TECHNICAL NOTE

HYDROELASTIC INFLATABLE BOATS: RELEVANT LITERATURE AND NEW DESIGN CONSIDERATIONS

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SUMMARY

Inflatable boats are considerably more flexible than conventional metal or composite vessels. The RNLI have developed an inflatable boat, the IB1, with improved performance which has been attributed to its flexibility or hydroelasticity. Current design methodologies for planing vessels predict the performance assuming it is rigid. Designing an entirely hydroelastic boat presents completely new design challenges and will require new design methodologies in the future. This paper considers how to approach an entirely hydroelastic planing vessel and how to divide the boat into practical problems. A design approach taking into account hydroelasticity could potentially improve the performance further by decreasing boat motions, reducing added resistance in waves and minimising the slamming accelerations.

This paper reviews the literature relevant to rigid inflatable and inflatable boats and shows the construction of the IB1. The hydroelastic design problem is broken down into three main hydroelastic events: global hydroelasticity, hydroelastic planing surfaces and hydroelastic slamming. Each event is defined, the relevant literature is reviewed and the possible advantages are discussed. A design approach is suggested using a hydroelastic design cycle. The hydrodynamic problem of interacting sponsons is briefly discussed.

NOMENCLATURE

l	Length of cantilever beam (m)
p	Internal pressure (N m^{-2})
P	Load at tip (N)
R	Cylinder radius (m)
IB	Inflatable boat
IB1	Inshore boat 1
RIB	Rigid inflatable boat
RNLI	Royal national lifeboat institution
VDV	Vibration dosage value (m s$^{-1.75}$)

1. INTRODUCTION

This project is supported and partially funded by the Royal National Lifeboat Institution (RNLI). The RNLI is a charity that aims to “save lives at sea” all around the coasts of the UK and Ireland. They design, build, maintain and operate a range of vessels for almost any situation and they own the largest fleet of inflatable boats (IBs) and rigid inflatable boats (RIBs) in the UK. This project will focus on the vessels used in littoral waters, primarily the D class inshore inflatable lifeboat also known as the Inshore Boat 1 (IB1), see figure 1.

The IB1 is a five metre inflatable lifeboat which is capable of achieving 25 knots in seas associated with a Beaufort Force 2 and can continue to operate safely up to and beyond seas associated with a Beaufort Force 5. It is powered by a 50 horse power outboard engine and weighs a total of 436 kg (all equipment except crew). It usually has three crew on board and is able to take a minimum of two casualties or one in the prone position. The RNLI use the IB1 in littoral waters where the water can be very shallow and there can be large steep breaking waves caused by the reducing water depth near the shore. The main difference between the IB1 and conventional high speed vessels or RIBs is its flexibility. The main material used within the IB1 is a rubber coated fabric which allows the IB1 to deform considerably. This deformation of the main components, such as the hull and sponsons, affects the fluid flow and this causes a hydroelastic interaction.

Figure 1: In the foreground shows the IB1 and in the background shows the Atlantic 85 RIB [1]

In 1998 the RNLI performed a feasibility study of the EA16 (the previous version of the D Class) and compared it to seven commercially available vessels that included; RIBs, pure IBs or a combination of both [1]. It was found that the EA16 gave the best overall performance and therefore the RNLI have been improving its design and performance through either designers experience or trial and error to achieve the optimum boat. Anecdotal evidence from the feedback of the crew has verified that the flexibility or hydroelasticity within the IB1 improves the performance, especially in waves and surf.

Compared with larger boats and ships, there is relatively little scientific understanding about the performance of RIBs and considerably less understanding about the performance of IBs. Their design is usually based on the experience of the designer or trial and error. There has been minimal research into the performance of RIBs and IBs for a number of reasons. One possible reason is that these vessels are primarily used for search and rescue or military purposes so the vessel has no direct profit making abilities. They are also manufactured in low numbers so there is minimal drive to invest capital in research and development.

The IB1 is unique when compared to almost every other planing vessel due to its highly flexible structure. The longitudinal stiffness is considerably less plus it has specific deck joints to provide control over the longitudinal deformation. The longitudinal bending and torsional twisting is called the global hydroelasticity. The planing surface is constructed from fabric allowing excessive deformation and this is called a hydroelastic planing surface. The fabric hull also causes a hydroelastic slam when a transverse slice of the boat impacts the free surface.

The high flexibility means the importance of hydroelasticity is more pronounced and there is a new area of hydroelasticity which is not commonly considered. This new and novel area is the hydroelastic planing surface. The hydroelastic planing surface links the hydroelastic slamming to the global hydroelasticity, through strip theory. Strip theory uses transverse slices of the vessel to predict the planing performance. So hydroelastic slams are the transverse strips used to predict the hydroelastic planing performance. Then the hydroelastic planing performance is used to predict the global hydroelasticity in waves. This means that all three areas of hydroelasticity need to be designed together. This leads to the question: how do you investigate a planing vessel that is entirely hydroelastic?

Currently hydroelasticity is used principally to calculate the stresses and strains in the structure, Price et al. [3] and Hirdaros and Temarel [4], or occasionally to study its effects on boat motion, Hirdaris and Temarel [4], Santos et al. [5] and Senjanovic et al. [6]. The design of the IB1 allows the hydroelasticity within the boat to be adjusted to affect the boat performance in many ways. Once sufficient knowledge is gained the boat can be tuned to optimise the boat performance. Hydroelasticity may affect the boat performance in the following ways:

- Boat motions and hence human exposure to vibrations
- Forward speed
- Added resistance in waves
- Slamming accelerations
- Stability when stationary

2. AIMS

The first aim of this paper is to provide a review of the current level of knowledge for these types of vessels. A review of the experimental and computational work performed on RIBs and IBs is provided.

The second aim of the paper is to divide an entirely hydroelastic planing vessel into manageable hydroelastic problems. The three main hydroelastic problems (hydroelastic slamming, hydroelastic planing surfaces and global hydroelasticity) are defined and the relevant literature is reviewed. The potential advantages from each hydroelastic event are discussed.

The third aim is to demonstrate to the research/academic community that hydroelastic boats could be designed to change their performance using parameters that are currently not considered in the design process of conventional vessels.

3. RIB AND IB LITERATURE REVIEW

The first inflatable boat manufacturer was Zodiac and they started in 1936, Williams [7]. The RNLI first introduced the D-class inflatable lifeboat in 1963 after extensive trials. In 1964 at Atlantic College in Wales the first rigid hull was glued to an inflatable boat to form the first RIB, Williams [7]. In 1972 the RNLI launched the Atlantic 21, their first RIB. Although these types of vessels have been around for many years there has still been little research into their performance. In 1981, 1998 and 2005 three international conferences were held in the UK to discuss the design and development of RIBs, [8, 9 and 10]. However most of the evidence was anecdotal and there was little scientific proof using experimental or numerical methods. The topics covered included: history, development, construction techniques, propulsion, problems with model test [57], self-righting issues, example boats, safety, influence of the helmsmen, electronics and equipment.

Dand [11 - 13] performed a number of experiments into the performance of the IB1 and measured the resistance and sea keeping performance of the boat at model scale and full scale. Austen and Fogarty [14] documented the development of the IB1 as new materials and construction techniques were being used. When the IB1 was introduced into service it suffered from performance problems due to the fabric floor, ventilation and cavitation so Dand et al. [15] used a careful trial and error process to restore the speed from 20 to 25 knots.

Haiping et al. [16] undertook experiments into the effect of sponson type on seakeeping performance. It was found that inflatable sponsons had lower response amplitude operators in heave and pitch than foam sponsons in both load conditions. This suggests flexible sponsons improve the ride comfort and seakeeping performance. A computational model of a RIB has been constructed by Lewis et al. [17]. Although the results looked promising the numerical model over-predicted the boat motions when compared to experimental results. Townsend et al. [18, 19] performed a multitude of experiments to characterise the seakeeping performance of a RNLI Atlantic 75 RIB. In [18] they studied the influences of speed, ballast, wave height, encounter frequency, and tube pressure on the boats motions of the Atlantic 75.

4. DESIGN OF THE IB1

It is important to understand the construction of an IB because it will demonstrate how the craft is able to deform. Figure 2 shows the main components within the IB1. The design of IBs does vary depending on their operational requirements, component materials and construction techniques.

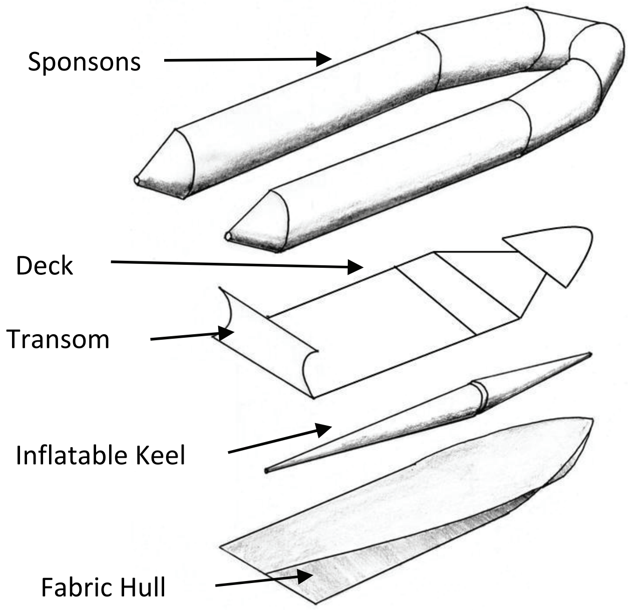

Figure 2: Main components of the IB1

Sponsons - these are the inflatable tubes that surround the boat. They are constructed from Hypalon®/Neoprene coated polyester fabrics and they are inflated to a pressure of 206 mbar (3 psi).

Deck - this is the stiffest structural component of the boat made from a composite sandwich panel. The deck is sectioned into four parts (plus the transom) to intentionally allow flexibility and each deck joint has its own stiffness due to the type of joint. The transom and forward deck section are bonded to the sponson but the other deck sections are slotted into place.

Inflatable keel - this is a tapered inflatable tube that is attached to the centreline of the fabric hull. It is constructed from Hypalon®/Neoprene coated polyester fabrics and is inflated to a pressure of 224 mbar (3.25 psi).

Fabric hull - this is a fabric sheet, constructed from two sheets of Hypalon®/Neoprene coated polyester fabrics, that is attached to the sponsons and transom and pulled taught over the keel.

5. GLOBAL HYDROELASTICITY

5.1 PROBLEM DEFINITION

This section investigates the global hydroelasticity of an IB by viewing the boat as a whole and studying the longitudinal bending and torsional twisting vibrations that exist. It has been observed that as the IB1 passes over an oblique wave the deck bends and twists which provides a smoother ride. This dynamic bending and twisting response is similar to the theories presented by Bishop and Price [20] which could be regarded as conventional hydroelastic theories. The flexibility of the boat will affect the wave induced dynamic response of the vessel which in turn affects the boat motion.

Figure 3 shows how global hydroelasticity can reduce the vertical motions of a deformable vessel. In conventional vessels there is a coupled interaction between the heave and pitch as a vessel "see-saws" over a wave; however, this interaction will change if the boat is able to bend over the wave. The first advantage of this is reduced boat motions leading to improved ride quality. A reduction of the boat motion means that less energy from the propulsion device is absorbed through vertical motion, which reduces the added resistance in waves. This allows either a higher top speed to be achieved or a smaller, lighter, propulsion device to be fitted. The final advantage is that the boat will be more stable, in pitch and heave, when stationary because the pitching motions will be reduced.

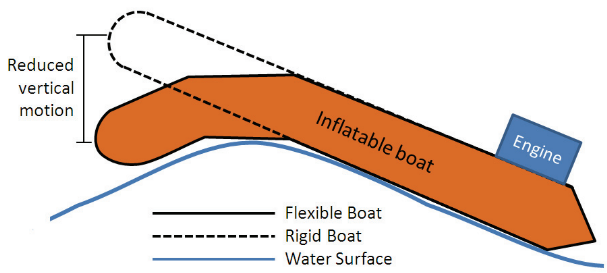

Figure 3: Reducing vertical motions through global hydroelasticity

An inflatable boat has many inter-connected parameters that will affect the global vibrations which include; deck properties (material properties and thickness), deck joints (number, position and stiffness), sponson and keel properties (material properties and internal pressures), fabric hull properties (material properties and pre-tensioned stresses), mass (centre of gravity and inertia) and construction technique. A static deflection experiment was performed by the authors and it was found that the dominant parameters in the deflection of the boat are the number, position and stiffness of the deck joints.

4.2 LITERATURE REVIEW

4.2 (a) Global Hydroelastic

Global hydroelasticity has been studied by many authors starting with the work of Bishop and Price [20]. Bishop and Price developed theories to describe symmetric and anti-symmetric hydroelasticity of ships, but these ships were displacement vessels and not planing vessels. There are numerical models capable of predicting the vertical motions and wave loads on a high speed craft, such as Santos et al. [5] and Chiu and Fujino [21]. Santos et al. [5] modelled a fast patrol boat which had a planing hull form, but it is noted that the approach used was not suitable for planing vessels. They found large differences between the full scale measurements and the numerical model results. To our knowledge no numerical model has yet been validated for a hydroelastic planing vessel.

The IB1 has distinct deck joints to allow the boat to hinge in certain points. These deck joints will affect the conventional theories of global hydroelasticity. Newman [22] developed an analytical method to predict the motions of a hinged barge. Hamamoto et al. [23] used a 3D coupled finite element method-boundary element method model to predict the motion of module linked large floating structures.

4.2 (b) Inflatable Cylinders

The stiffness properties of inflatable tubes and boundary tensioned membranes (the fabric hull) are not currently considered in hydroelastic models. Early work in the deformation of inflatable cylindrical beams started with Comer and Levy [24] by comparing them to an Euler-Bernoulli beam. The most recent and relevant work was performed by Wielgosz et al. [25] by using Timoshenko beam theory to account for the shear deformation. A finite element model was made using a stiffness matrix to include internal pressure. Veldman et al. [26] highlighted the importance of using the correct modelling theory; membrane or thin-shell theory. It would be expected that a very thin membrane would correlate better with membrane theory than thin-shell theory. However, [26] found better agreement using thin-shell theory than membrane theory even though the membrane was only 60 nanometres thick. It has not yet been established which theory should be used for Hypalon®/Neoprene coated polyester fabrics but this is a direction of research for the authors.

Leonard, Brooks and McComb [27] derived an equation for the maximum tip loading capabilities of an inflatable cylinder acting as a cantilever, see equation 1. This simply shows that the loading capabilities of inflatable cylinders are proportional to the internal pressure (p).

Equation 1: $P = \pi p R^3 / l$

5. HYDROELASTIC PLANING SURFACE

5.1 PROBLEM DEFINITION

The planing surface of IBs is normally constructed from fabric which has significantly less out-of-plane bending stiffness than conventional metal or composite hulls. This will allow the planing surface to deform considerably under different loading conditions, see figure 4. The problem is to find the shape of the fabric when it is in steady-state planing and the effect of this deformation on the planing performance. The parameters of a fabric hull are material properties and the pre-tensioned stresses. These parameters define the out-of-plane bending stiffness of a fabric therefore as they are increased the material becomes stiffer and comparable to a conventional planing surface. A better understanding of a hydroelastic planing surface could lead to an increase in forward speed.

Figure 4: Hull deformation of the IB1 at 19.4 knots from underwater [15]

Experiments by Dand [11, 12] were performed on an EA16 D Class at full scale and model scale to measure the resistance, sinkage and trim. The full scale boat was flexible and the fabric hull was able to deform but the scale model was rigid. The comparison of total resistance, see figure 5, showed that the full scale flexible boat had slightly higher resistance than the rigid scaled model. Dand et al. [15] attributed this to the change in trim angle due to the fabric hull deforming and causing a concave camber at the aft end of the hull. They also found an instability when the boat was accelerating on flat water which was described as a "pressure wave" slowly passing under the boat. It caused a "pulsing" motion primarily in pitch and heave. Whether the deformation was static or dynamic is unknown.

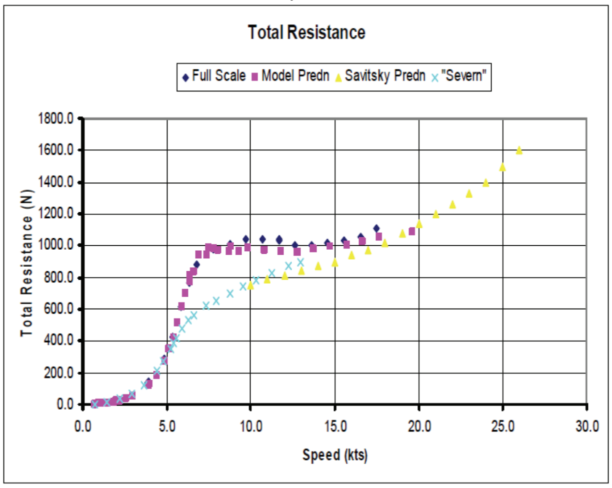

Figure 5: Comparison of the predicted and measured resistance of the EA16 D Class [15]

The first limitation is the “pulsing” motion instability found in the IB1. One hypothesis is that the reduced out-of-plane bending stiffness of the hull allowed the concave camber to form. This causes the pre-tensioned stresses in the fabric to change as the camber forms and also results in a change in the hydrodynamic forces on the hull. As the fabric stresses change, the deformation moves aft. The deformation causes a change in hydrodynamics which gives the operator the feeling of this “pressure wave”. It has also been reported that as this “pressure wave” passes under the hull the sponsons can be seen to deflect which indicates high forces and fabric movement. When this deformation reaches the transom the pressure is released and the cycle begins again. This motion is only found on flat water; waves cause the cycle to be broken. So there is a limitation in the minimum out-of-plane bending stiffness of the fabric hull to ensure this instability does not occur and this requires quantification. This belief was confirmed through trial and error when the EA16 was developed into the IB1. During the redesign it was found that the fabric had been permanently deformed and low quality control during construction led to a reduction in fabric tension. Once this had been taken into account and the fabric tension was increased the pulsing motion disappeared.

5.2 LITERATURE REVIEW

The most relevant literature to this problem is an analytical model developed by Makasyeyev [28] to describe the planing performance of a 2D planing elastic plate. However this model requires validation and the structural domain deals with conventional materials not membranes or fabrics.

No literature directly related to a membrane planing surface has been found. However this fluid structure interaction could be compared with the aeroelasticity of a membrane aerofoil, such as sails and membrane wings. Newman [29] noted skin friction can change the membrane tension and in an inviscid flow it is constant. A strong coupling between the frequency of the membrane oscillations and vortex shedding frequency has been shown by Song et al. [30], Rojratsirikul [31] and Gordnier [32]. Gordnier [32] importantly showed that the Reynolds’ Number caused the motion of the membrane aerofoil to change from a standing wave vibration to a dynamic vibration similar to travelling waves. None of the afore-mentioned literature contains a free surface which is vital for the planing fluid forces.

It is of interest to note that many new tender-boat designs now employ drop stitch technology for the hull. Drop-stitch technology involves two layers of fabric that are sealed together at the edges. Then threads are weaved perpendicular to the layers of fabric to control the shape when inflated, see figure 6. When the two layers are inflated it forms a stiff panel that could be compared to a composite sandwich panel, Bagnell [33].


Figure 6: Drop stitch technology [54]

6. HYDROELASTIC SLAMMING

6.1 PROBLEM DEFINITION

The problem addressed within this section is regarding the effect of hydroelasticity on the loads and accelerations of a 2D wedge vertically impacting a free surface. An IB has three main flexible components in the vertical direction which are the fabric hull, the inflatable sponsons and the inflatable keel, see figure 7. In reality these three components act together and will affect the response of each other. However, for an initial investigation each can be studied individually.

By considering a slamming event as hydroelastic it allows the possibility of changing the impact characteristics. The main characteristics that can be changed, from a boat motion perspective, are the peak acceleration and impact duration. It will also affect the structural loading but this paper will not explore that side of the problem, see Faltinsen [34] for more details. The new parameters for the hull are fabric material properties and pre-tensioned stresses and the new parameters for the inflatable keel and sponsons are material properties and internal pressure. Note that changing the internal pressure is the same as changing the pre-tensioned stresses. The other important variables are impact velocity, deadrise angle and inertia. A simple hull wedge impact was investigated by Townsend et al. [35] to study possible methods of reducing the vertical acceleration on high speed craft. Hull stiffness was reduced from 69 GPa (aluminium) to 6.9 GPa to investigate the effect of intentionally reducing the hull stiffness. It was found to have minimal effect on acceleration but it is anticipated that the fabric will have a significantly lower equivalent stiffness which may amplify the effect on acceleration.

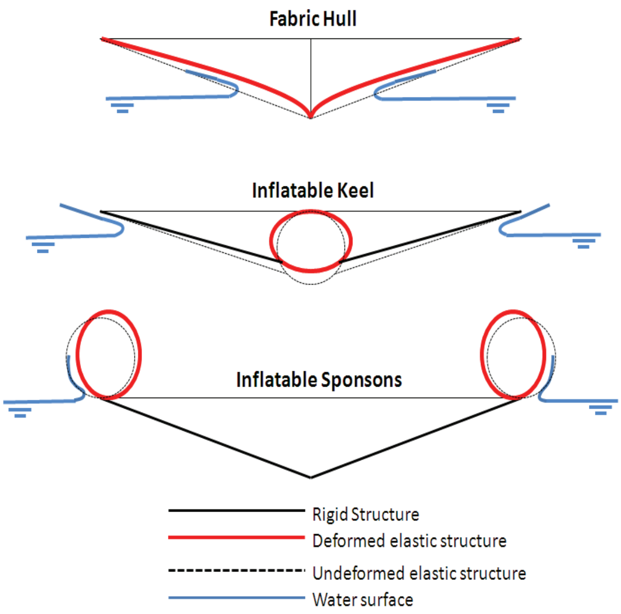

Figure 7: The flexible components within a vertically impacting IB

It has been proposed but not validated by many authors including Natzijl [36] and Pike [37] that sponsons absorb energy during slamming motions. Townsend [38] did investigate this concept but the internal pressure reduction was shown to have no effect. It is worth noting that the Atlantic 85 investigated by Townsend [38] had a hull shape which caused the sponsons rarely to come into contact with the water which is not the case for the IB1. The experiment proposed for the wedge sections with sponsons will answer this question and allow an investigation into the effect of material properties and internal pressure. Other variables that will affect the amount of energy absorbed by the sponsons include; sponson diameter, sponson overhang and sponson attachment.

6.2 LITERATURE REVIEW

Faltinsen et al. [39] provides a good review of this problem and discusses the challenges within it. Here is a list of particular effects that may require consideration: gravity, viscosity, air cushions, air pockets, air to bubble generation, water compressibility, air compressibility, flow separation and membrane behaviour.

Gravity can normally be neglected in this problem, Faltinsen et al. [39]. Viscosity is also commonly neglected but this could affect flow separation when there is not a sharp corner, which will be discussed later, Faltinsen et al. [39]. Air cushions and air compressibility were initially ignored but Bereznitski [40] showed the importance of including them, especially at low deadrise angles. Air pockets can occur when the structure is very flexible because the fabric hull can deform vertical upwards, as shown in figure 8. Faltinsen et al. [39] noted that the breakdown of air cushions into bubbles requires better understanding and the effect of this is unknown. Flow separation is another consideration and this can be described when there is a hard chine but Faltinsen [41] stated the round bilge flow separation is difficult to handle and here viscosity may need to be included. Finally the membrane behaviour is significantly different from that of conventional solids with nonlinear behaviour due to the interaction of the weave and weft, Lewis [42].

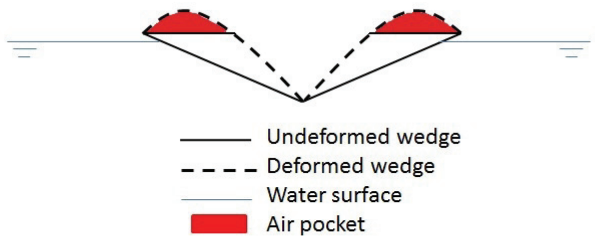

Figure 8: Air pocket formation

Faltinsen [34] divided this problem into two time scales. The initial time scale is that of the structural inertia phases where the large hydrodynamic forces lead to large accelerations of a small structural mass. This phase is very short compared to the second time scale. The second scale is that of the free vibrations phase and is the highest wetted natural period of the structure. The behaviour is that of the free elastic vibrations of the structure with the initial conditions obtained from the first phase. The maximum stresses occur in the free vibration phase. Faltinsen [43] discusses the importance of hydroelasticity as a ratio between the first period of natural vibration of a wet beam and the duration of the impact. It is quantified in terms of nondimensionalised parameters. Bereznitski [40] uses the same ratio except that it uses the natural vibrations of a dry beam. Bereznitski [40] says that if the ratio is greater than two then hydroelasticity does not play a significant role. Increasing either the material properties or pre-tensioned stresses in the fabric will alter the period of vibration therefore affecting the importance of hydroelasticity.

$$Ratio = \frac{Duration\ of\ Impact}{Period\ of\ Vibration}$$

Cooper et al. [44] were the first to study the deformation of a flexible membrane wedge impacting a free surface. It was found that during the free vibration phase the membrane vibrated at frequencies very near to its natural frequency, which depended on the pre-tensioned stresses.

6.3 CRITIQUE OF MODELLING METHODS

The problem of water entry of 2D bodies started in a purely hydrodynamic sense for a rigid body with the work of Wagner [55] and Von Karman [56] in the 1920s and 1930s. This work was advanced by many researchers but it was not until the work of Kvalsvold et al. [45] that the local hydroelastic effects were considered.

Using theory alone, Kvalsvold in 1994 studied the slamming-induced local stresses in the wetdeck of a multihull vessel for a doctor of engineering thesis and jointly published the results in Kvalsvold and Faltinsen [45]. The structure was modelled using a 2D Timoshenko beam and the fluid was modelled using Wagner theory. It assumed the fluid to be incompressible and irrotational; and air entrapment and cavitation were not included. This solution was complex and simplified by Faltinsen [34]. Experimental results from Faltinsen et al. [46] and Kvalsvold et al [45] agreed well with both theoretical solutions. Faltinsen [43] used the numerical solution of Kvalsvold and Faltinsen [45] to study the water entry of a wedge including the forward speed of the vessel by solving the coupled non-linear equations by a Runge-Kutta 4th order scheme. Korobkin et al. [47] demonstrated that it is possible to couple a finite element method for the structural domain directly with Wagner's theory for the fluid domain. The results were compared with a modal method using a beam model and the results showed very good correlation.

Lu et al., [48] used boundary element methods (BEM) for the fluid and finite element method (FEM) for the structure. The non-linear free surface boundary condition was satisfied and the jet was properly treated. Good agreement was found with the results of Zhao and Faltinsen [49].

Bereznitski [40] published an important paper on the role of hydroelasticity in the 2D slamming problem and uses four methods for solving the problem. The first is a Wagner's solution for a rigid body and this can be compared to the work of Faltinsen [34] for an elastic body. Bereznitski also used a self-developed code plus two commercial codes called MSC Dytran and LS-DYNA. Bereznitski commented that the most suitable methods were either MSC Dytran or LS-DYNA because they can both deal with the coupled hydroelastic interaction and include air cushion modelling. It is worth noting that MSC Dytran and LS-DYNA are quite similar and the equations for the state of water and air are the same, Bereznitski [40]. LS-DYNA has been used to study this problem by Bereznitski [40], LeSourne et al. [50] and Stenius [51]. Stenius [51] used finite element analysis based on multi-material arbitrary Lagrangian-Eulerian formulation and a penalty contact algorithm and the hydrodynamic loads correlated well with experimental results.

7. HYDRODYNAMICS

7.1 PROBLEM DEFINITION

As a vessel increases in speed, beyond the hump speed, the main resistance component changes from wave resistance to spray resistance, Payne [52]. The mechanisms for wave and spray generation are understood for planing vessels with hard chines, Savitsky and Morabito [53]. However, the IB1 and most IBs do not have chines and the mechanisms for generation are not well understood. Figure 5 shows the difference between the measured resistance of the IB1 and the Savitsky prediction. Therefore the problem is to study the wave and spray generation around a vessel with interacting sponsons with speeds from zero to planing and above.

Although this problem is not necessarily hydroelastic it is an important stage in predicting the performance of a RIB or an IB. Current theories, such as strip theory and Wagner's expanding wedge theory, do not consider the effect of a sponson. Therefore this section wishes to define the hydrodynamics around a sponson because the hydroelastic effects of a sponson cannot be explored until the hydrodynamics are understood.

By minimising the wave and spray generation it is possible to improve the top speed and acceleration of the craft. In addition, it has the capability to reduce the environmental damage from wave wash, although this may have an adverse effect on the boat motion. The problem can be viewed in 2D transverse slices that allow the effect of the sponsons on the added mass to be investigated; alternatively, the problem can be viewed longitudinally studying the effect of sponsons on the resistance of the craft.

7.2 LITERATURE REVIEW

Dand [12] performed resistance experiments on the IB1 at full and model scale. No measurements of the wave or spray generation were made but figure 9 shows that the spray is attached to the sponsons until it detaches to form spray sheets. This indicates that surface tension and the coandă effect need to be considered.

Figure 9: Spray generation of an EA16 at 19.4 knots [12]

An investigation into the boat motions of RIBs and specifically the RNLI Atlantic 85 were investigated by Townsend et al. [18]. It was found that the sponsons were rarely in contact with the water while planing, resulting in the sponsons having minimal effect on the high speed performance. Therefore the sponsons of certain RIBs have negligible effect on the wave or spray generation but this is clearly not the case for the IB1.

Waves can be measured using a wave probe but measurement of spray is less common and at present the ITTC do not have any recommended procedures for measuring spray or accounting for spray scaling. The location of the spray sheet separation from the sponsons also needs to be measured.

8. DISCUSSION

8.1. HUMAN EXPOSURE TO VIBRATIONS

High speed marine vehicles, such as the IB1, experience non-linear boat motion which results in high and low frequency vibrations with large accelerations. In 2002 a European Directive (2002/44/EC) was proposed to deal with the minimum health and safety requirements regarding the exposure of workers to physical vibrations. The exposure action value for whole-body vibration is 0.5 ms^{-2} r.m.s (or 9.1 $ms^{-1.75}$ VDV) and the exposure limit value is 1.15 ms^{-2} r.m.s (or 21 $ms^{-1.75}$ VDV). Boat motions and vibrations have been well reviewed in relation to high speed craft by Townsend [35]. Vibrations can not only cause long term injuries to the crew but they can reduce the crew's ability to perform tasks (during and after transit). Possible strategies to reduce human exposure to boat motion have included; suspension seats, suspended decks, active and passive fins, trim tabs, interceptors, gyrostabilisers, flexible hulls and elastomer coated hulls. Townsend et al. [20] showed that the RNLI RIBs exceeded the exposure limit value in a sea with the average of the highest 1/3 significant wave heights equal to 0.4m and average wave period equal to 10.6s. Dand [13] showed that the rigid scale model of the IB1 in regular waves, with a full scale wave height of 0.55m, could be exposed to peak accelerations of up to 4g in the crew's position. Whilst there is considerable debate in the marine community over the validity of applying the European Directive to high speed marine vessel the RNLI are investigating methods to demonstrate how the exposure of their crews and trainers to vibrations can be mitigated. The correct application of global hydroelasticity and hydroelastic slamming may help reduce the boat motions, in terms of vertical acceleration, that cause these high speed vessels to exceed the exposure limit.

Hydroelastic slamming has the ability to change the characteristics of a slamming event and reduce human exposure to vibrations. The authors believe that hydroelasticity will reduce the peak slamming accelerations but conversely it will also increase impact duration. At the current stage of understanding about human exposure to vibrations it is unclear which variable (peak acceleration or impact duration) is more important to reduce the harm to the crew. So it is unclear how effective hydroelastic slamming will be at this stage.

8.2. DESIGN CYCLE

So far this paper has broken an entirely hydroelastic boat into three main hydroelastic events. The next step is to consider how to design all three events together and a design cycle can be used with a specific order, see figure 10. The first event that requires examination is the hydroelastic slamming. This provides the added mass for the hydroelastic planing surface and the springing and whipping inputs for the global hydroelasticity. Then the hydroelastic planing surface can be studied which provides the calm water planing performance. Finally the global hydroelasticity can be considered to understand the planing performance in waves and the whipping and springing affects. A design cycle is required because all the hydroelastic events are coupled together, as explained in the next subsection.

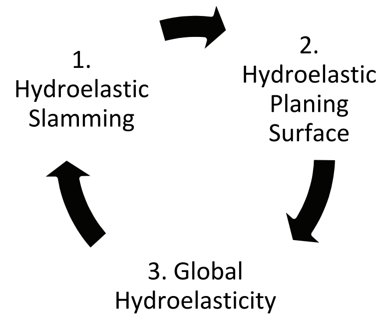

Figure 10: Hydroelastic design cycle

8.3. COUPLING OF HYDROELASTIC EVENTS

Global hydroelasticity has the potential to reduce the vertical motion from the coupling of pitch and heave. However this may lead to other issues such as the vessel no longer having the longitudinal stiffness to plane at maximum performance.

It appears that a flexible planing surface has a detrimental effect on performance and a rigid surface is more suitable. However, within the design of the IB1 a flexible hull is required to allow the advantages of global hydroelasticity and hydroelastic slamming to emerge. So it is important to quantify the minimum out-of-plane bending stiffness to remove any instabilities so that the maximum flexibility is available for global and slamming hydroelasticity.

Hydroelastic slamming may require a low transverse stiffness to improve the slamming characteristics but this may reduce the planing performance.

9. CONCLUSIONS

The literature that is directly linked to the design and performance of RIBs and IBs has been discussed. This shows how little research has been undertaken in this area. However, research in other fields that is relevant to the approach adopted for this project indicates that hydroelasticity does have the potential to improve boat performance.

The construction of the IB1 is described and this shows the areas of flexibility within the design which therefore show where hydroelasticity should be considered in the design of IBs. The optimisation of hydroelasticity may possibly lead to improvements in boat motion (reduced human exposure to vibrations), boat forward speed/acceleration, slamming accelerations, added resistance in waves and stability (pitch and heave) when stationary.

Global hydroelasticity was studied first. It may be possible to alter current theories to include the inflatable tubes and deck joints but no current theory has been validated for a hydroelastic planing vessel. Global hydroelasticity has the potential to improve the boat motions and reduce added resistance in waves.

The complex problem of a hydroelastic planing surface was then considered. Current results suggest that a flexible surface provides a low quality planing surface. However, a flexible surface is required to allow the other areas of hydroelasticity to function as desired.

In the hydroelastic slamming event three different elastic components were described: the hull, sponsons and keel. There are computational models capable of predicting the slamming accelerations and loads with conventional materials. Hydroelastic slamming could alter the slamming characteristics but at the current time the characteristics needed to reduce human exposure to vibrations are unknown.

The hydrodynamic problem of interacting sponsons was shown and the error in the current predictions for hull resistance was highlighted.

A hydroelastic design cycle was suggested to analyse the three hydroelastic events in a specific order. The coupling between the three events was examined and showed that a hydroelastic planing surface limits the possible longitudinal and transverse stiffness for global hydroelasticity and hydroelastic slamming.

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