FloatStab
A Tool for the Rapid Analysis of Flotation Stability Following Water Landing

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The computational techniques for orientation stability of a vessel or vehicle in the water are well understood. However, to our knowledge, the basic calculations are often difficult and tedious. In our experience, the algorithmic approach is often based on CAD computer data and interactive iteration to determine the flotation plain. From this point, the buoyancy center and resulting moment are easily computed. However, with the need to understand static stability at all flotation orientations, these rather manual computations become rather tedious.

This paper presents the results of an automated approach created by Irvin Aerospace Inc (Irvin) that we have named FloatStab. This tool, based on a Finite Element Model (FEM) of the basic vehicle can quickly rotate the vehicle to user-defined attitudes. It then completes the iteration for flotation plain and computes the related buoyancy center and moment. Fig. 1 presents a view of the FEM and the resulting submerged/above water element solution. Fig. 2 provides an example of the resulting buoyancy moment. Interpretation of this data will be thoroughly discussed in the paper.

Further, we will present the basic algorithm, including some significant algorithmic simplifications. The basic algorithm is based on Green's theory integration, with the use of finite elements.

We will also present generic results and basic analysis of the data. This includes both basic vehicle configurations, and those with floatation stabilization added. Finally, we will present some simple examples of both Dynamic Water Landing simulations and simulations of dynamic flotation such as with wave action. Fig. 3 presents an example of a FSI result for the dynamic landing of a spacecraft structure into water.

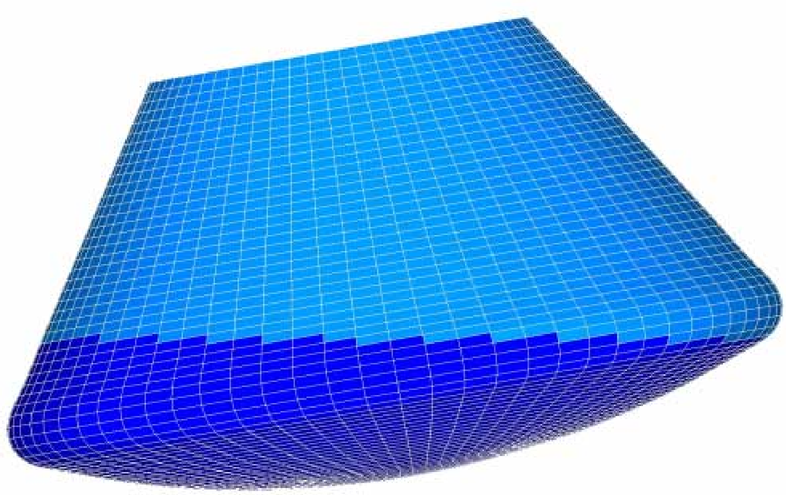

Figure 1. FLOATSTAB Analysis Result – Resultant Waterline

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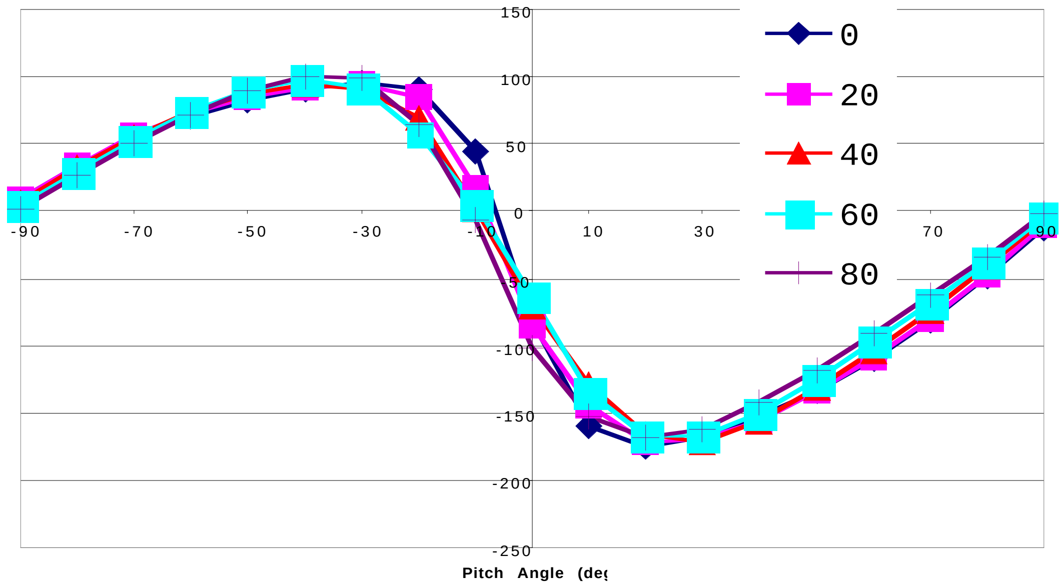

Figure 2. Example of Buoyancy Moment Versus Vehicle Attitude

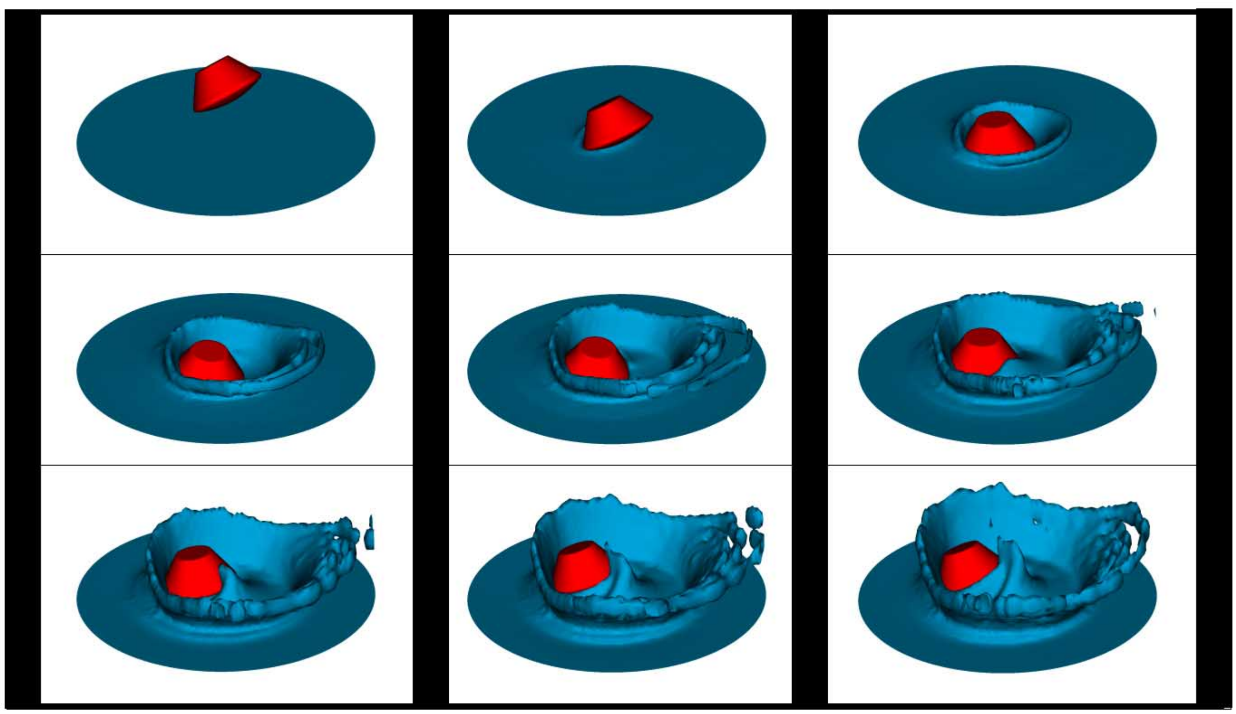

Figure 3. Image from Dynamic Water Landing Analysis

I. Introduction

DURING a number of recent programs, it became clear at Irvin that the computations for flotation stability required automation which was efficient in our Computer Aided Engineering (CAE) environment. Having significant ability to create finite element models to capture geometry, the discretization of the basic vehicle and flotation was an obvious approach. This approach becomes more compelling when FEA models for water or land landing also exist, allowing the simple transfer of existing geometry to the flotation stability tool.

The addition of geometric elements that represents stabilization or righting devices allows the quick understanding of the addition of these devices. In the final analysis, detailed simulations which include the underwater deformation of flotation devices will provide a higher fidelity. However, we believe that these simulations provide a significant understanding of righting and stability requirements and are inexpensive from a computational point of view.

II. Basic Algorithm

This section describes our basic approach to the design of the FloatStab simulation tool. In general, it became apparent to us that the ability to rapidly rotate various geometries through the full range of orientations would provide the best analytical data. The resultant buoyancy moments are then plotted versus attitude. The resulting plot is a series of moment curves that have both stable and unstable neutral points.

Having completed the calculations, the analysis of the data is similar to the analysis aerodynamic moments for a flight shape.

A. Why Finite Elements

We have significant experience and tools for the processing of finite elements. There are other approaches for the estimation or reduction of basic geometric shapes. However, in an environment with a number of other tools for the reduction of geometry to finite elements, we take the same approach for this portion of the analysis suit.

Additionally, in many cases, the existing FE data is quickly converted from land landing analysis, to water landing analysis and then to flotation stability analysis. One further potential analysis is the dynamic response of the final water landing configuration to wave excitation. We suggest that this portion of the analysis should be conducted in a Fluid Structure Interaction environment, computing the response of landed shape to wave action.

B. Basic Algorithm

The basic algorithm is rather simple. A plain is positioned vertically to represent the current water height. The Shell finite elements are sorted as being above or below the water line, based on position of the element centroid as compared to the current water level.

Following the sorting portion, the underwater volume is integrated and the resulting buoyancy is computed. Volume integration of the Shell Element is completed based on Green's Theorem, which is discussed in more detail below.

Current step buoyancy is computed based on displaced volume and basic water density.

The flotation plain is then moved, in an iterative nature until convergence criteria are met. Successful convergence criteria can include either a comparison of vehicle weight and current buoyancy or criteria for the change in buoyancy plain position (usually fractions of an inch). Both techniques have been used successfully.

Once the final waterline or buoyancy plain is determined, the buoyancy moment is computed and results for the current orientation are output.

The buoyancy moment is computed as the difference between the vehicle center of gravity (CG) and the buoyancy center. The buoyancy center is also computed through Green's Theorem integration.

Vehicle geometry is the rotated to the next orientation, these are user controlled angles in pitch and roll, and the computation begins again.

C. Green's Theorem Integration

Green's Theorem (GT) integration provides a theorem for the integration of a closed surface to compute a volume. The same theorem allows for the integration of a closed curve to compute an area.

Starting from this basic theorem and having familiarity with it from our airbag work with LS-DYNA. We began the construction of our FloatStab tool.

The basic theorem (please consult your Advanced Engineering Mathematics Textbook) involves the integration of the incremental area and the cross product of the normal of the current surface and the direction of integration. This is clearly a technique that is well suited for finite elements and the computations are rather routine.

However, the requirement for a closed surface, a basic tenant of the theorem, would require the computation of a closing surface if the geometry is not closed. Again we are familiar with this approach from our work with LS-DYNA. In the buoyancy calculation case, indeed we need a closing surface in our algorithm, as the open plain that represents the waterline must be closed. Fig. 4 provides an illustration.

In the process of creating the algorithm to compute this plain, we realized a valuable lesson. Since the basic algorithm includes the cross product of the current area normal and the direction of integration, great simplifications are possible by controlling these parameters. In our FloatStab algorithm, the basic vehicle geometry and direction of integration are controlled, such that the cross product of the closing plain (at the waterline) and the direction of integration is zero. Thus, we avoid the requirement to compute the closing plain, a rather significant algorithmic simplification.

III. Validation and Simulation Results

As with any new algorithm or simulation tool, the first step is to validate the results being produced by the model. Therefore, our first step was to test the basic GT integration algorithm. For this, we completed a macro in the Altair HyperMesh tool, which computed the same basic buoyancy volume, force and moment, but used 3D Finite Elements for the computation. Results were similar, with the simpler FloatStab FORTAN based tool, completing the calculations with a significant reduction in computational overhead. This statement is not a criticism of the Altair product, indeed we work quite closely with Altair, but rather an example that limited, scientific language based, simulations still have a place in the world of increasingly multi-discipline, do everything, simulation packages.

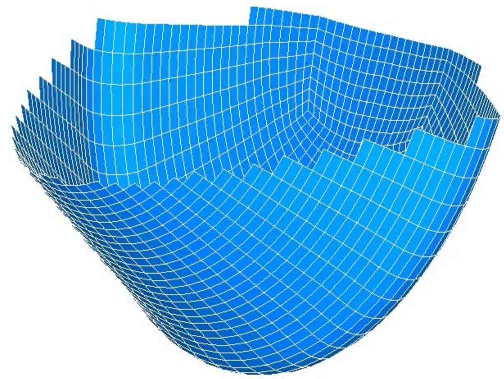

Figure 4. Image of Underwater Elements Illustrates Requirement for a Closing Plain

Fig. 5 provides a view of the submerged mesh from the simple 3D approach. Results from the 3D element approach and the FloatStab approach matched closely, providing a level of validation for the tool.

Having established some confidence in our tool and results, we begin to analyze water landing shapes. The most well known and readily available is the Apollo Command Module (CM). Fig. 6 provides somewhat simplified geometry of the Apollo CM, in the landing configuration, that is minus the forward heat shield.

The Apollo CM is well known to space flight buffs or those who worked the program, for having two stable neutral points in the water. These are classically known as Stable 1 (upright) and Stable 2 (up-side down); you will note this detail when you next watch the close of the movie Apollo 13!

Figure 5. 3D Element Analysis of an Apollo Shape

This was the reason for the addition of the post-landing righting bags that were a portion of the Apollo Earth Landing System (ELS). Fig. 6 presents a view from the Apollo 11 mission, where the capsule did complete the water landing in the inverted position.

Figure 6. Apollo 11 Initial Landing – Stable Inverted Position

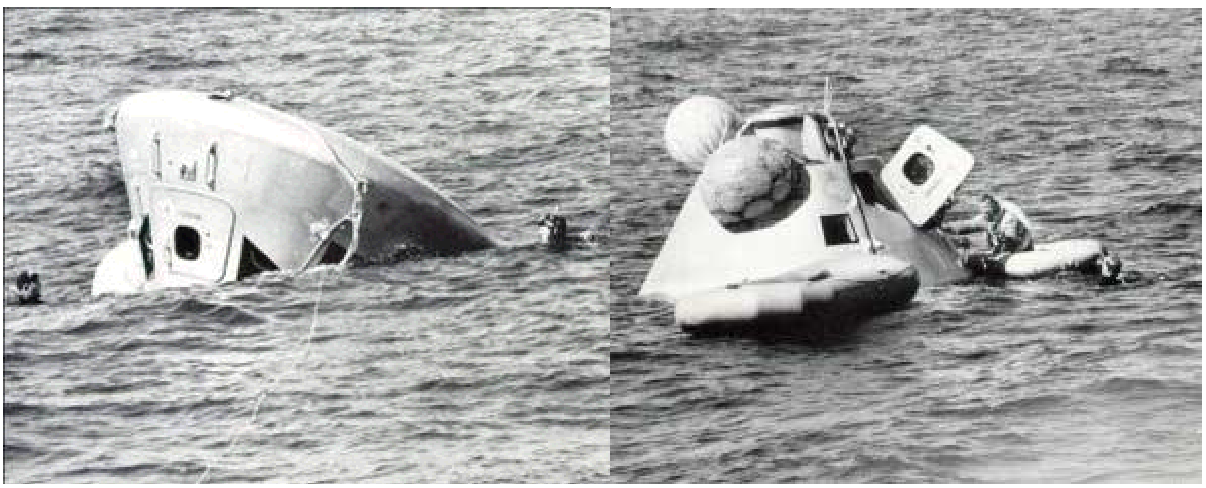

Figure 7. Stable Neutral Points Illustrated

Our analysis reveals similar results. Fig. 8 provides a series of buoyancy moment results from the FloatStab tool. These moment curves are similar to aerodynamic pitching moments and have a similar sign definition (as the author is comfortable with this convention) thus stable neutral points have a negative slope. The figure clearly identifies two neutral points that are stable, one upright, and the other inverted. Fig. 8 identifies the two neutral configurations, and displays the computational mesh. We should also note that the classic Apollo CG offset is included in this analysis, thus the asymmetric position at both neutral points.

During the Apollo program, the addition of post landing righting bags, or flotation bags were used to eliminate the undesired neutral point, or in this case ‘Stable 2’.

Fig. 9 presents a view of the computational mesh, for FloatStab, that incorporates these righting bags. Fig. 10 presents a plot of the resulting computations for buoyancy moment. Clearly the inverted position has been eliminated.

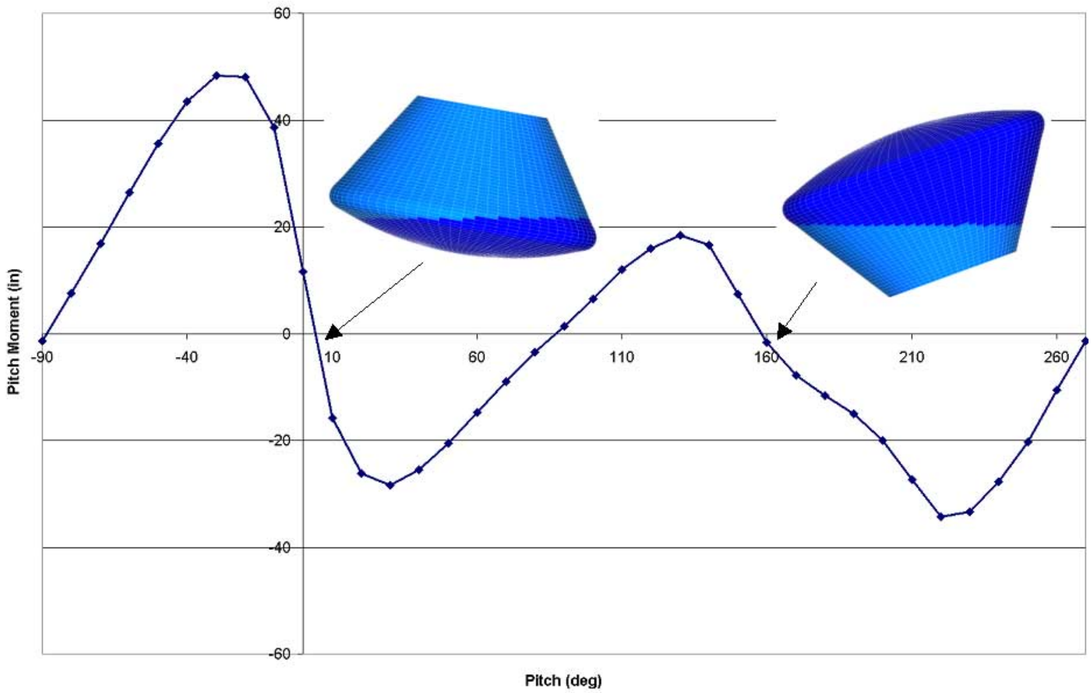

Figure 8. Neutral Point Result and Computational Mesh – Stable Neutral Points

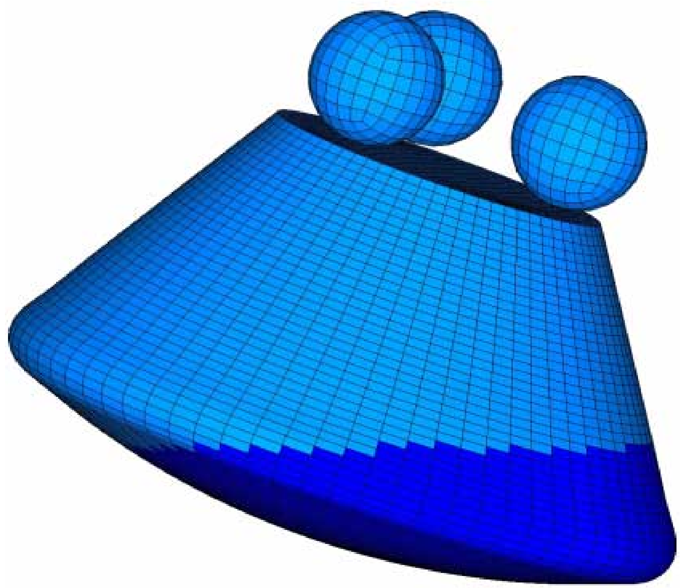

Figure 9. Apollo CM with Righting Bags

We have investigated many other shapes with this tool, most proprietary to a specific customer, and therefore not reportable here. In general, we can report that the lessons learned from the Apollo experience are possible the simplest of those to learn.

When investigating more complex shapes, such as cylindrical, winged and semi-winged aircraft, the elimination of undesired neutral points becomes much more complex. In many cases, the flotation aids added to stabilize and enhance one desired state, can create an additional, undesired and usually inverted state. Fortunately, at this point, we have an analysis tool that allows the investigation and early definition of such conditions.

IV. Higher Order Simulations

The results above have demonstrated the value of simple and though-out, specific analysis tools such as the algorithm outlined. However, the broader field of landing analysis includes much room for advanced simulations, such as Explicit FEA and Couple FEA and CFD, which we often term Fluid Structure Interaction (FSI). Examples of these are presented in this section.

V. Land Landing with Airbag Landing Attenuation

We have reported in many papers on the analysis of land landing, whether direct impact, landing bag attenuation of deformable structure on many occasions. For completeness we mention the subject here. The References provide suitable background.

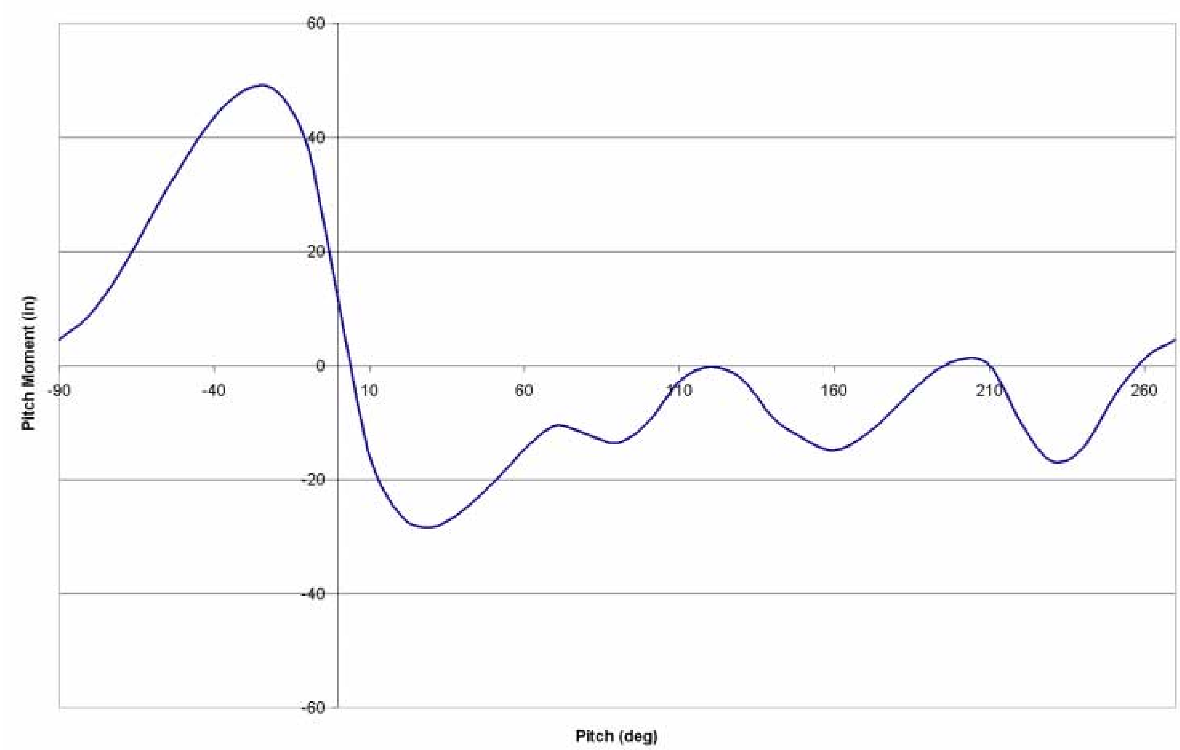

Figure 10. Resulting Buoyancy Moment Including Righting Bag

We should add that the same simulation techniques that typically have focused on landing bag performance are the same skills required for analysis of hard landing, soil deformation, deformable structure, or any other load attenuation technique.

VI. Water Landing

Similarly, we have recently reported on the analysis of water landing simulations. In that paper, we created comparisons between computer simulations and historical data, again from the Apollo program.

The results are compelling and are presented in Reference 11. However, the comparisons are somewhat limited, due to the available data.

We continue to strive for additional sources of validation data in this arena.

VII. Float Deformation

The issue of float envelope submerged shape is also an interesting topic for deeply submerged float systems. Here again, the use of higher order FSI class simulations is useful. In the FloatStab tool, presented above, the righting system geometry is considered rigid. And this assumption is appropriate for systems that are either highly pressurized and/or are used near the water surface. However, in some instances, the flotation system is either deployed after water entry, or the system might include a rather deep water penetration prior to surfacing. In these cases, further analysis either through FSI, or simplified FEA analysis would be of value. Similar analysis might also be required of the depending on the attachment scheme of the float envelope, which might move the location based on the basic forces involved.

Fig. 11 presents a result from an investigation of submerged float. These results were obtained from a structural analysis (FEA only), that incorporated a control volume for internal pressurization, that is, the internal pressure increases if the float volume is decreased. The outer loading scheme used a pressure versus submerged depth class approach.

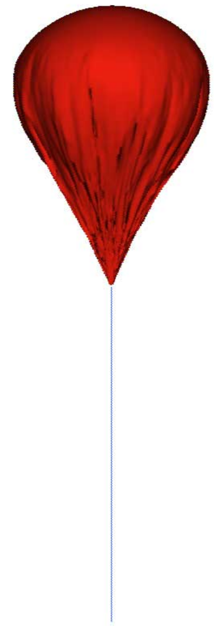

Figure 11. Float Deformation from Under Water Pressures Distribution

VIII. Flotation Stability

Another area of required investigation is the stability of vehicle and floatation following water landing. Stability investigations need to review both the response to CG movement (due to crew movement) and the response of the spacecraft or vehicle to wave action.

Both are possible in the FSI environment and we are currently working to further develop these modeling techniques. The response to wave action is the more complex simulation of the two. In this instance, we are working with simulations that will generate a wave shape and have that shape impact the floating spacecraft.

Various configurations of interest include the spacecraft in several configurations:

1) Basic Upright Configuration
2) Basic Inverted Configuration
3)

Figure 12. Illustration of the Ability to Generate Wave Action

With Right System Deployed

4) With Post-Landing Stabilization System

Fig. 12 presents an example of a fluid wave created to support such as simulation campaign. We are now ready to progress into the analysis of floatation dynamic analysis.

IX. Conclusions

The field of water landing in many areas is a lost art that dates back to the Apollo program. Many things have changed since the Apollo program, and most significantly, the number and sophistication of high order simulations is included here.

Our discussion began with a review of a relatively new approach to an old problem, the computation of buoyancy moments. We suspect that the ship design industry would find this result to be commonplace. However, to our community, it appears to be an interesting topic at the right time.

Irvin's higher order simulation tools and experience can also offer broad range of understanding of the multiple aspects of water landings, including impact, wave response, submerged performance, and response of the spacecraft to crew motion. These higher order simulations have an associated computational cost (or computer run time).

Finally, we have published in detail, in the past, definition and results of capabilities available for the analysis (and therefore design) of systems for the attenuation of landing loads during land landing.

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