Optimization of a Planing Hull Structure

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Abstract

This paper describes a method for optimizing hull structure design based on desired performance characteristics and expected operator maneuvering profiles. The dynamic and transient nature of hydrodynamic slamming poses a challenge in defining the hull loads a planing watercraft must be designed for. Varying wave periodicity, amplitude, and impact incidence angle compounded with disparate driver habits exacerbate the difficulties of developing designs loads. In-lieu of this, many high speed watercraft manufacturers resort to using a combination of classification society methods and semi-empirical testing to develop hull loads. The loads to which fast-planing watercraft hulls are designed can vary from constant pressures to literal hull drops that simulate real world extreme maneuvers the craft might undergo during its life. When gel-coat surface cracks are detected in early sea-trials, the manufacturers often extensively strain gage these hulls to measure the peak strains during subsequent sea-trials and then engineer post-priori reinforcements on the hull or substructure.

The use of Fluid Structure Interaction (FSI) techniques to develop a loads envelope for designing the hull of the watercraft is described in this paper. Once the methodology and the load envelope are defined these can be incorporated in an optimization model to develop a structurally efficient design that meets stiffness and fatigue stress limits. The use of the loads envelope is intended to provide an efficient, expeditious, and robust methodology for developing and optimizing the hull structure without having to perform computationally intensive non-linear FSI simulations in the design development phase. This method reduces the development process of the hull in that it concurrently optimizes the hull design for mitigating specific transient hydrodynamic loads from extreme maneuvers rather than a scaled up hydrostatic load profile in combination with any other loads that the hull designer may want to consider.

Keywords: Optimization, Fluid Structure Interaction, Hull Design, Composite Design

1.0 Introduction

The hull of a high speed planing watercraft is subject to multiple varying wave loads during operation. Some of these loads are extreme with few occurrences over its lifetime and others are of a lower magnitude but occur frequently. The former situation arises when a planing boat lifts from the water over the crest of a single large wave and slams the sea surface from a high altitude, while the latter situation would be represented when a watercraft skims the surface of the water during a low sea state with a multitude of low amplitude surface waves.

The current approach to hull design for many high speed watercraft manufactures relies on classification society panel methods using average constant stresses originally developed for vessels traveling at relatively low speed. This is well suited for designing freighters or
other large displacement hulled craft, but modern high speed watercrafts have different design goals.

The hull of a fast planing watercraft has to be strong enough to support varying loads, stiff enough for planing performance, and yet light enough for buoyancy and maneuverability considerations. These considerations are often not balanced during the design process and fixes are normally applied through physical testing by way of local heavy reinforcements in areas of concern that classification society design methods did not identify. To design a hull with consideration for slamming loads, the varying nature of wave impact loads must be taken into account. Mathematical or statistical approaches that have attempted to incorporate wave effects have become known as slamming theories. Most slamming theories developed so far were two-dimensional; i.e., they were limited to cross sections of infinite cylinders. For most practical impact problems, the body shape is complex or the effect of gravity is considerable. In such cases, analytical solutions are difficult to formulate.

The use of FSI (Fluid Structure Interaction) methods to develop a load envelope for designing fast-planing hulls provides a more computationally accurate and efficient means of quantifying design loads. Using FSI methods the transient dynamic slamming loads of a watercraft can be analytically determined. However, since these loads are transient dynamic in nature, they must be converted to linear equivalent loads before they can be used in a gradient based optimization algorithm. The automotive industry and more recently the aerospace industry have adopted a design approach where available design space is first topology optimized to develop the optimal structural layout. This is then followed by a more traditional size and shape optimization to fine tune the structure. The illustrations below describe the optimization process of a lightweight SUV frame:
This approach can provide an optimized design that balances weight, performance, durability, and construction efficiency if a comprehensive set of loads and constraints are considered early in the design process. It is imperative that dominant dynamic slamming loads and associated footprints be linearized and considered as part of the optimization. A methodology to convert the slamming loads into static equivalent linear loads is outlined in the next section. The static equivalent loads are then utilized with OPTISTRUCT® and the available package design space to develop an improved hull reinforcement design. A final transient dynamic simulation with the optimized design of the hull is then performed to validate the methodology.

### 2.0 Background Information

The linearization of slamming loads begins with a transient dynamic simulation utilizing FSI methodologies. The two primary methodologies for FSI simulation are Smooth Particle Hydrodynamics and Arbitrary Lagrangian Euler. The Smooth Particle Hydrodynamic (SPH) method is a meshless numerical solution based on interpolation theory. It allows any function to be expressed in terms of its values at a set of disordered points; so-called particles. The conservation laws of continuum dynamics, based in the form of partial differential equations, are transformed into integral equations through the use of a kernel approximation.

The motion of the particles is governed by the divergence of the stress tensor. The particles move in response to the stress gradient, which is found by performing a local fit to the stresses carried by the particles in the neighborhood of the particle being accelerated. Since SPH is intended for large deformations, each particle’s neighbor set must be allowed to vary as deformation and flow occur. Thus, a search for the neighbors of a given particle must be performed at each time step, and the stress gradient determined by the neighbor set is used to move the particle.

The kernel-based spatial gradient approximation used in SPH is basically a curve fit to the data values at the interpolation points in the neighborhood of the location at which the gradient is being approximated. The fit is performed by first multiplying the data value at each neighboring point by an SPH kernel function (usually a cubic b-spline), so that the kernel function at each particle is in effect weighted by the data value at that particle. The kernel function has compact support (is zero beyond some radius), so that only local neighbors enter into the sums. A continuous function is obtained from the discrete data by summing the weighted kernels.

One advantage of this particle treatment immediately stands out from the lack of physical topology so that deformation, contact, and complex geometries can be accommodated very easily. The SPH method is a complementary approach with respect to the Arbitrary Lagrangian Euler (ALE) method. The ALE method relies on physically meshing the environment and tends to be more cumbersome to set up. When an ALE mesh is too distorted to produce good results (for example in the case of a vortex creation), SPH is the alternative method of choice and the focus of this paper. Figure 1 below presents different configurations of SPH nets, the method by which the particles are packed together.
3.0 Determination of Slamming Loads

Determining the slamming loads that would produce the greatest effect on the watercraft required several FSI simulations beginning with still basins and progressing to wave interaction of various amplitudes and velocities. Drop simulations of a 6.5 meter boat were performed at different penetration angles in a still basin (Figure 2). The drop height of 4.6 m corresponded to a 9.47 m/s initial impact velocity.

The objective of these simulations was to determine the influence of the penetration angle on the hull stress and thus to determine which orientation produced the most extreme stress concentrations.

From these simulations it was determined that the most severe stress concentrations were due to a boat-to-water impact angle of 0 degree. When the boat impacted flat on the water surface, the deceleration of the boat was higher due to the large contact area. The mean deceleration pulse observed was 392 m/s² (40g). The deceleration of the boat was lower and more progressive when the boat entered the water with an angle due to the smaller effective area of contact with the fluid.

The figures below (Figure 3 to 5) show the SPH model setup and peak stress events for the hull and stringers of the boat when the boat impacted the water level (0 degree angle).
The loads envelope was then expanded to factor different surface wave conditions. A wave block was created whereby the height, angle, and impact velocity were varied to simulate different extreme impact conditions. Multiple drop simulations were performed with wave blocks representing various wave amplitudes and impact velocities. The drop height was maintained at 4.6 m which corresponded to an impact velocity of 9.47 m/s. **Figure 6 and 7** below depict some of these simulations with a wave impacting the boat at 5.55 m/s while the boat is dropped at differing vertical and horizontal velocities.
The objective of these simulations was to determine the influence of the wave geometry and velocity on the hull stress and to determine which wave conditions produce the most extreme stress concentrations. The impact maneuvers that resulted in the most severe stresses in the hull and stringers were retained to define the extremes of the load envelope.

### 4.0 Determination of Static Equivalent Loads

#### 4.1 Description of the Methodology

Once the most severe penetration angle and characteristic wave profile effects were determined, equivalent static load cases corresponding to the peak dynamic stress events were developed. Relative displacements of the hull were extracted from the dynamic simulation and input as enforced displacement constraints in a static simulation. The
process outlined below (Figure 8) shows the steps to convert the dynamic results to static equivalent loads for use with a linear optimization solver.

4.2 Application of the Methodology
The example below shows an application of the methodology on a peak stress event (t=15 ms) when the watercraft impacts the water at a 0 degree angle and a comparison of the Von Mises stress between the static equivalent loadcase and the dynamic simulation.

Determination of the relative hull displacement:
The relative displacement from the hull transient dynamic response is first measured with respect to a reference plane (Figure 9). Three nodes are chosen on an XY plane far enough from the impacted area and where the local deformation is minimal (so that the normal of the plane remains collinear with the global Z axis in this case for simplicity). The relative hull displacements with respect to our defined reference plane (Figure 10) are then plotted.

![Figure 9: Determination of the Relative Hull Displacement Reference Plane](image-url)
Application of the enforced displacement to extract the reaction forces:
The transient dynamic relative displacement results of the hull impacts were extracted with HyperView® (selecting only the displacements above a target value to reduce the total number of responses that must be considered; in this case displacements larger than 3 mm in the global Z direction were extracted) and applied in an OPTISTRUCT® static simulation.

Next nodal forces were computed from this enforced displacement static simulation for the entire hull bottom. These nodal forces were then used as the static equivalent loads for optimization or further static analysis.

Nodal forces generated from the reaction loads were used for loading as enforced displacements are not suited as constraints for topology optimization. This “equivalence of deformation” approach linearizes the transient dynamic loadings and was repeated for all maneuvers that had to be considered. The images depicted below (Figure 11 and 12) show a comparison of the Von Mises stress between the static simulation and the dynamic simulation at a given time (t=15 ms) for the hull.
The Von Mises stress intensity and locations compare well between the static simulation and the dynamic simulation of the hull. A similar comparison for the stringers is depicted in Figure 13 and 14.
4.3 Limitations of Approach
The linearization method outlined in the preceding section is applicable when stresses and deformations are within or near linear limits. The underlying assumption is that all the internal energy of the impact associated with the dynamic deformed state is wholly recoverable as elastic strain energy. While this linearization approach generally errs on the conservative side, the exclusion of strain rate effects during elastic recovery may lead to overestimation of static strains. The impulsive hydrodynamic slamming loads are conservatively assumed to be static and sustained. The observed non-linearities are generally confined to small regions where the stresses may be above yield while the global response is generally elastic making the approach valid for the full system.

5.0 Topology Optimization of the Hull and the Stringers

5.1 Background Information
Several industries, in particular aerospace and automotive, have incorporated optimization into their product development process as the technology is proven and has matured enough to be implemented into existing product development processes. Rising fuel costs and competitive pressures have motivated them to engineer their products to be as mass and cost efficient as possible within compressed product development timelines. Optimization is one of the key enablers to help meet these goals.

Topology optimization is a numerical technique based on finite element method and has been incorporated into OPTISTRUCT®, developed by Altair Engineering Inc. This process is currently being used by most automotive OEMs and several aerospace OEMs to help meet program weight goals while maintaining critical displacement, stress, stiffness, and modal performance.

Topology optimization uses finite element methods to generate optimal design concepts. Given a package space, loads, boundary conditions, and a target mass, the most structurally efficient material layout is determined. Initially, the specified mass is evenly distributed throughout the design space. The mass is then iteratively re-distributed within the design space in order to maximize stiffness. The resulting material layout provides the optimal starting point for the design. For this specific optimization, the topology feature of OPTISTRUCT® is used to define the shape and position of the internal reinforcements to reduce the stress on the hull.

5.2 Application on the Boat Model
Several loadcases were created using the methodology described in the previous section to accurately capture the loads from different slamming events. The objective in optimization is to reduce the peak stress on the hull and stringers by determining the optimal layout for the reinforcements. A design space that defines the packaging freedom is first defined allowing OPTISTRUCT® to then iteratively distribute the available material within the design space to maximize the stiffness while keeping only 10% of the original volume. The design space, illustrated in the figure below (Figure 15), is defined between the hull and the liner.
Figure 15: Optimization Design Space

Figure 16: Topology Optimization Results

The image in Figure 16 presents the results of the topology optimization performed on the structure where only 10% of the original design space was preserved. The topology results provide a road map for the optimum distribution of material. This must then be interpreted into manufacturable design modifications that can be packaged within the design constraints. It must also be noted that this solution also represents a trade-off of the best design improvements to mitigate the loads due to a full series of wave impact scenarios. To increase the stiffness of the hull and reduce the stress on the stringers and the hull the following design changes need to be implemented:

- The area where the liner is in contact with the hull in the central part of the boat must be reinforced enough to reduce the flexure of the hull.
- Ribbing must be designed between the liner and the hull along the sides of the boat at mid ship.

6.0 Validation of the New Design

To validate the methodology the recommended design improvements interpreted from the results of the topology optimization are modeled and a dynamic FSI simulation is
performed. The result of the slamming simulation of the new design is then compared with the results of the original design.

The new design reinforcements are shown in Figure 17 and were derived from the topology optimization results.

The new design reinforcements are shown in Figure 17 and were derived from the topology optimization results.

The vertical ribs provide an increase in the stiffness of the hull in bending while the thicker liner in the central area will reduce the stress by tying the sides of the hull together, effectively reducing the high deformation of the sides of the boat.

The thickness of the hull and the liner was reduced so the total mass of the boat is identical between the new design and the original design, thus preserving the impact energy.

The stress in the hull and stringers is compared between the new design and the original design through the Figures 18 to 21.
Figure 19: New Design | Peak Hull Stress Event

Figure 20: Original Design | Peak Stringer
The stress concentrations on the hull and stringers decreased by 25% with significantly reduced local peaks and the relative displacement of the hull (bending) decreased by 50%. The stiffer hull has the added benefit of improved planing performance and maneuverability of the boat at speed. Alternatively, if the boat performance was already adequate, the optimized results indicate the mass of the boat could be further reduced while balancing stress and displacement targets.

7.0 Conclusions

The use of Fluid Structure Interaction (FSI) techniques to develop a loads envelope for designing the hull of high speed planing watercraft was described in this paper. The transient dynamic loads obtained through simulation of slamming events are converted into static equivalent loads that can be used for design improvement or weight reduction. The correlation between these static equivalent load sets and the transient dynamic load sets are compared and found to be acceptable. The load sets are then implemented in a topology optimization model.

Topology optimization is used to improve the hull stiffness while reducing stresses at critical locations. The topology optimized layout provided a reduction of stress on the hull and stringers while improving overall bending stiffness of the hull. While in this study we have chosen to minimize the compliance of the boat and reduce peak stress levels, this approach could have been applied to reduce the mass of the boat while maintaining the same level of the stress and stiffness or any combination between.

The use of the loads envelope is intended to provide a robust methodology for developing and optimizing the hull structure with a comprehensive set of loadings that factor slamming loads based on a desired performance characteristics and expected operator maneuvering profiles. This requires linearization of transient dynamic slamming loads at the onset so that critical loads can be considered early in the design process together with the traditional hydrostatic loads and thus reducing the need for post priori testing.