned roles due to impact and Whole Body Vibration (WBV) exposure.

Whilst these injuries may be expected during operations in rough seas, the risk remains even in calmer conditions. One study [7] of HSC injuries reported that 61.5% of “deck-slap” injuries occurred during transit in calm seas, due to the reduced level of caution demonstrated by the helm.

Given that HSC transits can be the initial stage of critical military [8] or lifesaving operations, it is imperative to reduce these injurious and performance-limiting effects as much as possible.

1.2 MITIGATING IMPACT

Much of the existing focus on the protection of crews against slamming has centred on minimising the transfer of shock from the craft to those onboard, with shock-mitigating suspension seating now relatively commonplace onboard many professionally operated HSC. Whilst suspension seats have proven an effective option for reducing shock loads to individual occupants [9], a multi-level holistic approach to shock mitigation is required [10] to protect crews against injury. Examples of potential methods are listed in Table 1.

Table 1: Shock mitigation techniques

Category	Method
Design stage	Human-factored design Hull form
Behavioural	Specialist training Intelligent guidance systems Governmental guidance and regulation
Pitching reduction	Dynamic ballast Trim tabs Interceptor fins
Personal protection	Suspension seating Exoskeletal support

Whilst each method of shock mitigation brings its own merits to a combined overall approach, a specific advantage of the targeted reduction of pitching motions is that the benefits are applied to all occupants, as well as the craft itself. Decisions can be made during the design stage in order to optimise hull form for the intended application; for example, higher deadrise angles typically result in reduced levels of vertical acceleration at the bow [11], but experience higher running resistance. Designers may also reduce pitching motions through the addition of trim control systems such as trim tabs, interceptors, or dynamic ballast.

1.3 DYNAMIC BALLAST

The use of dynamic ballast systems on HSC originated in offshore powerboat racing, as a means of adjusting trim angle without compromising speed through the use of drag-creating [12] external appendages such as trim tabs, and has since been adopted by SAR organisations for use in rough-water operations. By taking on sea water into a forward ballast tank as required, craft displacement can be increased and Longitudinal Centre of Gravity (LCG) shifted forwards in order to increase inertial resistance, thereby reducing slamming. Tanks are most commonly located at the bow of the boat; as the largest accelerations typically occur there, and positioning the additional mass as far forwards as possible makes the most of the effective leverage.

Sea trials of a 7.5m lifeboat demonstrated that a ballast tank equal to 12% of the craft's original displacement, resulted in an approximately 50% reduction of average vertical acceleration levels, with an approximately 70% reduction of peak acceleration levels [13].

Dynamic ballast is also proven to be effective on larger craft; in one study [14], simulations compared a 24m aluminium naval patrol craft against an identical design featuring a lightweight carbon fibre hull construction. The structural mass of the carbon craft was approximately 50% lower than the aluminium version, with a total displacement reduction of 18%, corresponding to a 15% reduction in fuel consumption and CO2 emissions. However, the lower displacement of the carbon craft also meant that vertical acceleration levels were increased by 20% compared to the heavier aluminium version. The addition of a forward ballast tank on the carbon craft, equal to 4% of the total displacement, conversely reduced vertical accelerations by approximately 30%, resulting in improved rough water performance compared to the aluminium craft. It should be noted however that aluminium and carbon fibre have very different structural properties and behaviours; the above example relates purely to the range of vertical acceleration experienced at the bow.

There are clear benefits to the use of dynamic ballast on HSC, however the internal nature of the system makes it inherently more complicated to retrofit onto an existing craft than external systems such as trim tabs. It is therefore required that naval architects consider the use of ballast from the early design stage.

2. DYNAMIC MODEL

The simulation model of the dynamic ballast system has been developed to assist with performance estimations and feasibility studies during the design stage, in a similar manner to the performance prediction calculations provided by propulsion systems manufacturers. The simulation model is modular, and consists of three blocks:

- Ballast tank and scoop dynamics
- Smooth water dynamics of hull
- Rough water performance of hull

2.1 LIMITATIONS

The model is intended to provide insights during the early design stages when only limited amounts of craft data are available, but critical decisions on how best to meet performance requirements are being made. Therefore, the model remains a simplification of a complex hydrodynamic problem, with empirical formulas that have strict boundaries of applicability. The vertical acceleration model is based on the established Savitsky & Brown model, which has also been adopted by several classification societies such as DNV and RINA.

Due to the complexity of the subject, the validation and expansion of the dynamic model is ongoing. The reporting of HSC vertical accelerations currently lacks a standardised form [15], which makes the comparison of data from different sources often impossible and can introduce significant errors, which can complicate the validation process. Another potential source of error lies in difficulty to predict dynamic trim angle which mirrors vertical acceleration in rough water [16]. It must therefore be noted that this simulation model will be continually developed as more data is made available and validation is made possible.

2.2. INPUTS AND OUTPUTS

The most significant inputs and outputs of the model are listed in Table 2.

Table 2: Dynamic model inputs and outputs

Category	Inputs	Outputs
Boat	Length of waterline Chine beam Deadrise Mass (loaded) LCG Forward velocity	Mass flow rate to/from tank Average vertical accelerations Dynamic trim angle Hull resistance
Ballast system	Tank cross-sectional area Tank height Vertical location of tank Longitudinal location of tank	
Environmental conditions	Significant wave height	

Although many HSC manufacturers make technical specifications of their craft publicly available, there is no standardised format; for example, some may provide an estimation of total weight including fuel and engines, whilst others may provide only lightship data with an indication of maximum engine horsepower. Different variations to measuring beam, LCG, and deadrise exist, which complicates the selection of input parameters for the simulation. Therefore, for the future validation of this model, a questionnaire has been developed in order to consistently acquire appropriate data for all required inputs.

2.3. SIMULATION

For testing purposes, an existing model 13m fibreglass hulled RIB was selected; the model was selected based on the suitability of available technical data, the stated intended usage of the craft, and as a representative midpoint of the normal size range for applicable craft.

For these simulations, the ballast tank was positioned as far forwards as possible in order to replicate an integrated bow tank structure. The tank utilises baffles to minimise potential instability caused by the Free-Surface Effect (FSE) when the tank is only partially filled, so accounting for FSE instability is included in this simulation. An allowance of mass was included to account for fuel and passengers, and a tank volume of 12% of total loaded mass was selected based on previous studies [13].

The speed range was selected so that it covers pre-planing, planing hump, and pure planing speeds. The speeds were non-dimensionised to beam-based Froude numbers (FNB) to allow for easy comparison. The input parameters for this simulation are outlined in Table 3.

Table 3: Simulation parameters

Parameter	**Unit**	**Simulation 1**	**Simulation 2**
Length of waterline	m	12.2	12.2
Chine beam	m	2.9	2.9
Deadrise	°	22	20, 22.5, 25
Mass (loaded, excl ballast)	kg	10,000	10,000
LCG (excl. ballast)	m	4.27	4.27
Ballast tank volume	m^3	0…1.200	0…1.200
Ballast tank longitudinal location (from transom)	m	12.2	12.2
Significant wave height, H1/3	m	1	1
Beam-based Froude number	-	1.5, 2.0, 3.0	1.5
Forward velocity	m/s	8,10.7,16	8
Forward velocity	kts	15.6, 20.1, 31	15.6

Two simulation runs were made for this test of the model; in the first the speed was varied, whilst in the second the deadrise angle of the hull was varied.

3. RESULTS

Figure 1 shows the results of Simulation 1; the reduction in vertical accelerations (Acc_z) has been plotted against FNB and ballast tank volume (V_tank). To have a better understanding of the model’s sensitivity, the effect of dynamic trim angle was plotted separately (upper surface) from the combined effect of trim angle and ballast mass (lower surface).

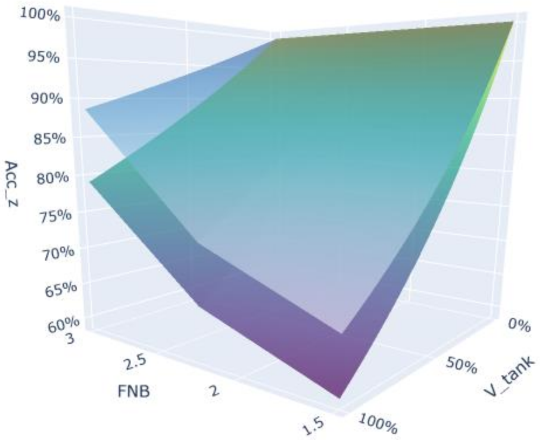

Figure 1: Simulation results, Beam-based Froude number

The increase in tank volume corresponds with a 22-43% decrease in vertical acceleration levels across different speeds.

Figure 2 shows the result of simulation 2, with the reduction in vertical acceleration levels (Acc_z) at the bow plotted against the deadrise angle (Beta) and ballast tank volume (V_tank).

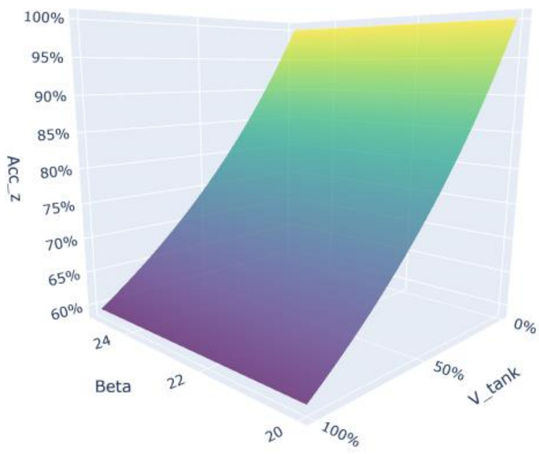

Figure 2: Simulation results, deadrise angle

4. DISCUSSION

4.1. MASS EFFECT

Due to the increased inertial resistance generated by the additional mass, the lower surface demonstrates consistently lower vertical acceleration levels compared to the upper surface showing the effect of trim only. At higher speeds, this difference as a proportion of overall potential acceleration reduction increases. For example, at FNB = 1.5 the effect of trim angle accounted for 75% of the total reduction of vertical acceleration. In other words, the effect of added mass accounted for 25% of the reduction in vertical accelerations.

However, as the speed was increased to FNB = 3, the effect of trim on vertical accelerations reduced. Here the trim and added mass played equal parts in reducing the vertical accelerations, suggesting that the "mass effect" gains importance as speed increases. The positive correlation between speed and the effectiveness of increasing mass makes sense, as the forces resisting the change of trim angle increase with speed.

This also emphasizes the significance of the dynamic trim angle in reducing vertical accelerations. By adjusting the LCG or generating additional lift, the dynamic trim angle can be altered. To simplify the comparison, we can consider the impact of extra lift as a shift in effective LCG (LCGe).

The LCGe depends on the extra lift, which can be attained by employing external devices like trim tabs and interceptor fins. The shift in the LCG on the other hand is influenced by the distribution of mass, which can be achieved through the utilization of a dynamic ballast system.

The shift in LCG is hence not affected by the speed of the craft or environmental conditions, and remains a constant effect upon the craft while the system is engaged. However, the magnitude of the LCGe varies with craft speed and is susceptible to disturbances like flow turbulence and water aeration, making it less reliable in heavy seas.

4.2. DEADRISE

Boats with steeper deadrise angles experience lower vertical accelerations, but typically have higher running resistance [11] resulting in higher operating costs. Conversely, boats with shallower deadrise angles are more efficient in calm water, but can experience high levels of impact in heavy seas. However, as highlighted in Figure 2, the model suggests that shifting LCG forward with ballast in the bow can reduce vertical accelerations on a shallow deadrise craft, to levels even below that of a similar craft with a steeper deadrise.

4.3 SHOCK MITIGATION

The reduction in vertical acceleration peak levels allows for synergisation with the use of suspension seating. When subjected to large accelerations which exceed the maximum shock displacement allowed by the seat’s suspension mechanism, some designs of seat can bottom-out. This sudden stop amplifies rather than dampens the levels of shock to which the occupant is exposed [17]; using ballast to reduce the peak accelerations experienced by the craft as a whole [13], assists the suspension seat in operating as intended.

It is significant that the accelerations are reduced at the bow, because subject to the deck layout and passenger positioning, impact related injuries can be more common at the bow of the boat [7].

4.4 FURTHER STUDY

Further study is required to address a range of questions that were not covered in this simulation, and to identify potential routes for optimisation. The added mass of 12% was selected based on previous studies, but it warrants further exploration to weigh the balance between having larger amounts of ballast in order to achieve greater effects, against the amount of below-deck space taken up by the tank. The potential reduction in speed from greater amounts of ballast should also be explored.

In some cases, it may not be practical or possible to position the tank directly in the bow of the boat, so the effect of ballast positioned closer to the LCG should be examined.

Studies have shown that shock from sudden roll motions as the result of vertical impact can be a source of pain and discomfort [18], whilst the increase of mass has been proven to dampen such roll motions as well as the vertical pitching motions [19]. Further study could examine whether these roll movements could also be minimised through the use of dynamic ballast, as indicated by the results of Townsend et al [13], showing reductions in acceleration across each axis.

5. CONCLUSIONS

It must be stressed that the dynamic model requires validation using real world sea-trial testing. Given that this simulation model is a simplification of a complex issue, results should be taken with a degree of caution. However, these initial findings offer at least an indication of the benefits of dynamic ballast on high-speed craft for trim control and shock mitigation, as well as the potential for new avenues of design considerations.

The results of the above simulations, coupled with previous findings on dynamic ballast by Townsend et al [13] and Garme et al [14], offer interesting prospects for HSC designs. There is a clear reduction in vertical acceleration levels through the use of dynamic ballast, which remains effective across a variety of craft designs and operating conditions. Dynamic ballast could therefore potentially help designers to bridge the gap between craft optimised for high-speed calm sea transit, and those designed for rough sea operations.

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