Fluid Structure Interaction: A Community View

Prepared for Dr. Paul Hess, ONR Code 331

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Abstract: Conducting fluid-structure interaction (FSI) experiments and simulations is a critical naval engineering capability for the U.S. Navy. However, past workshops on FSI problems have revealed that the FSI community is split into different technical groups. Furthermore, the user communities — practicing engineers and platform teams — are also separate. In July 2016, a cross-community working group of almost 60 people was convened at the University of Michigan Ann Arbor. This working group explored current and anticipated use cases for FSI simulation. Research challenges were also discussed. From this cross-community discussion, it was also possible to start to develop a common taxonomy of FSI problems and modeling approaches. This report documents the state of practice revealed by this working group.

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Based in part on FSI Working Group Discussions Held in July 2016

Contents

1 Executive Summary

1.1 Scope and Purpose

This document presents a map of the current situation in the fluid-structure interaction (FSI) discipline. This map was developed at the request of the Office of Naval Research (ONR) which noted that a current state-of-the-art summary did not exist, and that past FSI workshops and conferences had revealed a varied understanding of the scope of FSI activities today. Under the leadership of Dr. Paul Hess and Dr. Tom Fu from ONR Code 331, a series of small-group discussions were held leading to a major working meeting in July 2016. The working meeting featured almost 60 participants. Through this two day event the state-of-the-art in FSI, navy FSI use cases, and future research challenges were documented (Sections 2 and 3). From this work, a synthesized taxonomy of common FSI problems and solution approaches was made, along with a network representation of the scope of the FSI problem (Section 4). Finally, an overview of common challenges that were identified by the group is included (Section 5). These activities and this report focus on creating a faithful image of the entire FSI community without determining prioritized areas or a recommended research strategy.

1.2 Major Activities

Four major activities are reported in this document:

1. **State of the Art Summaries:** Three experts in different parts of the FSI domain presented summaries of their knowledge at the beginning of the Ann Arbor event. Dr. Joe Gorski of Naval Surface Warfare Center Carderock (NSWCCD) presented an overview of numerical and experimental fluids modeling (Section 2.1), Dr. Neil Pegg from Defence Research and Development Canada (DRDC) presented an overview of structural prediction and full-scale trial measurements (Section 2.2), and Professor Chris Earls from Cornell University presented a summary of numerical coupling approaches (Section 2.3).

2. **Comments on Navy Use Cases:** A series of Navy use cases for FSI predictions were developed by a mixed NAVSEA, industry, and academic team. These use cases covered global (platform level) FSI response, local (panel or plate level) FSI response, and propulsion device and appendage FSI. The group assembled in Ann Arbor annotated these use cases and proposed new use cases. Additionally, the group plotted existing numerical and experimental methods that could be used for each use case in terms of prediction fidelity, with further ranking on the engineering readiness of each method. Finally, short and long term research goals and applications were developed for each category of use case. This data is summarized in Section 3, and the complete workshop output is listed in Appendix A.

3. **Future Research Questions:** Based on the results of the discussion around the Navy use cases during the first day of the Ann Arbor event, eight research questions were posed to the community. These questions were discussed on the second day of the event. Discussion started in sub-groups, and the sub-group responses were recorded and debated in both plenary and walking poster comment sessions. The questions and summarized responses are presented in Section 4 of the report. The full output from the group, floor, and poster session discussions is included in Appendix B. The eight questions were:

    - **How can we better utilize machine learning and data processing to improve the generation and understanding of large experimental and computational data sets?**

- **What are the current limitations of fluid simulation methods for FSI problems and how can we reduce them?**
- **What are the current limitations of structural mechanics solution methods for FSI problems and how can we reduce them?**
- **What are the current limitations of coupling approaches to FSI problems and how do we address them?**
- **What physics and applications require us to address the full 2-way coupled FSI problem? When can we use other approaches?**
- **What are the current needs for Verification and Validation? What uncertainty quantification developments are needed?**
- **What experiments are required to advance our understanding of FSI?**
- **What are the key problems with user training and human interaction with complex FSI numerical simulations?**

4. **Taxonomy and Scope:** An early concern of ONR was that the FSI community lacked a common taxonomy for discussing the domain — for example that researchers in slamming, propeller, and weapon effects all used different terminology for related problems. This was apparent at the Ann Arbor event, where it was clear that there wasn't a common definition of FSI. In an effort to address this problem, a simple three-decision terminology tree was developed. The taxonomy can describe broad categories of related FSI problems in terms of the degree of coupling, phases of fluid involved, and non-linearity of the structure. Additionally, a summary table of common numerical methods was produced and a diagram of the overall process of using FSI tools to make a prediction, considering R&D, V&V, application, approval, and human capital was generated. These are presented in Section 4.

1.3 Discussion

Overall, the results from this study show that the FSI community appears vibrant. In many use cases, a range of engineering methods was proposed, some with high readiness today and others with lower readiness but possessing promise to improve the fidelity of FSI predictions when ready. It was clear that there was a desire for improvements across a broad range of methods, from simple reduced-order design models to complex coupled Large Eddy Simulation (LES) approaches. A few of the more commonly mentioned research challenges included: modeling across large spatial scales, handling the "big data" problem associated with modern numerical codes or experimental sensing systems, multi-phase fluid flow and non-linear structures for both propulsors and weapon effects, experimental sensor improvements, and designing and validating better coupling algorithms. There was a clear desire from the community to move forward with benchmark experiments. Such experiments would ideally be designed and implemented with experimentalists and numerical modelers working side-by-side. The community seems aware of these interactions and ready to work together. Challenges around big data, predicting which situations will lead to extreme events, and the human role in FSI also appeared. While the community seems aware of these issues, the discussion in Ann Arbor revealed a lower level of consensus on how to address them.

2 Introduction

This document presents a community view of the state-of-the-art, challenges, and opportunities around the fluid-structure interaction (FSI) discipline for naval applications. This view has emerged from over one year of discussion and debate within the community. This process started out with a small number of government and academic members of the community reviewing FSI for the Office of Naval Research (ONR) under the leadership of Dr. Paul Hess and Dr. Tom Fu in ONR Code 331. From these initial conversations, it became clear that the FSI community was highly fractured — engineers and researchers in different areas (e.g. wave impact vs. weapon effects) often did not share a similar language or understanding of the other's approaches. An example of this is that some consider fluid-structure interface, where fluid pressures are mapped over to structural models without any return feedback part of FSI, while others do not. In light of this situation, ONR promoted small-group discussions, expert outreach, and finally convened a community-wide working group that met for two days at the University of Michigan in July 2016. This working group meeting was well attended, with 23 participants from government, 27 from academia, and 8 from industry. During all of these discussions, a careful effort was made to record the community's view of the FSI landscape faithfully. This report documents this viewpoint. It is explicitly not a roadmap, or research funding recommendation, but instead a map of the FSI landscape as it currently exists and is experienced by academics, research scientists, and application engineers.

Of course, within any large and dynamic community, there are differences of opinion and different viewpoints. The goal of this report was to include the full breadth of viewpoints in this document. However, to form a coherent document the authors needed to structure the results of the discussion into topics, themes, and supporting ideas. This structure should be viewed as the author's best effort to reflect the community, though we are sure some would hold a different ordering and structure in their own mental images of this community. The FSI landscape is also evolving, with new numerical, experimental, and full-scale investigations underway. Thus, this viewpoint represents a static snapshot in the summer of 2016 of a changing landscape. For those new to the FSI world, or to those immersed in it, we hope having such a view of this discipline will prove helpful in engaging others and in furthering our understanding of FSI for naval applications.

To better focus the discussion, a specific scope of FSI problems was defined. This scope was primarily a reflection of expertise available to the group that carried out these discussions, and is not a reflection of the importance or value of the excluded topics. Given the Navy's long-standing involvement with ship hydrodynamic loading, propulsion, and weapon effects, those topics were selected as the primary focus. Other areas, including internal flows in machinery, fire simulations, chemical and biological agent dispersion and similar topics were excluded from this discussion. A complete list of included and excluded topics is presented below.

Topics included:

- Global ship structural loads
- Local exterior loads (e.g. slamming)
- Local interior loads (e.g. sloshing)
- Appendage loads
- Propulsor performance
- Acoustic noise
- Weapon effects on ships

Topics excluded:

- Materials
- Resistance
- Seakeeping topics beyond those included above
- Weapon modeling
- Fire
- Chem-bio
- Air-wake
- Machinery/internals (e.g. Piping)
- Aircraft
- Multi-body effects
- Thermal
- Spray
- Wake
- Icing

The remainder of this report is divided into sections by topic. In the remainder of the introduction, summaries of the current state-of-the-art in fluid simulation, structural simulation, and coupling approaches are presented. These summaries were prepared by experts in these fields invited by ONR and were presented at the beginning of the working group in Ann Arbor. After this, a summary of the state-of-the-art in current FSI use cases and the challenges of future needs is presented. These sections represent the primary product of the working group in Ann Arbor and are supported by extensive appendixes at the end of the report listing the full discussion from Ann Arbor. Based on both small-group discussion and the result of the working group in Ann Arbor, a taxonomy and overall scope of the FSI problem is then outlined. Finally, discussion and conclusions are presented. The main body of the report is supplemented with several appendixes that offer lessons learned from the Ann Arbor working group and the process of attempting to establish a common viewpoint.

2.1 State-of-the-Art in Fluid Simulations

Dr. Joe Gorski of the Carderock Division of the Naval Surface Warfare Center presented Hydrodynamics as Related to Fluid-Structure Interaction. Traditional hydrodynamic analysis has focused on the areas of speed, resistance, powering, hull form design, maneuvering and control, seakeeping and loads, and propeller design and analysis. Fluid-structure interaction is typically considered important for unsteady interactions such as wave interactions, extreme events such as slamming, water on deck, and propeller crashback, and analysis of flexible structures and appendages. Uncertainties exist as to whether the fluid loading changes the structure and if structural changes impact the hydrodynamics. Research issues that impact real ship and propulsor configurations include scaling effects, operational envelopes and regimes, and repeated unsteady responses and behavior. A detailed understanding of one particular situation is of limited value if it cannot translate to broader understanding because real geometries and real world effects have an influence on different configurations.

NSWCCD's Maneuvering and Seakeeping Basin (MASK) was used as an example of current state-of-the-art facilities for experimental investigation of FSI. The basin is 360 feet long, 240 feet wide, and 35 feet deep, with a state-of-the-art wavemaker capable of simulating ocean conditions up to sea state nine. Extreme events can be simulated, including the production of designer waves to match a specific surface profile, but one of its limitations is that it is not currently capable of measuring the subsurface flow field in a routine manner. Experiments are performed with instrumented models. However, even with very controlled, simple experiments there can be a wide variation in the measured results, particularly for extreme events in waves. An example of such variability is the testing in the long basin illustrated in Figure 1, in which a 20-foot long wave impinges on a flat plate. Figure 2 shows the variation in impact pressure that was measured during each different experimental condition.

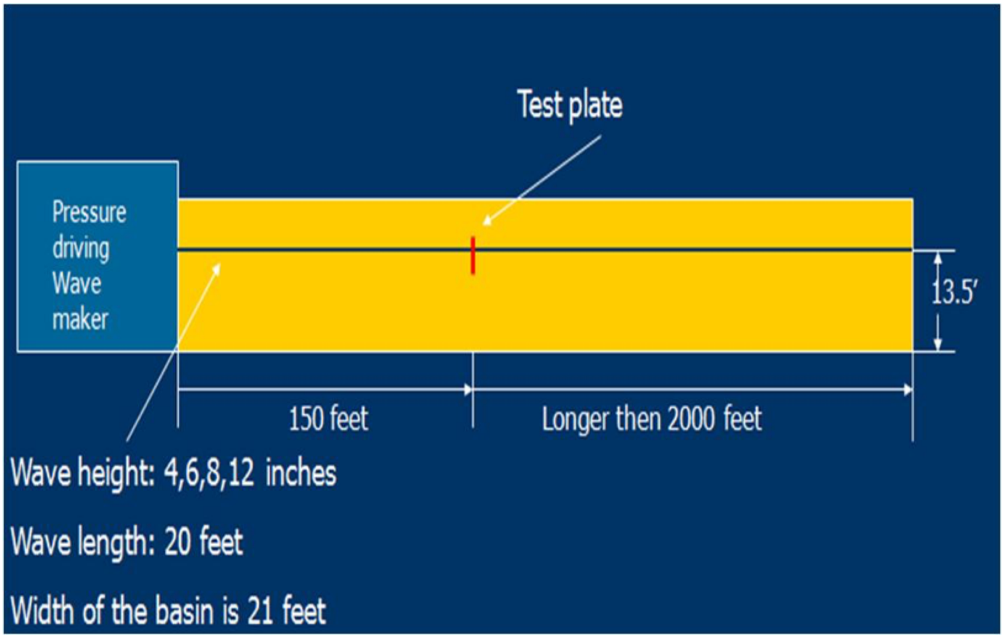


Figure 1: Test setup for flat plate wave impact simulations

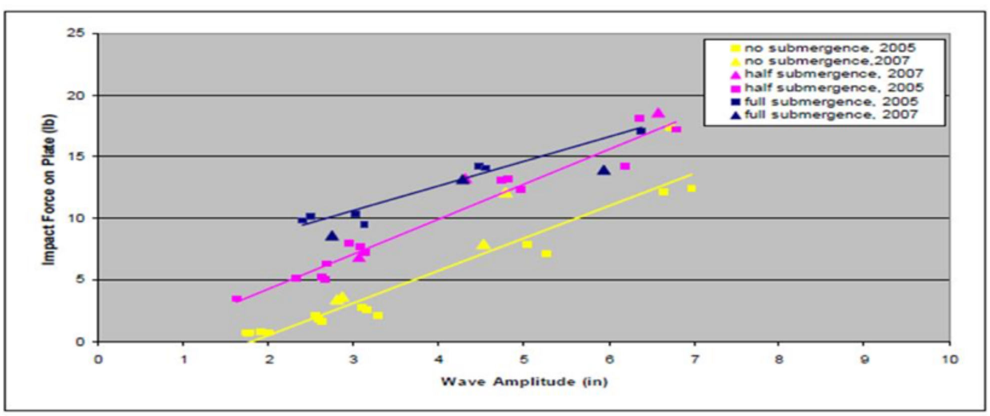


Figure 2: Variability of the impact load in flat plate wave impact simulation.

Computational fluid dynamics can offer insight into physical phenomena. However, one should not assume that the most complex methods will always produce the best results. All methods have given both good and poor results, and require an understanding of the underlying physics to use them properly. Linear simulations will not correctly predict highly nonlinear problems and poorly resolved Reynolds-averaged Navier-Stokes grids will provide poorly resolved solutions.

The range of methods available is illustrated in Figure 3 (and also discussed further in the taxonomy section), going from the linear frequency-domain codes to Reynolds-averaged Navier-Stokes equations. The linear methods are often good for conventional hull forms operating at various speeds. Potential flow methods can be used for nonlinear time-domain simulations with events such as slamming and whipping modeled separately. They require many hours of simulation in irregular waves. High-fidelity Reynolds-averaged Navier-Stokes methods are the dominant ship analysis tools used when viscous effects are important. Their use will continue to increase in the future. Large eddy simulation (LES) and hybrid RANS/LES methods are needed in examining complex flow structures where detailed turbulence information is needed for predicting ship performance.

Figure 3: Hydrodynamic methods. Taken from P. Temarel et al., Report of Committee I.2 Loads, *17th International Ships and Offshore Structures Congress*, 16-21 August 2009, Seoul, South Korea, Volume I, Pages 127—210

Analysis of fluid-structure interaction is encompassed by a wide range of simulation tools and experimental information, but the most complicated tool is not needed for everything. There is a need to determine where two-way coupling is necessary for solving the problem or where separate analyses of the fluid and the structure are adequate. The more extreme events are typically the most problematic, especially as extreme events can happen in a relatively short time as part of a long duration event. Extreme events impact lifetime loads and need correct interaction, such as imposing slamming and whipping loads on top of normal hull girder bending. Validation of fluid-structure interaction analysis methods is complicated, and there is a need to ensure that the correct comparisons are made to make relevant conclusions. Issues of scaling of model tests need to be addressed. The ultimate question to be answered is whether there is trust in the analysis, computations, and experiments.

2.2 State-of-the-Art in Structural Simulations

Dr. Neil Pegg of Defence Research and Development Canada presented an overview of the current state-of-the-art in structural simulations. There are many different types of ship structure analyses depending on loading conditions and particular phenomena being investigated. Dr. Pegg presented three different taxonomies, dealing with analysis, structural response, and of fluid—structure interface (not interaction).

For structural analysis, Dr. Pegg presented:

- **Static wave balance:** In most traditional ship structural analyses, the ship is statically balanced on a wave, from which hull girder bending moments and other load effects can be obtained. These loads are used in simple beam theory calculations or in refined finite element analyses. In the static case it is assumed that there is no fluid-structure interaction between the ship structure and the hydrostatic loads.
- **Quasi-static loading:** In dynamic (quasi-static) loading by long waves, fluid-structure interaction is normally handled by a frequency-domain panel method hydrodynamic analysis code linked to a finite element analysis, with inertia forces required to achieve a balance of forces. This type of analysis is used with a design operational profile and statistics to obtain the extreme and cumulative fatigue loads for design.
- **Vibration:** Vibration calculations treat fluid-structure interaction through the concept of added mass effects, either by analytical calculations (Lewis forms and beam theory) or fluid elements in finite element calculations. In most cases the added mass is approximated as a constant. Vibration analysis of ship structure is performed on global hull and local structure, usually to avoid resonance with known forcing functions such as propeller excitation.
- **Wave impact:** Dynamic wave impact calculations are a more challenging aspect of fluid-structure interactions. Computational fluid dynamics methods are used as well as the results of model and full-scale experiments. Time-domain calculations are made, with possible separation effects by cavitation considered. These analyses are used to augment quasi-static analysis to include whipping and springing and to get local pressure loads.
- **Dynamic underwater explosion:** Far field dynamic underwater explosions (UNDEX) are analyzed in fluid-structure interaction computations by boundary/acoustic elements. Example codes include the USA code. For near-field explosions, computational fluid dynamic codes such as the Chinook code are used. These methods can model the initial shock wave, bubble pulse, jetting, and bulk cavitation effects.

Each analysis approach has developed its own toolchain, acceptance criteria, and modeling approach.

Different structural responses used today include:

- Elastic (stress-based) response measures
- Ultimate strength response measures
- Buckling prediction
- Fatigue life prediction

Additionally, there are many non-linearities that impact structural response, including load calculations, material, and geometric non-linearities. In terms of fluid-structure interface, much of the work today is done with linear approaches. These approaches translate wave pressures over the entire hull into local stress ranges. The structure of many fluid-structure interface approaches include a unit pressure taken per finite element on the hull, a unit wave per single heading, speed, or frequency of encounter in a hydrodynamics code, and the interface between hydrodynamic analysis panels and finite elements. In this interface the finite elements and panels do not usually match, and an interpolation to the finite element centroids is made and or the hydrodynamic panel pressures are calculated implicitly at the finite element centroids. These calculations are made with an operational profile that defines the statistical wave spectra, headings, and speeds that the ship will encounter through its life or operation. This profile is used with hydrodynamic codes and finite element models to define extreme values and cumulative loads.

A central challenge in structural analysis is that many failures originate at length scales that are orders of magnitude below platform size, as illustrated in Figure 4. Overall hull girder response to loading must be scaled down to local areas of irregular geometry, and these, in turn, must be scaled down to smaller-scale irregularities and possible defects (at the weld level) in structure to predict failure.

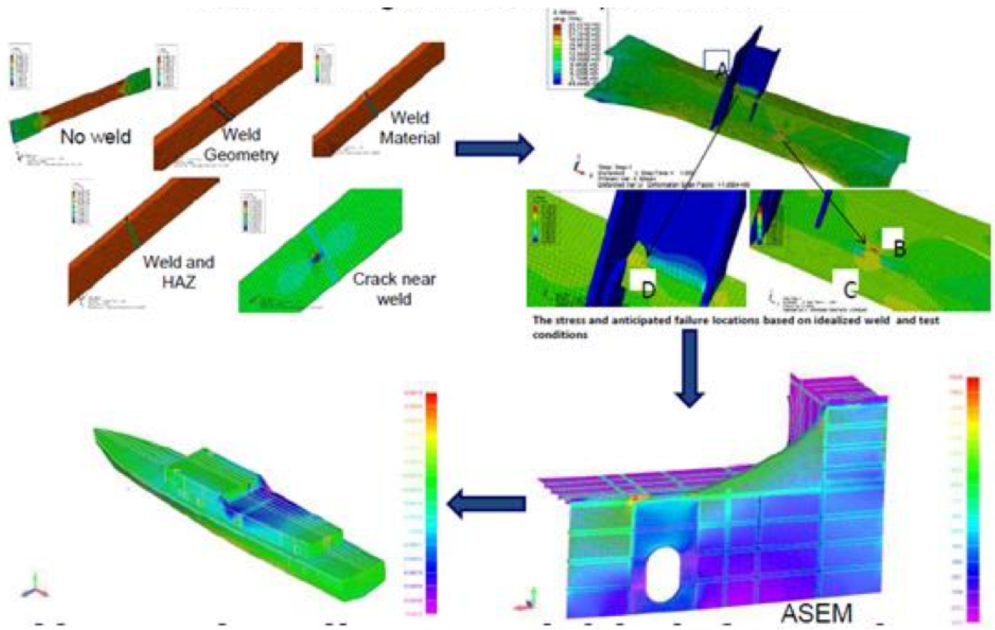


Figure 4: Range of scales and scalability challenge of structural calculations

The DRDC Below-Water Vulnerability Program works on the development of validated numerical models for naval platform vulnerability assessment. In model development, model validation is performed with experiments or sea trials to update the analysis models. Areas considered include high strain-rate materials, plates and stiffened panels, scaled hull girder whipping tests, and full-scale shock tests. Applications and deliverables include high-fidelity coupled computational fluid dynamics and finite element analysis for platform performance assessments, damage templates for design, and safe stand-off distances. Outcomes of these analyses are an improved understanding of the vulnerability of existing ships, improved force protection, and the improved survivability of future ships.

Another tool available is the Chinook/LS-Dyna coupling. Chinook and LS-Dyna are run in parallel, with Chinook run on multiple processors for computational fluid dynamics, and LS-Dyna typically run on one processor for nonlinear structural response. Data is exchanged between the two codes at predefined coupling times, and the data exchanged depends on the type of coupling. For small-deflection coupling, the 2-way coupling exchanges data on pressure and velocity, but large deflection coupling also exchanges data on displacement of fluid and structure.

The resources of Defence Research and Development Canada are enhanced by several cooperative international research programs. Close proximity underwater explosion effects have been jointly investigated by Canada, the Netherlands, and Sweden through a memorandum of understanding since 2005. The goal is to create a validated numerical prediction capability for the close proximity underwater explosion loading and damage. The scope of the program includes reduced-scale experiments to measure loading and response. Simulations of experiments are made with simplified loading models and improved material failure models based on measured high-strain rate properties. The scope of the program is illustrated in Figure 5.

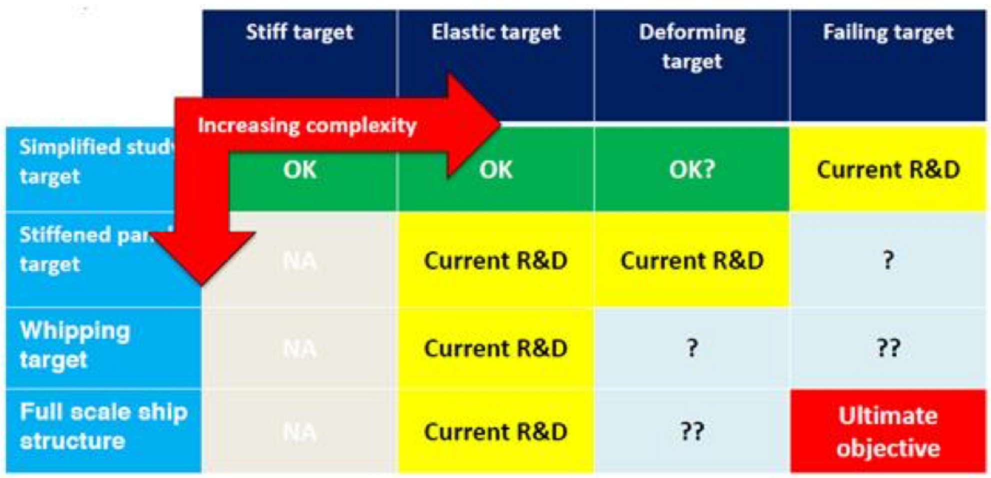


Figure 5: Scope of cooperative program in close-proximity underwater explosions

Slamming loads are being investigated in the program Cooperative Research Ships, which is proprietary to the 27 members, who represent shipyards, suppliers, operators, navies, classification societies, and research organizations. The program has undertaken a series of projects encompassing experiments and numerical studies to try and predict structural loads from slamming by augmenting a nonlinear time-domain panel code with computational fluid dynamics (CFD) analysis of slamming to try and get complete pressure load time histories.

PANSHIP NL with Cooperative Research Navies has membership of the Canadian Navy, Netherlands Ministry of Defence, DGA Hydrodynamics, Royal Australian Navy, Royal Netherlands Navy, Royal UK Navy, U.S. Coast Guard, and MARIN. MARIN has led the effort to combine model tests, full-scale trials, data, and numerical simulations to better predict the complete load pressure history.

Computational fluid dynamics is now used routinely by Defence Research and Development Canada to predict propeller loads. Both panel codes (PROCAL) and Rankine-averaged Navier-Stokes (RANS) codes (ANSYS CFX, Star CCM+, OpenFOAM) are used. In general, the panel codes work well near design conditions, but the RANS codes are better at off-design or extreme conditions such as crashback, but are more computationally expensive.

A key part of validating structural predictions are full-scale trials. Tests and trials used to obtain data and verify and validate analysis methods range from small-scale component tests for fatigue, medium scale model tests for ultimate strength of structural members, large scale model tests for ultimate strength of the hull, and full-scale sea trials. One structural loads trial was conducted in 1997 on the destroyer HMCS Nipigon. The event had seven days of dedicated short term trials from

December 1 to December 11, 1997. Operations were conducted in the North Atlantic, Newfoundland Region in a range of sea states from a significant wave height of 1.5m to 5.5 m. Measurements were taken at 8 and 18 knots in five directions relative to the waves; head, bow, beam, quartering, and following seas. There were seventy runs, each run for 20 or 30 minutes in duration. Figure 6 shows the extent of instrumentation of the ship during the trials. The results of the sea trial measurements were then compared to finite element analyses as shown in Figure 7. Comparisons can never be precise because of the many uncertainties involved, including uncertainties in sea loads, as-built fabrication, material performance, limit states, and overall model uncertainty.

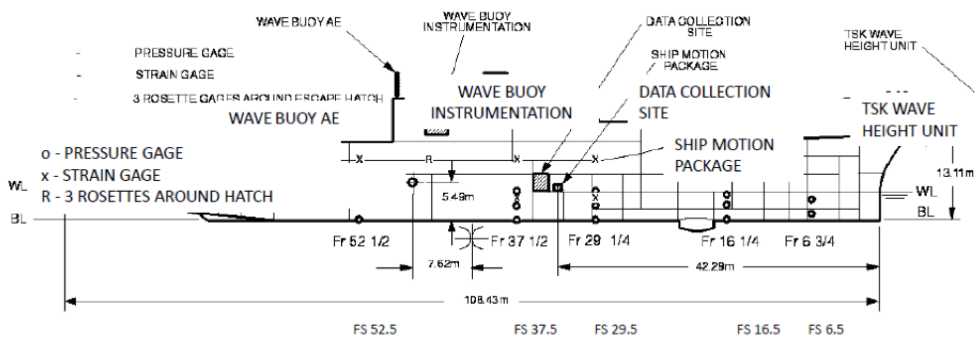


Figure 6: Instrumentation of HMCS Nipigon during 1997 sea trials

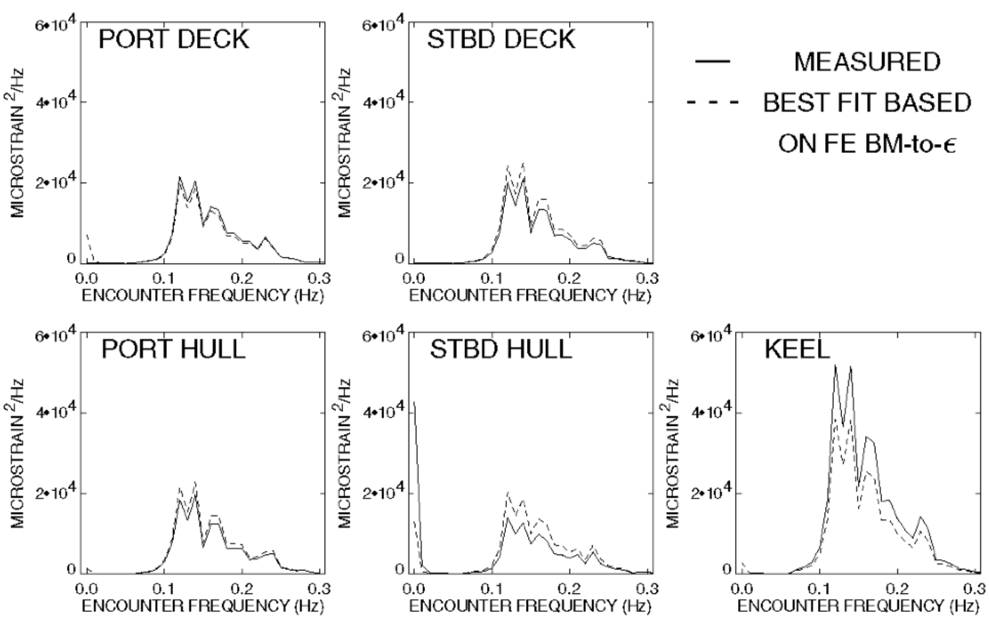


Figure 7: Comparison of measured strains from trials to finite element analysis of HMCS Nipigon

2.3 State-of-the-Art in Coupling Between Fluids and Structures

Dr. Chris Earls of Cornell University presented the topic "Perspectives on FSI Coupling Approaches: Emphasis on Naval Applicators." There are many fundamental challenges to the field of fluid-structure interaction simulation, including a theoretical understanding of the dominant and emerging coupling methods such as convergence properties, error bounds, computational scale and complexity, visualization and data transfer of huge datasets, and software engineering across legacy codes and pairing these codes to new high-performance computing architectures. One of the fluid-structure interaction coupling strategies that bear on naval applications is predicting hydrodynamic loading, including primary hull girder bending and predicting secondary loading such as slamming, whipping, and sloshing. Other applications include calculation of stability and seakeeping, maneuvering and resistance, weapons effects, and multi-phase events such as spray and icing.

There are two general approaches to fluid-structure interaction coupling, loose and tight coupling. Loose coupling, also referred to as weak, staggered, or explicit coupling, is used for such problems as aero-elasticity and bridge engineering where the density of the fluid is much less than the density of the structure. An example of fluid-structure interaction in bridge engineering is the analysis of vortex shedding, which can cause large displacements when resonance of the vortices with the structure occur. Loose coupling usually adopts a partitioned coupling approach. Tight coupling, also referred to as strong or implicit coupling, is used for problems such as blood flow within vessels, heart valve motion, and ship hydrodynamic loading. Tight coupling may involve either monolithic or partitioned coupling strategies.

In loose coupling, within a given solution time step (increment), the pressures, and velocities in the fluid during the first half step are taken as those of the structure in the subsequent half step; thus completing the time step (increment). In tight coupling the pressures and velocities of the fluid and the structure are iterated on, to ensure satisfaction of conservation equations, before closing out the time step. Also within the context of tight coupling, the contribution of mesh motions to the conservation equations must be considered (e.g. using arbitrary Lagrangian-Eulerian (ALE) methods). In some conditions, loose coupling will remain stable through successive iterations, but in other cases numerical instability may occur, and tight coupling will be required.

In naval applications tight coupling will sometimes be required because of the density ratios and problem domain geometries. Two types of tight coupling are used, monolithic and partitioned coupling. With monolithic coupling the tight coupling begins at the level of governing equations of the fluid-structure interaction system. There is a single data structure that embodies discretization of the fully coupled linear system of fluid and structure. A single solver is used for the combined fluid-structure system. With partitioned coupling two different solvers are used, one for the fluid, and one for the structure. Partitioned coupling requires software coupling to glue the two independent solvers together in a principled way. The coupling physics is handled by the software coupling, which must respect the particulars of the individual codes to be coupled.

Monolithic coupling offers the advantage that the coupling occurs at the governing system level, the tightest scheme available. With a self-contained fluid-structure interaction solver there is less communication overhead during the interaction solution and there is a single software tool that will need to be maintained. However, monolithic coupling is not ideal because a single solution strategy (e.g. the finite element method) must be used for both the fluid and the structure. The coupled system contains very different types of field variables, and so numerical ill-conditioning is a concern. Because of the constraints on keeping the solution strategy for the fluid and structure the same, it is difficult to update the solver to match advances in the state-of-the-art for each component, such as the latest turbulence or materials models.

Partitioned coupling is advantageous in that having separate solvers allows for the most efficient solution approach for each domain in the problem: using finite elements for the solid and finite volumes for the computational fluid dynamics. Partitioned coupling leverages the existing substantial investment in legacy code development and permits the legacy codes to continue to evolve independently of each other. However, partitioned coupling requires a robust coupler that properly respects the conservation of mass, momentum, and energy within the FSI transmission conditions. Partitioned coupling requires careful consideration of communication overhead to remain efficient and it is difficult (or potentially impossible) to prove things formally about convergence and solution error bounds since the fluid and structure domains are modeled using different methods (i.e. finite volume and finite elements in the same analysis).

An example of the use of monolithic coupling is shown in Figure 8, where a numerical analysis was made of the model of the notional Joint High-Speed Sealift ship. The model had an internal spline along its length to support the sections of the model and to determine bending moments as the model was tested in waves. The figure shows the finite elements used for the structure and for the fluid.

A schematic of the partitioned coupling scheme is shown in Figure 9 where the coupling manager software uses several interfaces to simultaneously run the computational fluid dynamics code and the computational structural dynamics code. Partitioned tight coupling can be computationally expensive as conservation of momentum, energy, and mass must be respected at the structure-fluid interface at the end of each solution time increment. This requires sub-iterations during each time increment to achieve the desired conservation to user-specified tolerances. Additional complexity in the conservation laws arises from the need to update the fluid mesh boundary during sub-iterations in accordance with the arbitrary Lagrangian-Eulerian (ALE) finite element formulation in which the computational system is not a priori fixed in space.

An example of using partitioned coupling is shown in the solution of Turek and Hrons Problem, Case FSI3 in which a flexible plate is held in a moving fluid as shown in Figure 10. The finite-element code CU-BEN has been coupled with the computational fluid dynamics code OpenFOAM.

Alternatives to the tightly-coupled partition approaches, which are expensive to run, are the semi-implicit schemes, developed for problems where strong-enough coupling is sufficient. A diagram of the process is shown in Figure 11. With semi-implicit coupling, mass and momentum are conserved, but energy is usually not quite conserved, which is likely not a big concern for subsonic flows in naval applications. Known stability proofs for semi-implicit schemes are based on an analysis of the resulting weak form description of the governing coupled system, thus restricting application to cases where finite elements are used for both the fluid and the structural domains.

In conclusion, different coupling strategies are appropriate for different FSI scenarios such as significant added mass effects or peculiarly shaped domains. Different coupling strategies incur different computational costs, and possess different solution stability properties. Solution accuracy and subsequent fidelity to the real-world depends strongly on the correct selection of the coupling method. There is much research that should be done to determine appropriate coupling strategies for each dominant naval application theme, although there will be no single perfect solution. Sophistication is required on the part of the analyst in achieving useful fluid-structure interaction solutions such as selecting the appropriate coupling scheme and diagnosing and mitigating stability issues. The foregoing is predicated on the existence of a robust, validated suite of flexible fluid-structure interaction tools to select from: this suite does not currently exist.

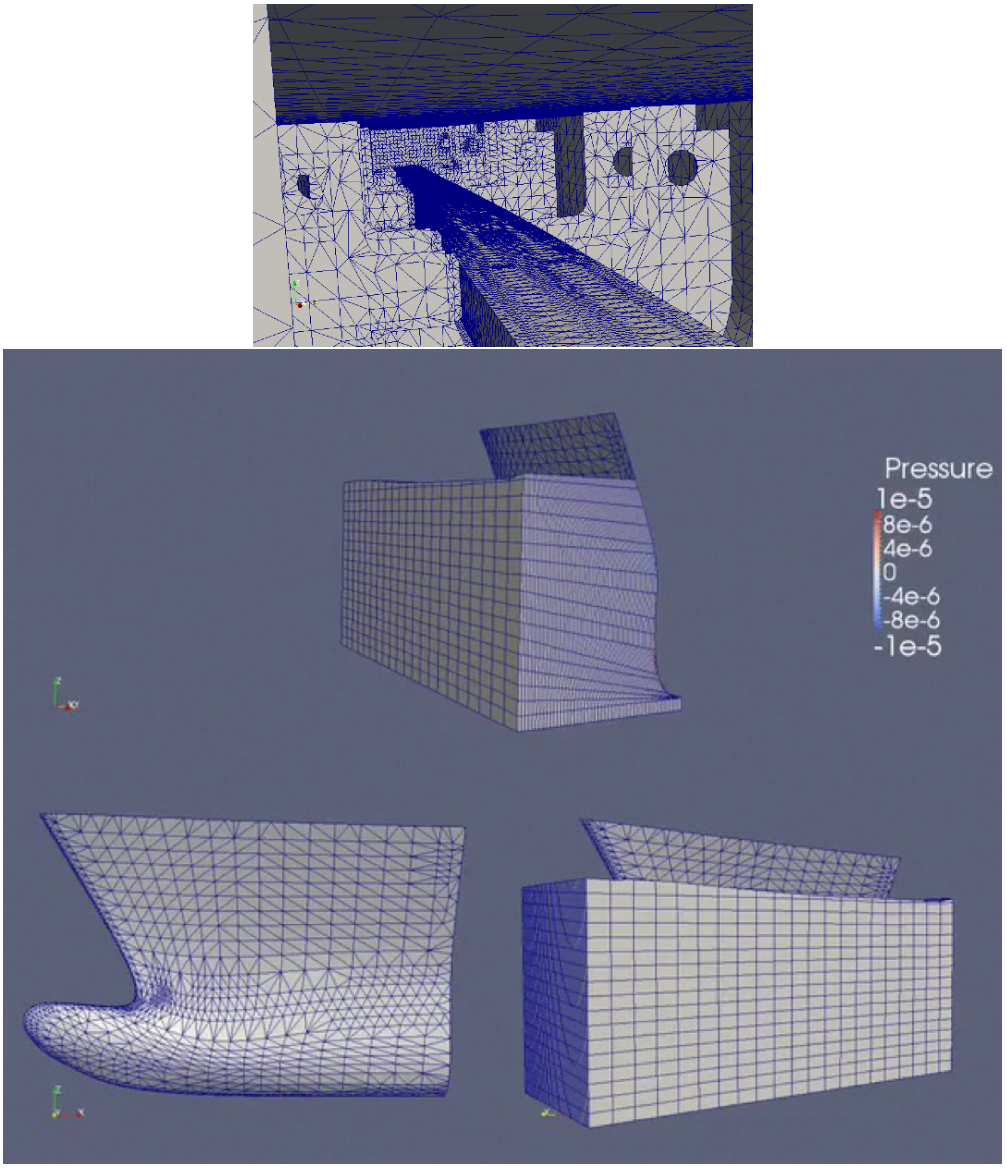


Figure 8: Monolithic coupling applied to the analysis of the notional joint high-speed sealift ship. The upper figure shows the detailing of the internal structure of the splined ship model that had been tested in a wave-making tank.

3 Summary of Use Cases and Future Needs

3.1 Use Cases

Working with engineers from NSWCCD, several current and anticipated FSI use cases were developed in slide format. These slides were circulated to the working group attendees for reflection before the working group. During the fist day of the working group, the participants were divided into nine groups of five people. Three groups addressed platform (global) level FSI responses. Four

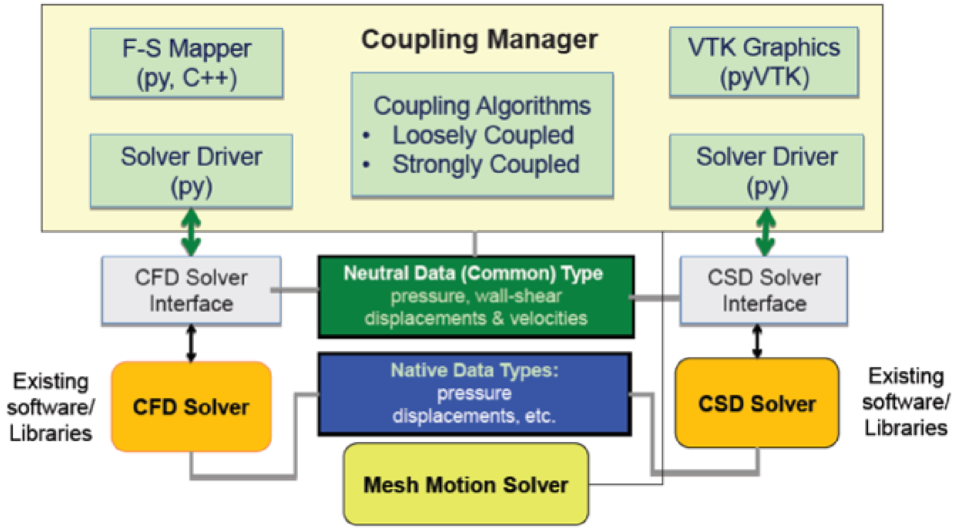


Figure 9: Partitioned coupling between the computational fluid dynamics (CFD) solver and the computational structural dynamics (CSD) solvers. (Kim and Miller, NSWCCD)

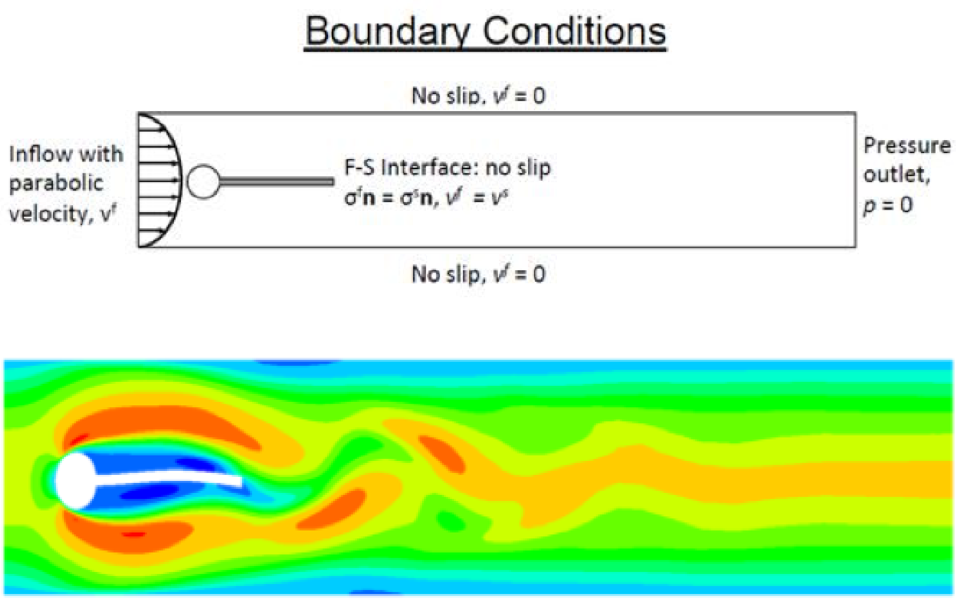


Figure 10: The analysis of flexible plate in a moving fluid analyzed in a partitioned coupling scheme.

groups addressed local level FSI responses. Two groups addressed propulsor and appendage FSI. Each group was tasked with reviewing the proposed use cases, and then adding corrections and proposing new use cases. In a wrap-up session, the groups in a common area met and combined their outputs from the day. These slides were then printed on large-format paper and placed for final open comment via sticky notes at the working session on the final day.

In addition to the use case descriptions, the group were asked to complete two additional documents.

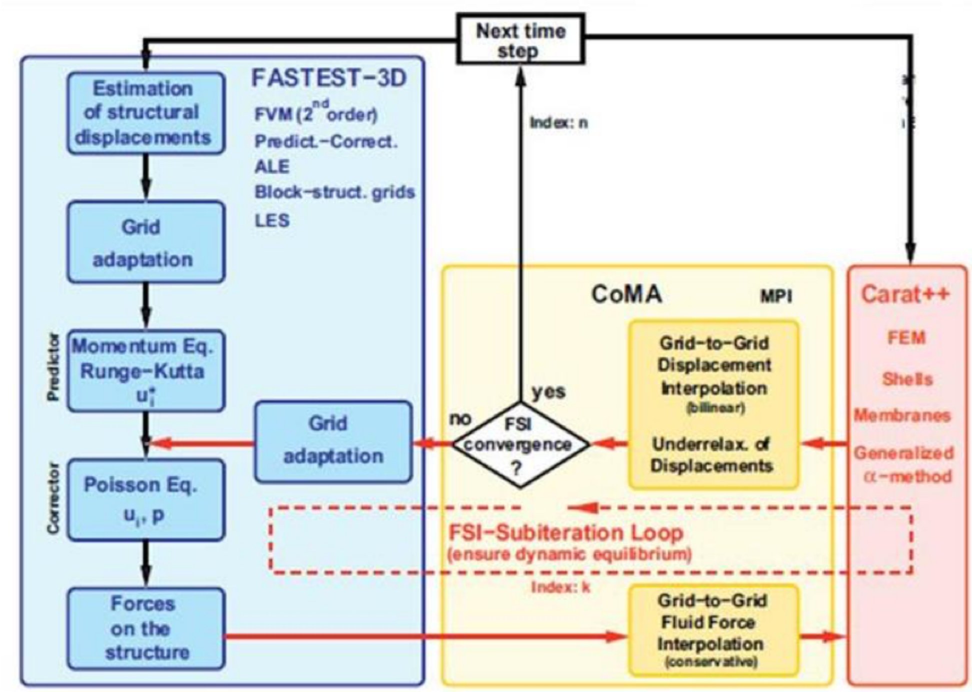


Figure 11: Semi-implicit coupling (after Michael Breuer et al. Fluid-structure interaction using a partitioned semi-implicit predictor-corrector coupling scheme for the application of large-eddy simulation. *Journal of Fluids and Structures*, 2012, 29, pp.107-130.).

First, for each use case the groups were asked to plot current numerical or experimental methods on axes of fidelity — one for fidelity in the fluid domain and one for the structural domain. Such points represent concepts or techniques, not specific simulation codes or experimental facilities. Each point on the graph was also assigned a Technical Readiness Level-inspired readiness level. These engineering methodology readiness levels (EMRL) follow the following definitions:

- **EMRL 0** Future academic proposals
- **EMRL 2** Current academic research at PhD level
- **EMRL 4** Code or protocol formulated, but only usable by developer, no or limited verification and validation
- **EMRL 6** Code or protocol documented, usable by small number of experts, some verification and validation
- **EMRL 8** Code or protocol in widespread use, verification and validation largely complete

The method fidelity plots help compare methods in term of their current readiness and potential for future development. Finally, each group also came up with a future vision plot. The vision plot proposes a wish-list of potential research topics for five, ten, and twenty years out. Additionally, future applications of FSI methodologies were also listed. These applications included both specific platforms, as well as more general techniques that would impact multiple platform types or acquisition programs. For the global and local FSI areas, one EMRL plot was made per use case, with one future vision plot for the entire area. For the propulsors and appendage FSI, the working teams felt an alternative approach would better describe their domain. A common ERML plot was made for all applications, but separate future vision plots were made for each use case. The full plots and text generated are included in the appendix of this report, the remainder of this section briefly summarizes them.

For global loading, the dominant use cases were integrated global loads on monohulls and multihulls, underwater explosions, and flexible (fabric) structures. For integrated global loads, several mature simulation capabilities exist, however, determining extreme event sequences and load combination methods are not as mature. Additionally, preliminary design tools for multihulls are currently lacking. Underwater explosions and flexible structure techniques are evolving but overall were rated less mature. Here, integration of local responses or failure modes into the overall global loading is still needed. The groups involved in this area of discussion saw many future research challenges, improved hydro-elasticity, methods of different fidelities, improve FEA model generation were all cited as near-term goals. Longer-term goals include tying models to local deformations and failures, increasing computational capacity, and understanding difficult phenomenon such as structural damping. Short term applications involve predicting a single extreme event for physics-based rules, while longer-term applications include multiple extreme events, better understanding of when FSI is needed, and finally comprehensive lifetime simulation.

For local FSI, significantly more use cases were considered. These include impact and slamming on boats, local slamming pressures, sloshing, cumulative damage from local external slamming, AIREX, wave slap and secondary non-impact pressure, and ice impact. The last three use cases were not discussed by the groups at the Ann Arbor event, so the input on these cases comes only from prior input from small group discussions. In general, techniques for local FSI were seen as less mature than global FSI, with most ERML values at 4 or less, and many areas having EMRL values between 0 and 2. In this area, it is clear that current work in FSI is focusing on two-way coupled codes capable of handling viscous fluids, with the desire to extend to non-linear structural response. Much work is being done on the transition to multiphase fluid flows as well. Understanding the boundary conditions — e.g. the motions and maneuvering of small craft that set up the impacts — is also a central challenge. This is also true for large-ship local FSI, where accurate boundary conditions from both the global ship motion and distributed wave field are required. For future goals, broad developments in experimental, numerical simulation, and data processing were all identified. Longer term goals include improved sensing, and transition to design tools. Verification and validation, as well as uncertainty quantification were also highlighted by the groups. Future applications consist of both scale experiments to support research goals, as well as improved lifetime prediction capability for platforms.

Propulsors and appendages produced three use cases, propulsor and appendage dynamics, unconventional propulsors and appendages, and acoustics of propulsors and appendages. The last use case had research goals, but no use case description slide. FSI was seen as a potential enabling technology by this group — by designing foils that take advantage of FSI, improved performance may be possible. This was a different outlook than the global and local response groups which saw FSI as primarily a modeling challenge to be minimized. In general, the desired tools for this domain still have EMRL values below four, with many below two. Large deformations, the potential for multi-phase flows, the desire to use composite structures, and the importance of acoustic prediction all combine to make this a challenging research area. However, the advantage would include appendages with both active and passive FSI control, leading to higher propulsion efficiencies, reduced noise, and higher safety. Research needs again spanned numerical and experimental disciplines.

For numerical methods, multi-phase turbulence modeling, improved composite material modeling, and better coupling, especially to acoustic codes were short term goals. Longer-term goals extended on these short-term goals to include integration with control, real-time structural health detection, and ability to handle maneuvering platforms. Reduced-order models for design were also identified as a research need. New experimental methods identified include the need to be able to simultaneously measure hydrodynamic, structural, and acoustic phenomenon. Progression of applications saw the short-term application of small deflection, passively-controlled appendages, with a move towards larger deflections, active control, and smart materials in the 10—20 year time frame.

3.2 Future Needs

At the end of the first day of the Ann Arbor event, participants identified common or interesting research challenges from their day one discussions on post-it notes. The event organizers met that night, reviewed the notes and use cases presented, and developed eight questions on future research to be answered on day two. These questions were answered in group settings, in two rounds of four questions so each participant could provide their input on two questions. Each group then presented their discussion to a plenary session, where further questions and suggestions were made. Finally, a walking poster session was held where participants could further comment on any topic of interest. The questions and a brief summary of the responses are listed below. In many cases, the responses to the questions were quite varied, so the summaries below only capture major or common points. In the appendixes to this report, the full questions, sub-topics, and complete responses (including plenary discussion and walking poster session issues) are presented. This more detailed description should be consulted to get an idea of the full scope of the discussion around these issues. A future working group dedicated to a further exploration of these topics would be worthwhile.

1. **How can we better utilize machine learning and data processing to improve the generation and understanding of large experimental and computational data sets?** Improvement in both automating gridding and geometry, as well as pattern recognition and dimensionality reduction of output sets, were identified. How to exploit legacy data, and how to use machine learning to replace physical models were also mentioned.

2. **What are the current limitations of fluid simulation methods for FSI problems and how can we reduce them?** Improvements from design models, potential flow models through LES models were all requested. The ability to model acoustics and erosion on appendages were highlighted. UNDEX modeling, multi-phase cavitation, including multiple time scales of the different processes involved were also mentioned. The ability to blend multiple fidelity simulations in one model either spatially or temporally, and the ability to correctly identify phase-resolve waves leading to extreme events to simulate was also identified.

3. **What are the current limitations of structural mechanics solution methods for FSI problems and how can we reduce them?** Challenges around scalability of calculations, the ability to automatically mesh/re-mesh after damage or fragmentation were noted. The ability to refine meshes automatically around local damage or failures was particularly highlighted. Composite/metal joints and structural damping also need further investigation. Modeling approaches short of 3D-FEA for early stage design was also highlighted.

4. **What are the current limitations of coupling approaches to FSI problems and how do we address them?** Convergence of the coupling approaches used today, guidance on best practices, along with experimental validation, were all seen as near-term goals. Longer term goals include working on more complex problems — fragmentation, bubbly flows, and uncertainty quantification. A standard coupling application programming interface or specification was also highlighted.

5. **What physics and applications require us to address the full 2-way coupled FSI problem? When can we use other approaches?** This question was seen as largely unanswered at the current time, with approaches including parametric exploration and machine learning proposed to develop this knowledge for increasingly complex problems. A long list of factors to consider for this decision was generated and discussed during the floor session. Uncertainty quantification and coupling to non-linear codes were also highlighted.

6. **What are the current needs for Verification and Validation? What uncertainty quantification developments are needed?** A set of clear, canonical problems with isolated physics was seen as a near-term goal. Careful structuring to understand coupling, scaling, and facility bias will be needed. Collaboration between experimental design and numerical simulation was also needed. Longer term goals include better uncertainty estimation and sensing capabilities.

7. **What experiments are required to advance our understanding of FSI?** A series of increasingly complex benchmarks were proposed. These start with simple single-phase, forced motion cases and run through larger multiphase problems. The spatial scale of the model should start with simple components and proceed through more ship-like models. Clarity in boundary conditions, repeatability, understanding of scale effects, and the ability to make the data accessible to the community were all highlighted. Developments in instrumentation would also be required.

8. **What are the key problems with user training and human interaction with complex FSI numerical simulations?** Ideas including blind tests, consortia of developers, and promoting shared code ideals were all discussed.

4 Taxonomy and Scope of Application

Over the course of several FSI events, it became clear that there wasn't a clear definition of:

- What exactly constitutes FSI
- How development in different FSI "stovepipes" connected or could support each other
- The complete scope of activities required to go from defining an FSI problem to actionable information for platform design or analysis.

In both the run-up to the Ann Arbor event, and through offline discussions with members of the FSI community, member's input on these questions was solicited. In reviewing the use case, technology, and future challenges highlighted during the Ann Arbor event further information on these questions came to light. This section attempts to provide a high-level view of these questions. The goal in doing so is to provide a map-like view of the technical terms, technical methods, and scope of the entire field of FSI application. This information should be considered as one view of the community

— other perspectives are equally valid and could be more useful in certain applications. However, as a way of enabling cross-discipline communication and showing the relationships between various FSI efforts, the current imperfect model is presented in this section.

4.1 Taxonomy

4.1.1 Description of FSI Problems

At the end of the first day of the Ann Arbor event what constituted FSI was unclear. Several participants noted that some of the use cases presented did not fit their working definition of FSI. However, follow-up questions revealed that there wasn't a standard FSI definition shared by the community. Based on these discussions, and a review of the use case comments, the following simple taxonomy is proposed to classify FSI problems. It is important to note that this taxonomy focuses only on the *problem* not the *solution* strategy to the problem. Solution approaches, in both the fluids and structures domain, are discussed in the next section.

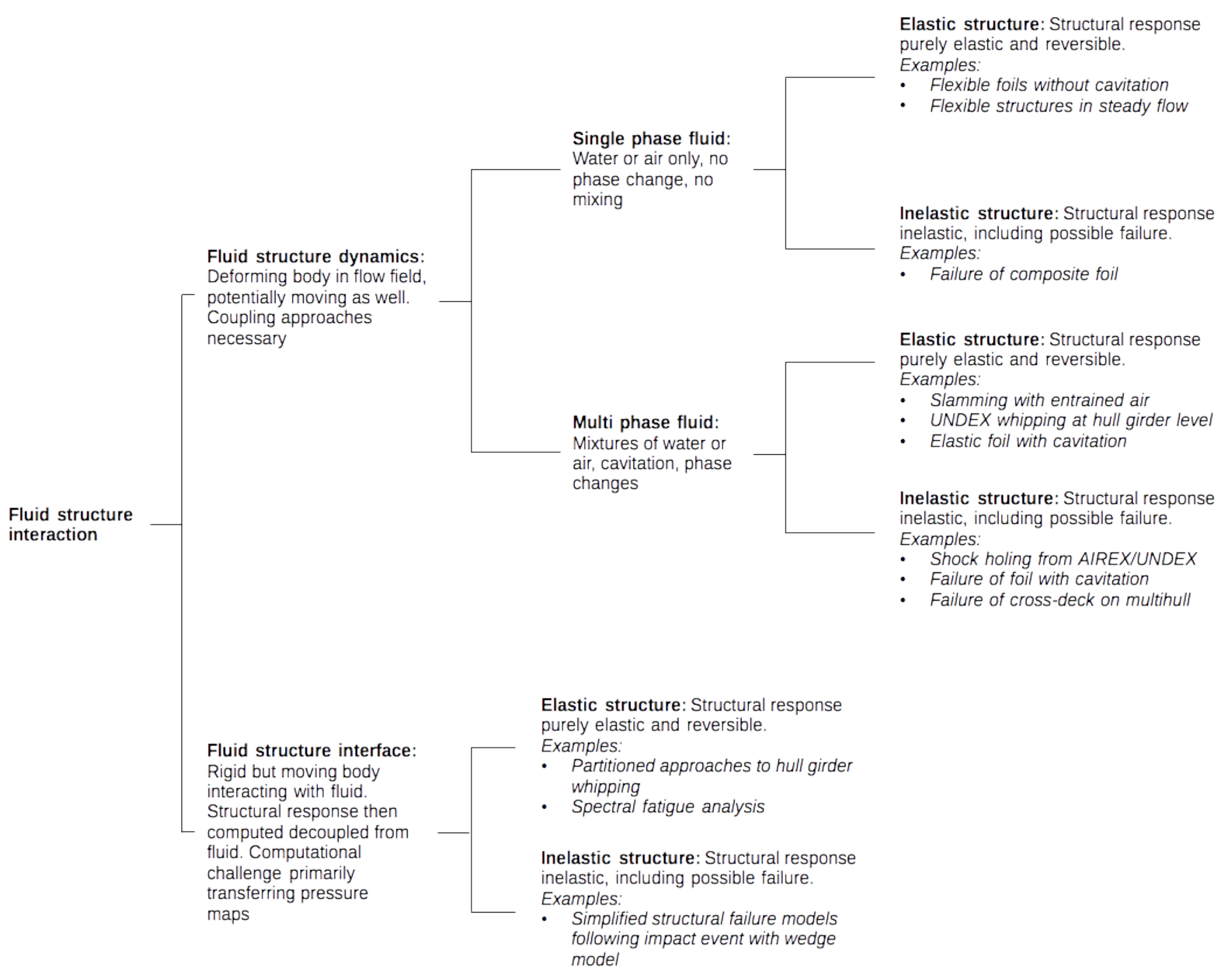


Figure 12: Draft taxonomy of FSI problems by fluid and structural model approach

During the workshop, two main branches of FSI emerged. The first, the lower branch of Figure 12, was termed fluid-structure interface. The lower branch normally involves a rigid body moving through the fluid, and pressures from that body being recorded and transferred to structural models. This approach is marked by a lack of feedback from the structural deformation to the fluid domain — a partitioned approach. While it was clear that many use cases relied on fluid-structure interface, many participants did not consider interface part of the traditional fluid-structure interaction (FSI) domain. However, the rigid body is still interacting with the fluid, changing the fluid from radiation and diffraction interactions, so it was decided to include this under the large umbrella of FSI, but as a separate branch. Many codes and approaches in this area appeared mature and tested.

The other primary branch was named Fluid-structure dynamics (FSD). Here, the deformations of the body are transmitted back into the fluid solution, though the degree of coupling may vary from simple one-way time-stepping coupling through to more complex iterative two-way schemes. FSD was further divided by the type of fluid model used, either single or multi-phase flow. Single-phase flow indicates the presence of either air or water in the fluid simulation, where multi-phase indicates a changing mixture of fluid and air through effects such as cavitation or bubbly flows. Furthermore, the type of structural model used, either elastic or inelastic can further classify the problem. The most complex FSI problems are the multi-phase inelastic approaches, for assessing ultimate strength under weapon or fluid impact loadings.

What emerges is a simple taxonomy that is useful in classifying FSI problems or prediction capabilities by asking no more than three questions. First, does the structural deformation influence the fluid? Second, does the fluid consist of one phase? And third, is the structural model fully elastic? Some thought was given to the timescale of the FSI problems as well, but it was decided not to add time to this hierarchy as many of the slower-responding problems naturally group themselves in the fluid-structure interface branch. Differences of time scale beyond this are usually more relevant in developing solution approaches, not describing problems.

4.1.2 Description of Numerical FSI Solution Methods

Beyond a taxonomy of the types of FSI problems faced by the Navy, it was clear that a list of common FSI computational tools would also help the community understand the current state-of-the-art. A small group of subject matter experts at NSWCCD and academia prepared a draft listing of the common calculation approaches used today. These approaches were separated by calculation type — fluids and structural approaches, and then tabulated. The listing of fluids codes are in Table 1, and the structures codes are in Table 2. Note that the codes in these tables are simply examples, not an exhaustive list. Both structures and fluid computational approaches are marked by a wide variety of modeling fidelities. Simpler potential flow codes remain in extensive use, especially for fluid-structure interface problems. Likewise, for some partitioned approaches, simplified methods are in use for quite complex structural collapse calculations (e.g. NSWCCD ultimate strength code ULTSTR), when a coupled approach is not necessary. At the high end, both communities are involved in developing codes that take days to weeks to run, even on high-performance computers. This wide range of calculation approaches tracks well with the taxonomy presented in Figure 12, where the FSI description is being used to describe a wide range of problems and complexities. However, it does underline the challenge in understanding the full scope of FSI today.

Table 1: Table of computational fluids dynamics (CFD) approaches

CFD Type	**Assumptions**	**Uses and Description**	**Codes**	**Computational Requirements**	**Typical Run-Times**
Potential Flow Solvers					
Conformal Transforms	• Inviscid • Irrotational • Incompressible 2D	Two-dimensional lifting surfaces. The shape is defined by performing a series of coordinate transformations of flow past hydrodynamic [mathematical] singularities (sink, source, doublet, or vortex) in the complex plane.	• Customized codes	Workstation	Seconds
Integral Methods (Panel, Boundary Element, Potential)	• Inviscid • Irrotational • Incompressible	External flows around complex geometries where the boundary layer is thin. The boundary is defined by small panels containing hydrodynamic [mathematical] singularities (sink, source, doublet, or vortex). It is generally good at calculating lift and pressure drag when flow remains attached. Used for aircraft and ship lift and drag calculations.	• Das Boot • FREDYN • Tempest • LAMP	Multi-core or multi-processor workstation	Minutes to a few hours
Inviscid Flow Solvers					
Euler	• Inviscid	All flows where negligible viscosity is a good assumption. Solved on a discretized domain. The equations are elliptic when flow is steady and hyperbolic when it is not.	• SAIC NFA • Customized codes • All RANS and LES codes	Multi-core or multi-processor work stations	Hours
Viscous Solvers					
Navier-Stokes	• Laminar • Continuum	All flows where the maximum Reynolds number indicates the flow is below the transition to turbulence. Solved on a discretized domain.	• SAIC NFA • Customized codes • All RANS and LES	Multi-core or multi-processor Workstation or cluster	Hours to days

Table 1: Table of computational fluids dynamics (CFD) approaches

CFD Type	**Assumptions**	**Uses and Description**	**Codes**	**Computational Requirements**	**Typical Run-Times**
Direct Numerical Simulation	• Continuum	Solves the complete Navier-Stokes equations on a discretized domain. Generally limited to very small domains because it requires an extremely fine grid (Kolmogorov scale) and extremely small time step (to meet Courant condition).	• Customized codes • Many RANS and LES codes	High-performance computer	Days to week
Reynolds-Averaged Navier-Stokes (RANS)	• Turbulent • Continuum • Turbulence modeled • Steady flow	Solves the RANS equations on a discretized domain for flows where the majority of the domain is above the transition to turbulence.	• UNCLE • Navy FOAM • Fluent • CFDSHIP-Iowa • STAR-CCM	High-performance computer	Hours to days
Unsteady Reynolds-Averaged Navier-Stokes (URANS)	• Turbulent • Continuum • Turbulence modeled	Solves the unsteady RANS equations on a discretized domain for flows where the majority of the domain is above the transition to turbulence. It implicitly assumes that the empirical turbulence models developed from steady flow conditions remain applicable.	• UNCLE • Navy FOAM • Fluent • CFDSHIP-Iowa • STAR-CCM • Comet	High-performance computer	Hours to days

Table 1: Table of computational fluids dynamics (CFD) approaches

CFD Type	**Assumptions**	**Uses and Description**	**Codes**	**Computational Requirements**	**Typical Run-Times**
Large Eddy Simulation (LES)	• Turbulent • Continuum • Turbulence modeled to subgrid scale	Solves the low-pass filtered Navier-Stokes equations on a discretized domain for flows where the majority of the domain is above the transition to turbulence. It implicitly assumes that the empirical turbulence models developed from steady flow conditions remain applicable and that the small scale turbulence has a universal structure.	• Navy FOAM • Fluent • SAIC NFA STAR-CCM • Comet	High-performance computer	Hours to days

Table 2: Table of computational structural mechanics (CSM) approaches

CSM Type	**Assumptions**	**Uses and Description**	**Codes**	**Computational Requirements**	**Typical Run-Times**
Simplified Engineering Methods					
Rigid body dynamics	• Rigid body motion • No structural response	Used to capture overall body motions e.g. ship hull in waves. Can be used to extract local pressures where FSI effects are minimal.	• LAMP • OpenFoam • Customized codes	Virtual none but depends on fluid code	Seconds to days
Panel level and structural unit level models	Reduced order models of local response in valid range	Used to determine structural response characteristics on local level to inform global level e.g. panel response to capture hull girder behavior or global stresses for fatigue analysis.	• ULTSTR • Hullwhip • MAESTRO • Customized codes	Multi-core workstation	Seconds to minutes
Finite Element Analysis (FEA) Methods					
Linear FEA	• Response is linear i.e. no yielding, contact, severe deformations	Used to determine global and local level material and structural response in a single analysis for a wide variety of loads ranging from wave loading to underwater explosions. High utility in determining inputs for secondary analysis for determining fatigue, equipment response, and allowable stress levels for safe operation.	• NASTRAN • ABAQUS • SIERRA/SD • MAESTRO • Others	Multi-core workstation to High-performance computer	Seconds to days
Non-Linear FEA	• Non-linear material or structural response	Used to determine global and local level material and structural response in a single analysis for severe loads e.g. weapons effects, collision, grounding, ultimate hull-girder strength. Successful execution requires extensive definition of inputs and high level of analyst experience.	• ABAQUS • LS-DYNA • SIERRA/SM • DYSMAS(PARADYN)	Multi-core workstation to High-performance computer	Hours to days

4.2 Scope of Application

Much of the previous exploration of the FSI problem domain focused primarily on the problem of simulating the physics of FSI events. However, it was clear in talking to end users in industrial settings such as the American Bureau of Shipping (ABS) and governmental settings such as Naval Sea Systems Command (NAVSEA), United States Coast Guard (USCG) and DRDC that the challenge in FSI predictions extends beyond simulation of physics. In Figure 13, a wider view of implementing FSI prediction methods is shown. The goal of this figure is to document what sorts of supporting activities are occurring in parallel with the development of new methods of predicting the physics of FSI problems. These supporting activities often frame the problem, provide data to validate FSI simulations or turn FSI simulations into decisions. Understanding the scope of the problem is necessary to fully understand the scope of work underway for FSI solutions.

The rough flow of Figure 13 is top to bottom, showing the components required to make a decision on a FSI problem. These activities do not need to follow this flow temporally — for example basic research developments in simulation technology start independent of a specific need and then are picked up by engineers when the need arises. However, the items shown on the chart are viewed as necessary for a complete engineering prediction. Proceeding with gaps in the chart increases the possibility that the engineering prediction will lead to an incorrect decision. In reality, the links shown in the chart may be bi-directional or iterative. The correct physics may not be initially identified, and after trying one type of model, it may be necessary to go back and re-evaluate what is important. Additionally, for local phenomenon, FSI predictions may also rely on linked global models to get correct boundary conditions for both the platform motion and flow field. However, for clarity on this plot, the iterative nature of development is not explicitly shown.

Starting at the top of the chart in the blue color, a need for a type of FSI prediction is posed, and the dominant physics involved is identified. This leads to three related pathways — investigating the phenomenon through full-scale measurements, model scale experiments, and numerical simulation. Should numerical development be selected, there are a number of areas in which this development may take place. This is shown in the green-colored nodes on the top-left of the image. During the FSI working group discussions, it was clear that there are many current avenues for numerical improvement underway. In addition to adding new physics to numerical simulations, code acceleration and data analysis topics now feature prominently in this area of development. Additionally, such codes should be verified, or shown that they faithfully implement the desired numerical model.

Both full-scale trials and model-scale experiments are also avenues for investigation of FSI problems. Here, much of the discussion in the working group centered around the need for developments in both instrumentation and facilities. Many FSI events are highly dynamic, short time-scale events and the ability to accurately sense and record both the fluid and structural response in 3-D space during such events remains challenging. During the working group meeting, it was clear that there was a strong desire for canonical FSI experiments on simplified geometry to help in code validation and understanding of critical physics. Additionally, full-scale trials often need the ability to both understand and sense the operational environment of the vessel. Data from full-scale trials and more complex experiments can be used to directly address the FSI question, or can be used to further validate either model-sale methods or numerical methods.

Such validation campaigns are extensive, and with modern sensors, the amount of data created is large. Thus, archiving, visualizing and using this data, both for direct FSI prediction and numerical simulation validation was seen as a key step in the process. These processes are shown in the red, yellow, and orange boxes in the center of the chart. Note that here too there is a “big data” problem that needs to be confronted, as modern data acquisition systems can quickly generate terabytes of data. Thus, data mining, visualization and archiving also appear in this part of the chart.

The combination of numerical, experimental, and full-scale trials can be used to understand better the physics of FSI problems. However, to make a design or operation decision from such simulations requires further information. Acceptance criteria — related to the likelihood of the response occurring and the consequence of the response must be established. Developing such criteria requires understanding of both the variability in the FSI process and the extreme responses that may be seen in service. Some of the required processes for generating such information are shown in the light blue box on the lower right hand side of the chart. To make a decision based on FSI simulation, several pieces of information are needed. First, some sort of uncertainty quantification is required to evaluate the uncertainties in inputs to the FSI simulation and their impact on the results. Additionally, prediction bias and variation must be estimated as well. Together, these measures will give a statistical idea of the magnitude of the variability of the FSI prediction, and how large a safety margin may be needed in service. Such stochastic description of the uncertainties also form the basis for reliability analysis of extreme events, also discussed in this box.

A second challenge is fully understanding the operational environment of the platform. Understanding when the conditions likely to cause a significant FSI response will occur, and how frequent such conditions are forecast to be over the vessel’s life is also required. Such probabilistic characterization is needed to understanding the likelihood that particular levels of response will occur. As most FSI processes are inherently non-linear (with the notable exception of some fluid-structure interface problems discussed above), a final challenge in this box is understanding the extreme, or design values of the response. If sufficient simulations can be run, and the physics of the problem behaves well-enough (does not change at extreme responses), it is possible to fit statistical descriptions to these simulations and extrapolate extreme responses.

However, such extrapolation may not always be practical owing to either lack of data or complex FSI responses that are hard to describe with a small number of parameters. Additionally, such extrapolation procedures have the disadvantage that the actual extreme response is no longer being simulated with either numerical or experimental methods — it is an extrapolated response detached from any specific simulation. An alternative approach is to characterize stochastic processes so that inputs likely to produce extreme outputs can be identified. Such approaches allow snippets of the underlying process to be directly simulated with numerical or experimental tools, thus allowing the entire build up and extreme response to be computed, visualized, and studied. These approaches are still at a research stage but may offer an alternative approach to developing design responses that can be used for decision making.

Finally, the lowest box shows the final engineering use of an FSI methodology. The upper part of the chart discussed previously provides a validated prediction approach and realistic decision criteria. Two additional items are required to make use of these tools — the information required to run the tools (e.g. input parameters) must be known, and trained users must be available when the prediction is required. With these items in place, the FSI need identified at the top of the chart can be met. This chart shows that related developments in uncertainty quantification, experimental facilities, full-scale trials, instrument design, big data processing and mining, and stochastic processes help transition FSI methods from simulating physics to making decisions.

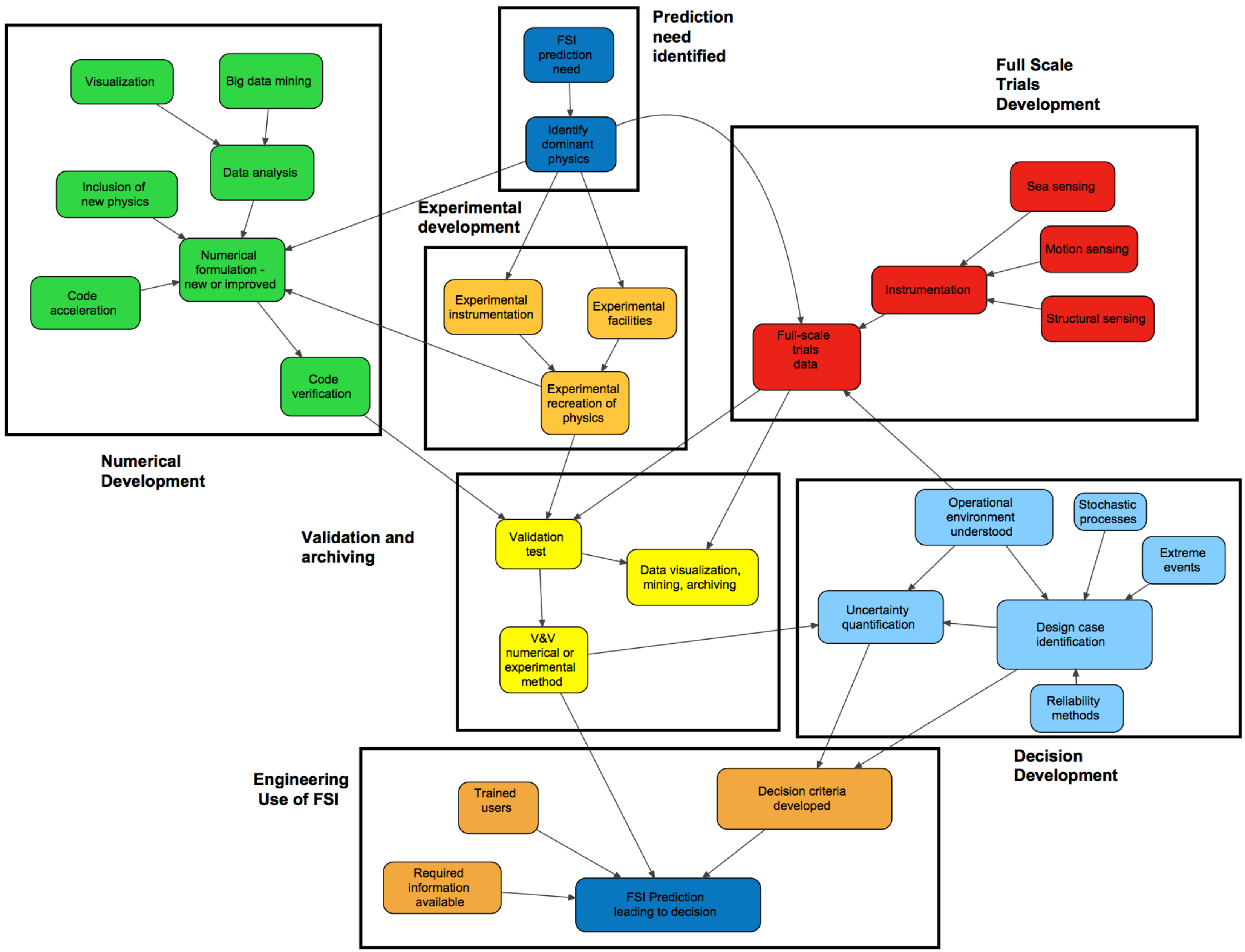


Figure 13: Contributing components to an FSI Decision

5 Discussion

An image of a large and dynamic community emerges from the analysis of the proceeding sections. As anticipated from previous FSI workshops and conferences, historically this community has been divided into specific domains. However, the Ann Arbor event showed that such divisions do not preclude fruitful exchanges of ideas and collaboration when the opportunity arises. In this section, certain themes that appeared significant or repeatedly appeared are presented, along with some discussion of their implications. As the objective of this effort was to document and report, not prioritize, no effort has been made to turn these into a prioritize list or strategy. Specifically, future naval strategy and budgetary limitations were not addressed at the event or in this report, both of which would be required before assessing priority. Exclusion of concepts from this discussion also does not imply a lack of priority — several concepts appear self-explanatory and will not be repeated here.

One of the most significant findings was that the community itself did not have a common working definition of fluid-structure interaction. Many application-focused engineers would lump large wave-body interaction problems into FSI, while the more research-oriented members tended to define FSI more narrowly in terms of two-way coupled problems. It is hoped that the taxonomy proposed here, and the listing of the types of approaches will help the community understand which part of the FSI problem is being discussed.

It is equally clear that the community has a long list of research challenges. Numerical code improvements, experimental facility and instrumentation development, as well as full-scale trials and validation continued to bubble up in different group discussions. Several topics appeared especially frequently. First, there is a clear desire for the continued development of FSI models of varying fidelity — reduced order models for design, potential flow, RANS, LES were all requested. Many of the EMRL plots created on the first day of the Ann Arbor event contained methods ranging from EMRL of eight to two. The range in EMRL levels further indicates that there is a wide variety of tools in use and development at the current time. Often, this means that there is a tool-to-problem matching problem, in that for each application engineers must select the appropriate modeling strategy. Coupled with this there is a need to train engineers in the capabilities, assumptions, and limitations of these methods. Accessibility and transferability of codes from academia to end users such as NAVSEA, ABS, USCG, DRDC are parts of this challenge.

Computational improvements at the higher end of our current capabilities were also highlighted repeatedly. In general, coupling approaches, FEA structural models with non-linear responses including failure/fragmentation, and the higher-end viscous flow simulations were all specifically identified as needing further development to meet projected use cases. Coupling approaches appeared generally less robust than baseline fluid and structural modeling approaches. The problem of modeling large spatial domains with different levels of fidelity in different regions was also seen as a common challenge. The structural community is primarily worried about capturing local failures in connections, or being able to remesh and model progressive damage starting in one area of the structure. The fluids community is interested in differing resolutions close to interfaces with boundary layers or multi-phase boundaries, while the general fluid can be represented in a coarser fashion. The desire to capture such spatial variation is in part driving the desire for more computational power.

There was also strong recognition of the “big data” problem. Both experimental sensing methods at model scale, full-scale trials, and numeric computations are capable of rapidly generating terabytes of information. Data sets of this size pose a number of challenges. The mechanics of storing, transferring, and archiving them are difficult. For numeric computations, it is common now to post-process on the high-performance computer where the code was run. HPC-based post-processing works fine for the immediate needs of the project, but if the data set is to be shared, or if there is a desire to re-analyze the data at some point in the future, it is not clear that this model will work. Often, the researcher does not own or control the high-performance computer, and may not be able to assure access to the machine, the data, and the required software in the future. Experimental data sets are more likely to be under the direct ownership of the researcher, but the challenges of archiving and sharing such data remains.

Beyond the mechanics of transfer and access, such large data sets pose additional problems. The ability to visualize such data, ask questions, and identify critical results is not well developed for data sets of this size. Machine learning and data mining approaches may help in this regard. However, among the experts assembled in Ann Arbor, there was little technical understanding of what would be required to allow this to take place. Here, tighter collaboration with computer scientist and information experts is probably warranted.

Cross-discipline collaboration also emerged as a strong theme. While not all FSI problems have compatible time-scales or physics, it was clear that there was common ground in several areas of code development (specifically coupling) as well as instrumentation and experimental analysis. Also notable was the strong desire between experimentalist and numerical analysts to collaborate on benchmark experiments. It was clear that the experimentalist felt they would benefit from designing the experiments in collaboration with numerical simulations. Developers of numerical codes also felt that it would be beneficial to be involved in the experimental design. The ability to adjust the experimental program and numerical models in parallel during the design, execution, and post-processing of the experiment would be of significant value. This points towards the need for integrated planning of future experiments across multiple organizations. Several current projects that might provide a proof-of-concept for this approach were mentioned at the event.

Finally, some areas were identified during the small-group study phase of this project and the post-processing of the Ann Arbor event that appear significant, but were not discussed in detail. First among these is the need to generate extreme or design cases to study with the higher-end FSI capability. It is clear that at the high end, the analysis of a short event will still consume hundreds to thousands of CPU hours, implying that only a limited number of analysis cases can be considered. Especially for wave-induced responses, a challenge emerges in trying to efficiently determine what series of wave elevation inputs (phase-resolved wave train) would produce an extreme response. The ability to generate such sequences, along with a reasonable probability associated with them occurring (or no higher response occurring) would significantly improve the ability to apply such FSI predictions in approval settings.

Additionally, the impact of the human analyst was highlighted in the complete scope of the FSI application, but not discussed at the workshop. For many codes, the answer can change depending on the modeling options and procedure used by the analyst. Additionally, not all options and features are rigorously documented, further highlighting the experience of individual analysts. This situation becomes even more complex when the results of the analysis are written up and often passed on for further discussion and decision making. At this stage, there is a large loss of information about assumptions, limitations, modeling strategy and what is truly significant in the results.

In certain situations, this can lead to incorrect decisions being made based on the reduced amount of information available as the simulation and simulation results move from the code developer, to the analyst, to the decision makers. How to address these issues is not clear at the present time. While cooperative code development, version control strategies, and blind code trials can all help, further thinking of the human role in creating FSI prediction seems important when considering the complete scope of FSI applications.

6 Conclusions

A map of the current FSI landscape has been presented. State-of-the-art summaries on fluid simulation and experiments, structural simulation and experiments, and numerical coupling approaches were prepared by experts in these fields. Based on U.S. Navy use cases, a two-day event was held in Ann Arbor, Michigan where members of the FSI community further documented current FSI methods, future applications, and research needs. From these sources of data, a simple taxonomy of different types of FSI problems was developed to resolve the confusion around what is and is not FSI. Additionally, dominant numerical modeling approaches for both fluids and structures were extracted into tabular form. Finally, a diagram of the scope of the FSI decision domain was created, showing the strong need for numerical modeling, experimental modeling, and full-scale trials to interact. Discussion around these results highlighted several common research challenges.

In summary, the current FSI landscape appears vibrant, with many related research efforts moving forward. In many areas, promising new techniques are being developed, though the group readiness ranking of many of these methods indicates that more work needs to be done before they can be transitioned to wider applications. There are important interactions between the experimental and numerical parts of the community, specifically around planning benchmark experiments. The community seems aware of these interactions and ready to work together. Challenges around big data, predicting which situations will lead to extreme events, and the human role in FSI also appeared. While the community seems aware of these issues, there is less consensus on a direction forward to resolve them. It is hoped that the map produced here will encourage a common terminology for FSI, enhanced collaboration, and inventive research to fill the gaps identified by the community.

7 Acknowledgments

The authors wish to acknowledge the support of Dr. Paul Hess and Dr. Tom Fu, ONR Code 331 for this activity through discussions on framing the problem, providing technical insight, and in executing the Ann Arbor event. The assistance of Sallie Kne from the NA & ME department, the graduate student helpers from the NA & ME department, and the Ford Presidential Library in Ann Arbor are also gratefully acknowledged.

Appendices

A Full Use Cases

A.1 Global Ship Loading and Response FSI

A.1.1 Monohull Global Structural Response in Waves

Monohull Global Structural Response in Waves

Problem Description

1. Prediction of integrated (coupled?) hull girder bending, torsion, and shear in high sea states
2. Extreme values and load combinations needed
3. Fatigue load spectrum also needed

Research Objectives:

1. Efficient phased-resolved extreme event identification
2. When FSI is relevant
3. Statistical description
4. Improve classification rules
5. Robust load combination both global and local for extreme values an fatigue spectra
6. Impact of non-linear and rare wave forms/groups

Figure 14: *USS Cole* in heavy weather

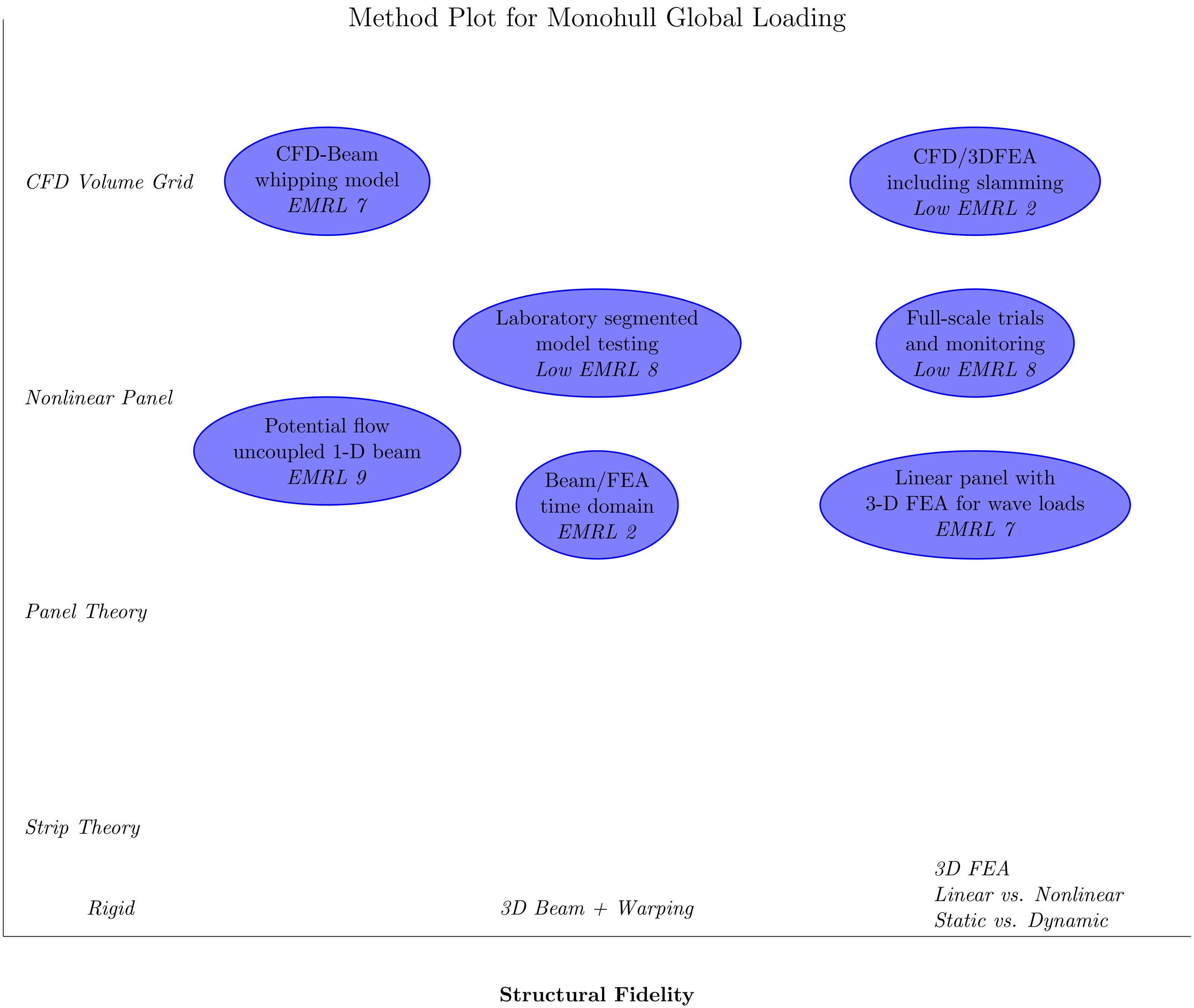
Important Physics & Phenomenology:

1. Relatively long duration wave forms periods of 1 s to 1 min for global response
2. Local slamming and impact loads may combine to magnify green water and exit loads
3. Structure dynamic response whipping and ringing, (springing?) important to include resonance frequencies
4. Oblique loads lead to combined vertical, horizontal, and torsional response
5. Extreme wave forms, wave groups may impact extreme values as propulsion and control

Challenges:

1. Phase-resolved waves needed to simulate extreme response including coupling to FEA
2. Load combination factors for extreme responses
3. Critical design-stage load range of prediction capabilities needed
4. Global response depends on local loads
5. Local load depends on global response
6. Complexity limits users training or simplification

Approaches & Example Codes: Regression/simplified e.g. Spectra/Jensen, Non-linear strip theory Tempest, VERES, Non-linear panel codes AEGIR, LAMP with internal hydro-elastic model, coupling to global ship response FEA e.g. MAESTRO, Abaqus, URANS, Euler


Method Plot for Monohull Global Loading
Hydrodynamic Fidelity
CFD Volume Grid
Nonlinear Panel
Panel Theory
Strip Theory
Structural Fidelity
Rigid
3D Beam + Warping
3D FEA
Linear vs. Nonlinear
Static vs. Dynamic
CFD-Beam
whipping model
EMRL 7
CFD/3DFEA
including slamming
Low EMRL 2
Laboratory segmented
model testing
Low EMRL 8
Full-scale trials
and monitoring
Low EMRL 8
Potential flow
uncoupled 1-D beam
EMRL 9
Beam/FEA
time domain
EMRL 2
Linear panel with
3-D FEA for wave loads
EMRL 7

A.1.2 Multihull Global Structural Response in Waves

Multihull Global Structural Response in Waves *(see also monohull table)*

Problem Description

1. Prediction of integrated hull girder bending, torsion, and shear in high sea states on each hull, and connecting moments and shears
2. Extreme, fatigue and combined loads needed
3. More complicated idealization of structure
4. Need for simplified models for early-stage design

Research Objectives:

1. Efficient phased-resolved extreme event identification
2. Robust load combination both global and local for extreme values and fatigue
3. Impact of non-linear and rare wave forms/groups
4. Intermediate fidelity structural models for multihulls
5. Need relevant design load cases

Figure 15: *HSV-2* at high speed

Important Physics & Phenomenology:

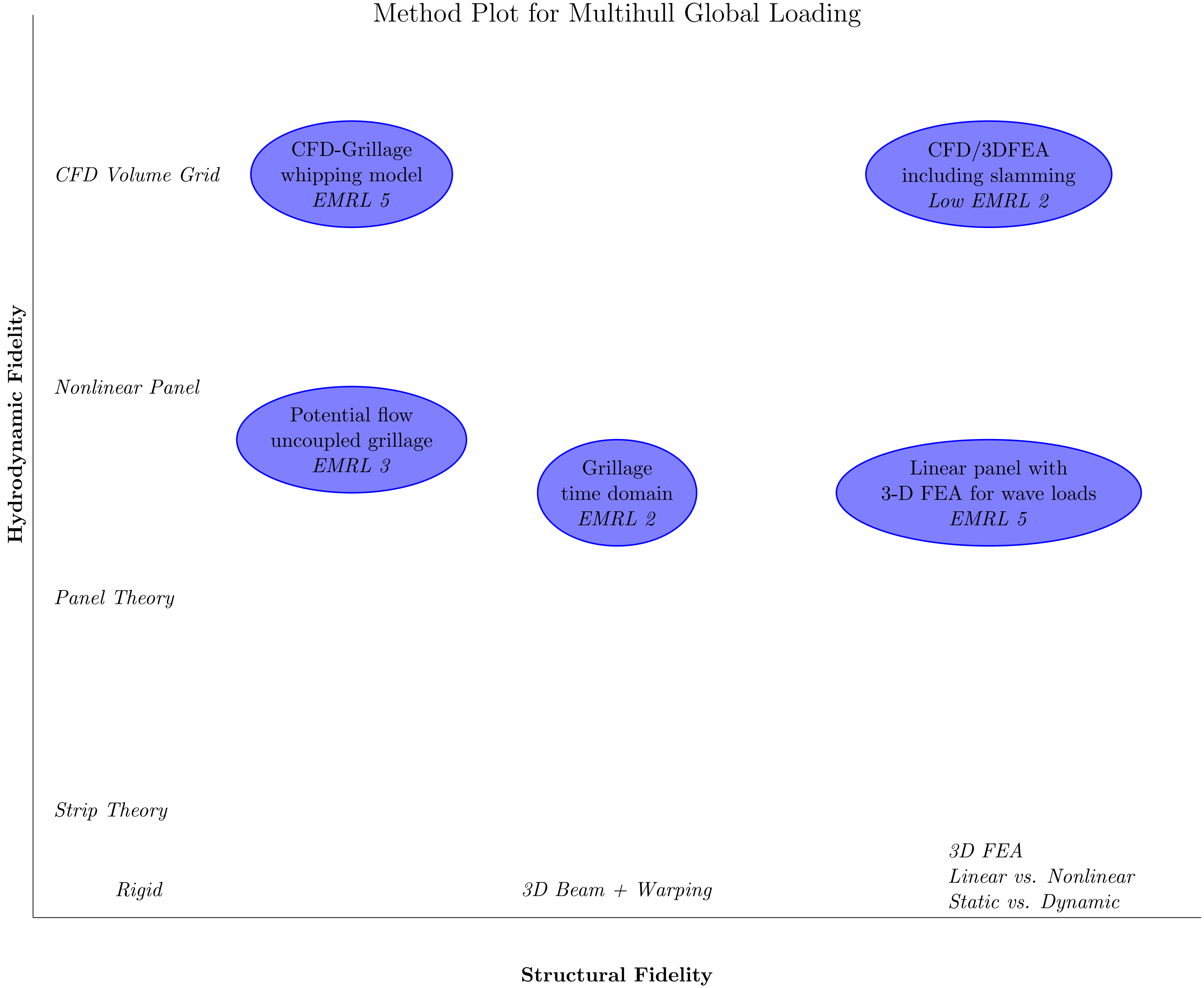
1. Relatively long duration wave forms periods of 5-20 seconds for global response
2. Local slamming and impact loads may combine to magnify
3. Structure dynamic response, and flexibility of large cross decks must be included
4. Oblique loads lead to combined vertical, horizontal, and torsional response
5. Extreme wave forms, wave groups may impact extreme values
6. High forward speed
7. Limited operational envelope may impact conditions where extreme values occur
8. Different resonant frequencies due to different materials, hull form and speed

Challenges:

1. Phase-resolved waves needed to simulate extreme response including coupling to FEA
2. Load combination factors for extreme responses
3. Multi-hull loading lacks early-stage design methods
4. Critical design-stage load range of prediction capabilities needed
5. Need more test data
6. Accuracy and sensitivity to more complex mass distribution

Approaches & Example Codes: Non-linear strip theory VERES, Non-linear panel codes AEGIR, LAMP with internal hydro-elastic model, coupling to global ship response FEA e.g. MAESTRO, Abaqus

Method Plot for Multihull Global Loading



A.1.3 Underwater Explosion (UNDEX) Response

Underwater Explosion (UNDEX) Response

Problem Description

1. Prediction of loading and response of vessel to explosive underwater loads (Pressure wave, ballistic impact, bubble pulse, jetting)
2. Material failure simulation

Research Objectives:

1. Continue replacement of full-scale trials with numerical simulations
2. Better ability to model responses and failures at different length scales
3. Increased computational capacity

Figure 16: U.S. Navy Shock Trial

Important Physics & Phenomenology:

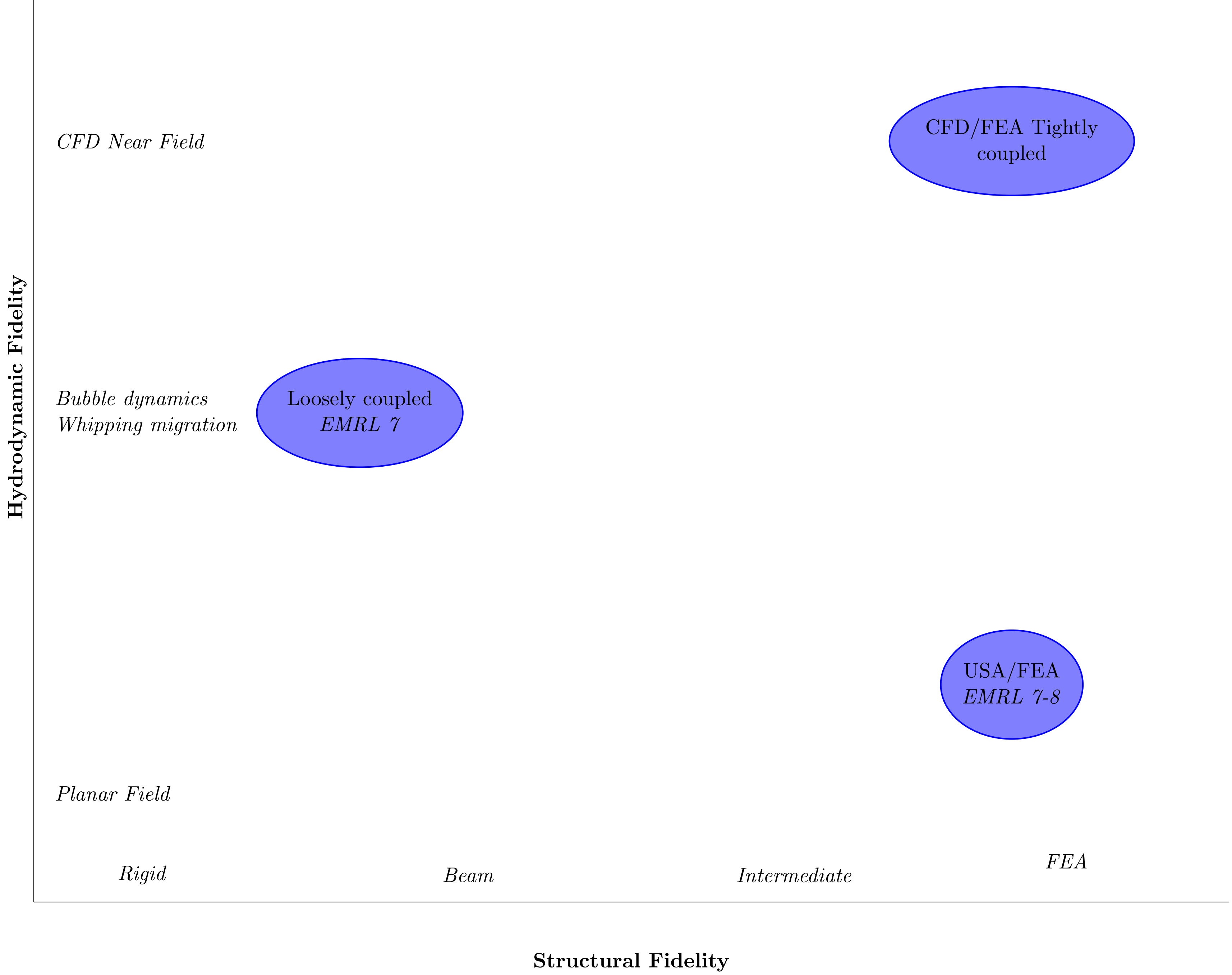
1. Global elastic and local plastic/fracture response of structure.
2. Inherently involved length scales from plate thickness to compartment/full ship scale.
3. Extreme pressure and density gradients in water and explosive including shock propagation
4. Short to medium time scale- usually milliseconds but up to multi-second for whipping

Challenges:

1. Evolving FSI interface due to fracture including venting into interior of structure
2. Accurate modeling of bubble dynamics and generally accurate tracking of multi-material and FSI interfaces difficult in context of hydro codes
3. Computational requirements for current codes are extensive and limit number of analyses performed.

Approaches & Example Codes: DYSMAS, NESM, LS-DYNA/USA, EPSA/FLEX, ABAQUS

Method Plot for UNDEX



A.1.4 Highly Flexible Ship (inflatables)

Highly Flexible Ship (inflatables)

Problem Description

1. New structures, e.g. drop stitch and other inflatable
2. Low structural density with large deformation

Research Objectives:

1. Develop models and hypothesis for behavior
2. Experimental basis for validation
3. Multi-body interactions

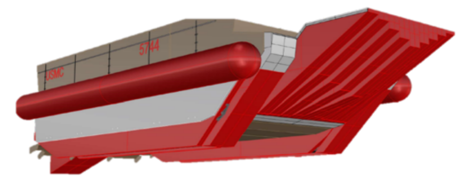


Figure 17: Hypothetical inflatable structure

Applications:

1. Buoyant kits for marine vehicles
2. Flexible ramps and causeways
3. Under water explosion protection
4. Ballistic protection

Important Physics & Phenomenology:

1. Textile behavior
2. Inverse density problem low density structure, high density fluid

Challenges:

1. Multi-component, multi-body problems
2. Extremely complex fiber patterns
3. Large structural displacement

Approaches & Example Codes: Custom high-fidelity tools, very high structural fidelity

Note: Owing to immaturity of this use case, no method plot is available

Future Research and Application Goals for Global Loading FSI

5 Years

Research:
- Full FSI hydro-elastic
- Codes to determine when FSI is important.
- Intermediate fidelity structural models for early design.
- Coupling algorithms for 2-way non-linear FSI
- FEA for complex materials
- CAD FEA translation
- Multi-fidelity methods
- Laboratory experiments using MDO to design

Application:
- Establish physics based rules
- Analyze single extreme event

10 Years

Research:
- Effects of local deformation on pressure load distribution
- Uncertainty quantification

Application:
- Determine when FSI affects design When it is needed Vs. design margins
- Deterministic slamming design
- Highly flexible structures
- Analyze multiple extreme events

15 Years

Research:
- Faster computations to allow broader range of problems
- Detailed weld calcs. in CFD/FEA time history calcs.
- Adaptive structures
- Structural damping

Application:
- Fatigue
- Comprehensive lifetime simulation
- Composite / flexible structures. Impulse loads for metallic structures

A.2 Local Ship Loading and Response FSI

A.2.1 Impact and Slamming on Boats

Impact and Slamming on Boats

Problem Description

1. Prediction of impact pressures on small, high-speed, dynamically-supported vessels
2. Prediction of unusual hull geometry- steps, oblique waves, sharp discontinuities
3. Mix of materials in use with different properties aluminum, composite, inflatable components

Research Objectives:

1. Ability to predict design pressures
2. Ability to apply predictions to design
3. Ability to accurately predict overall vessel motions and accelerations for other structural reactions

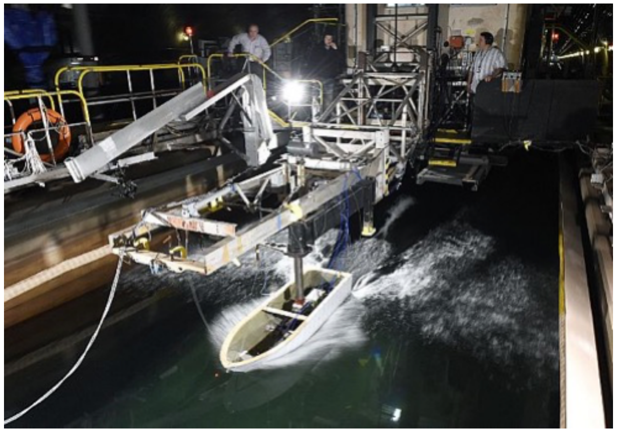


Figure 18: Planing boat test at NSWCCD

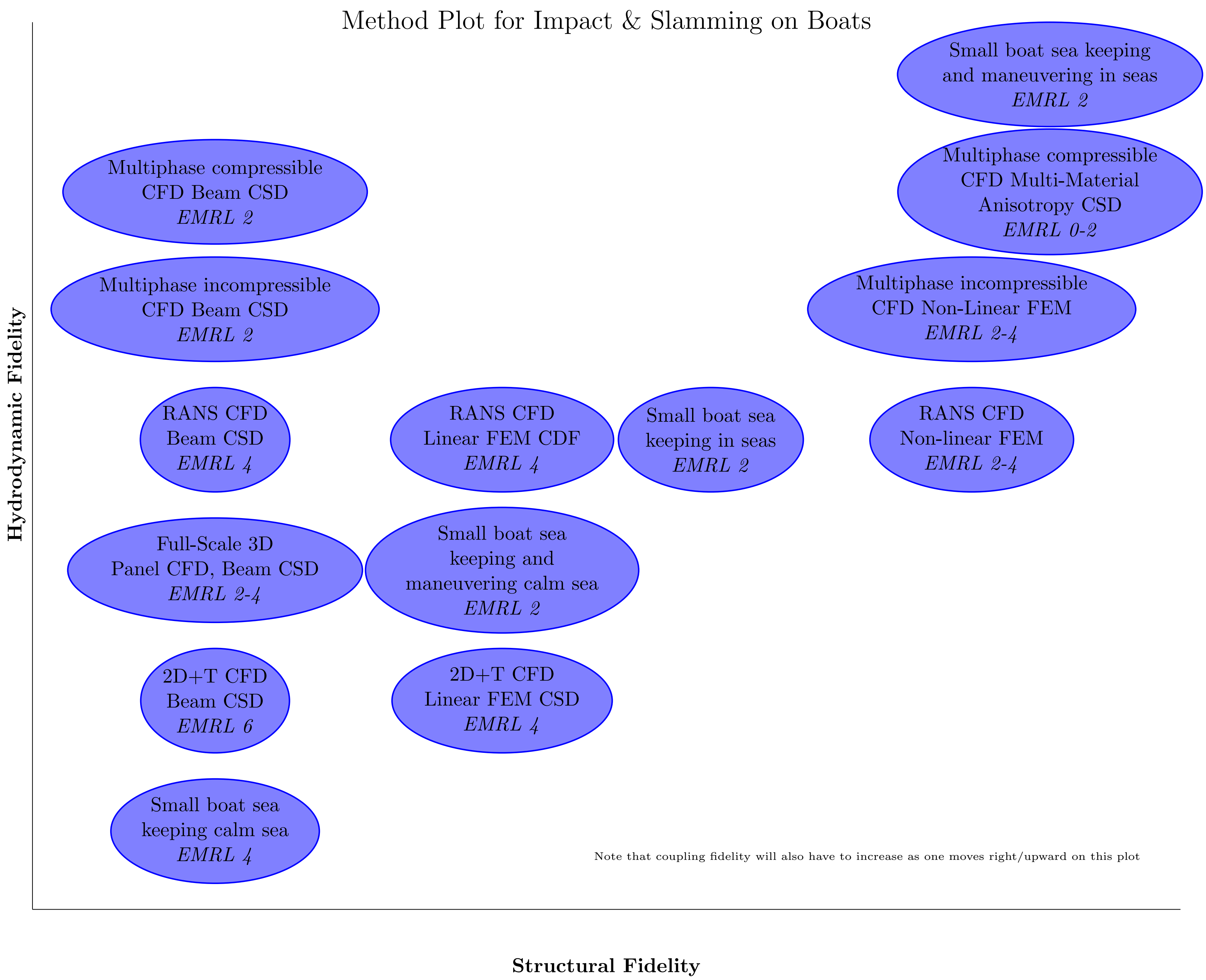
Important Physics & Phenomenology:

1. Vessel response highly non-linear involving water exit and entry
2. Vessel largely supported by dynamic lift vs. buoyancy
3. Air/water multi-phase flow problem
4. Impact pressures vary over different spatial scales
5. Impacts and slams are dynamic events with short time scales 0.01-0.1 seconds

Challenges:

1. Multi-phase flow
2. Need to predict vessel motions and local flow to get pressure correct
3. Coupling between pressures and overall vessel motions
4. Computational time requirements

Approaches & Example Codes: Viscous RANS/LES approaches - OpenFOAM, StarCCM; Simplified models based on sectional entries PowerSea, some LAMP derivatives; Experimental model testing; Coupling to FEA codes as needed for structural response Abaqus etc.


Method Plot for Impact & Slamming on Boats
Hydrodynamic Fidelity
Structural Fidelity
Small boat sea keeping and maneuvering in seas *EMRL 2*
Multiphase compressible CFD Beam CSD *EMRL 2*
Multiphase compressible CFD Multi-Material Anisotropy CSD *EMRL 0-2*
Multiphase incompressible CFD Beam CSD *EMRL 2*
Multiphase incompressible CFD Non-Linear FEM *EMRL 2-4*
RANS CFD Beam CSD *EMRL 4*
RANS CFD Linear FEM CDF *EMRL 4*
Small boat sea keeping in seas *EMRL 2*
RANS CFD Non-linear FEM *EMRL 2-4*
Full-Scale 3D Panel CFD, Beam CSD *EMRL 2-4*
Small boat sea keeping and maneuvering calm sea *EMRL 2*
2D+T CFD Beam CSD *EMRL 6*
2D+T CFD Linear FEM CSD *EMRL 4*
Small boat sea keeping calm sea *EMRL 4*
Note that coupling fidelity will also have to increase as one moves right/upward on this plot

A.2.2 Local External Slamming Pressures

Local External Slamming Pressures

Problem Description

1. Prediction of local pressures (grillage to plate scale) and associated structural response
2. Impact many platforms bottom and bow flare for monohulls, cross-structure for multihulls

Research Objectives:

1. Accurate prediction of important physics
2. Ability to assess vs. structural adequacy

Figure 19: *USS For Worth* Bow Flare Impact

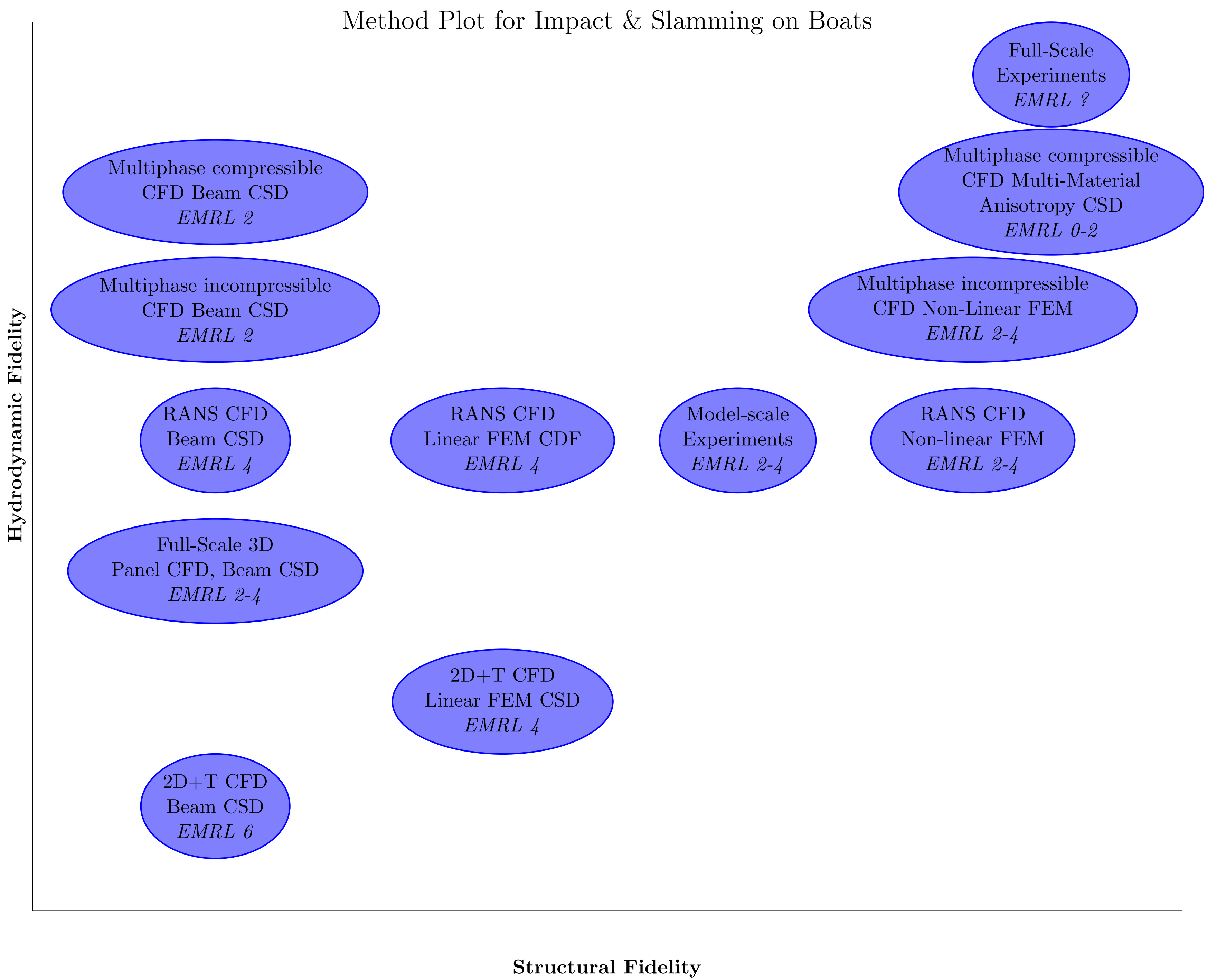
Important Physics & Phenomenology:

1. Relative motion of ship and possibly ship-disturbed wave field
2. Medium time scale, 0.01 - 1 second
3. Air-water mixture impacting deforming structure
4. Panel-level length scale for structural significant peak pressures 1m-10m
5. Boundary conditions for peak pressure involve vessel-length length scale

Challenges:

1. Difficult local fluid/structure dynamics including disturbed free surface and air entrapment
2. Large pressure changes over short length scales
3. Only linear elastic coupling simulated so far, but relevant structural limit state is non-linear plastic deformation
4. Challenging to assess structural limit states under short-term dynamic loading

Approaches & Example Codes: Potential flow entire-vessel codes coupled to simplified slamming model- e.g. LAMP; Viscous flow codes directly coupled to finite element codes e.g. NavyFOAM/Abaqus


Method Plot for Impact & Slamming on Boats
Full-Scale Experiments *EMRL ?*
Multiphase compressible CFD Beam CSD *EMRL 2*
Multiphase compressible CFD Multi-Material Anisotropy CSD *EMRL 0-2*
Multiphase incompressible CFD Beam CSD *EMRL 2*
Multiphase incompressible CFD Non-Linear FEM *EMRL 2-4*
RANS CFD Beam CSD *EMRL 4*
RANS CFD Linear FEM CDF *EMRL 4*
Model-scale Experiments *EMRL 2-4*
RANS CFD Non-linear FEM *EMRL 2-4*
Full-Scale 3D Panel CFD, Beam CSD *EMRL 2-4*
2D+T CFD Linear FEM CSD *EMRL 4*
2D+T CFD Beam CSD *EMRL 6*
Hydrodynamic Fidelity
Structural Fidelity

A.2.3 Sloshing

Sloshing

Problem Description

1. Motion of fluid in internal tanks, docks, and other compartments on vessels
2. Simulation of free surface elevation and impacts on tank boundary

Research Objectives:

1. Efficient prediction of free surface
2. Capturing two-way feedback between ship motions and tank fluid
3. Accurate prediction of impact pressures

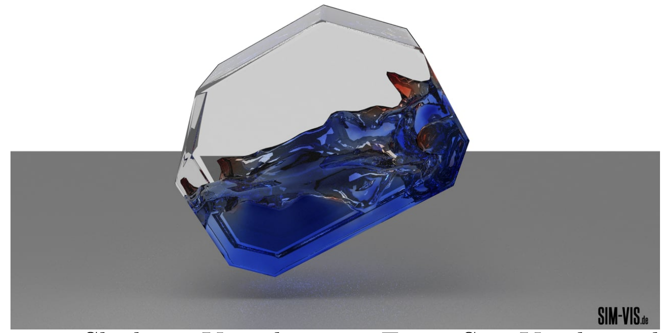


Figure 20: Sloshing Visualization From Sim-Vis.de under CC license

Important Physics & Phenomenology:

1. Violent shallow-water flows
2. Short-term impact events on vertical bulkheads and tank overheads
3. Multiphase air-fluid dynamics important to resolve peak impact pressures
4. Fluid motions driven by vessel motions, both need to be accurately modeled
5. Large tanks may also impact ship motions

Challenges:

1. Complex, highly-nonlinear free surfaces
2. Multiphase flows
3. Tank boundary deformations change peak impact pressures
4. Coupling with body motions

Approaches & Example Codes: 2-D fluid simulations, time-histories transferred to FEA models; Coupled 3-D CFD simulation to FEA code


Method Plot for Sloshing
Coupling Global Ship Motion to Tank Flow. Coupling Structure Air and Water in Tank
EMRL 0-2
Hydrodynamic Fidelity
Structural Fidelity

A.2.4 Cumulative Damage from Local External Slamming

Cumulative Damage from Local External Slamming

Problem Description

1. Prediction of long term structural responses after multiple discrete events

Research Objectives:

1. Development of long term inspection guidelines
2. In service instrumentation
3. How does deformation (& historical deformation) change response over time? Over life?

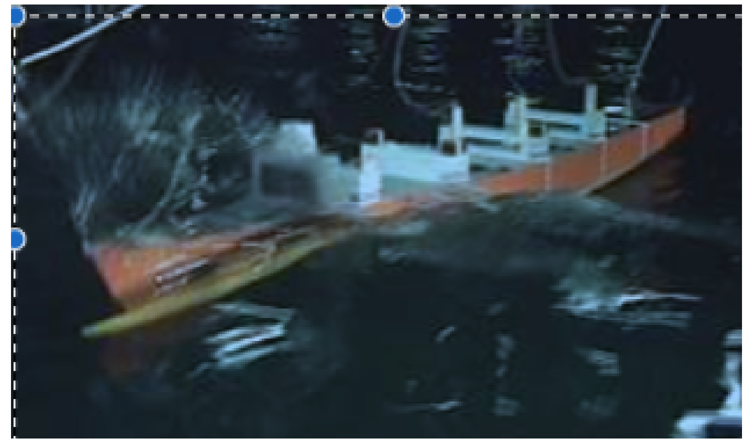


Figure 21: JHSS slam event at NSWCCD testing

Important Physics & Phenomenology:

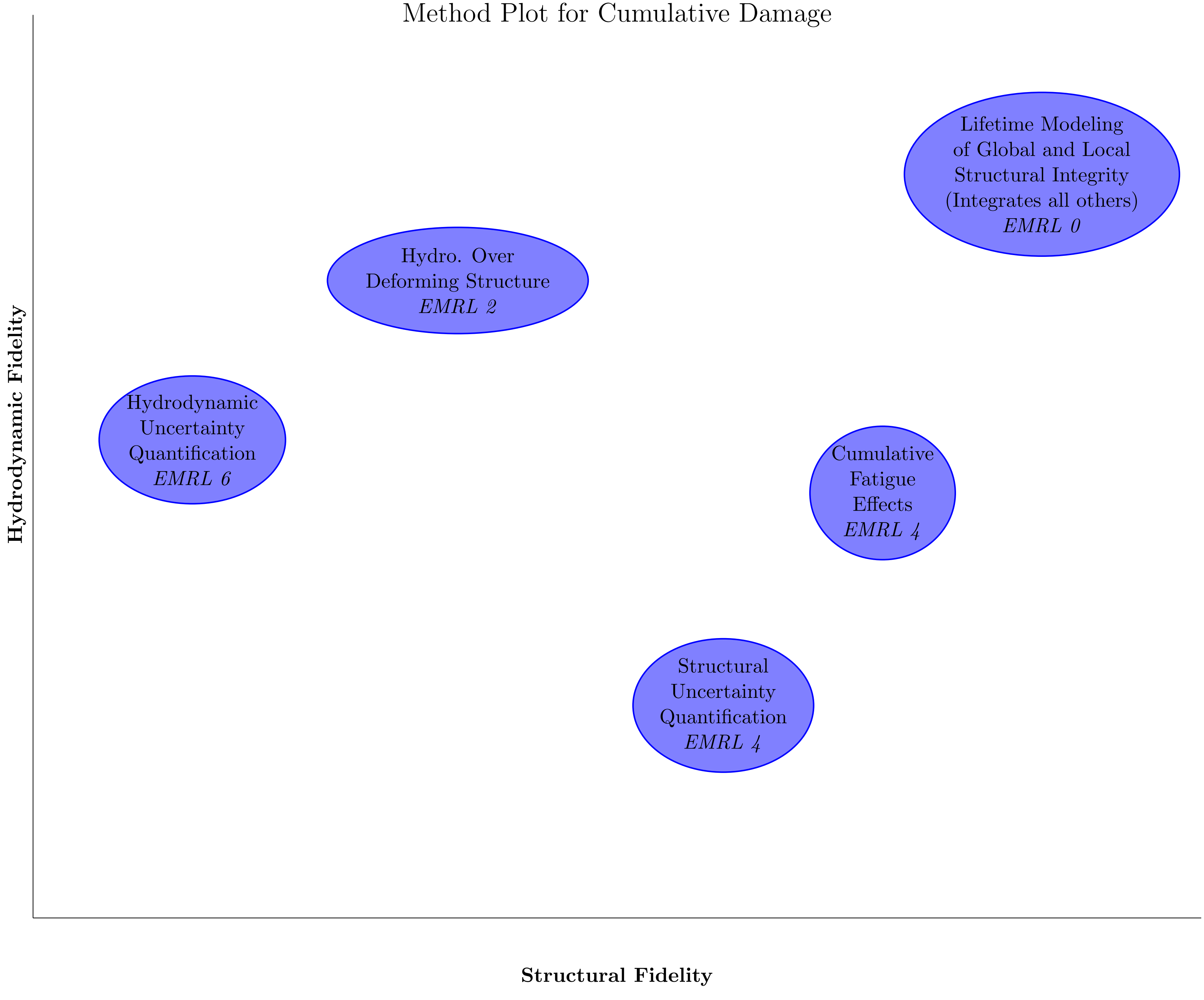
1. Plasticity over time
2. Long term/time scale effects
3. Environmental/Operation Uncertainty (modeling, propagation, quantification)

Challenges:

1. What to do with full scale/large data sets to inform future design? Maintenance?
2. Repeatability of numerical & physical experiments
3. Validation metric vs. one-to-one comparison
4. Structural element formulation capable of capturing the response history

Approaches & Example Codes: Design an experiment to analyze panel deformation, Plate element?

Method Plot for Cumulative Damage



A.2.5 Air Explosion (AIREX) Response

Air Explosion (AIREX) Response

Problem Description

1. Loading of structure from airborne explosion, including non-linear deformation and fracture of the structure
2. Both internal and external originated loads are important

Research Objectives:

1. Improved computation capacity for novel structural materials
2. Improved computational efficiency

Figure 22: AIREX Damage to *USS Stark*

Important Physics & Phenomenology:

1. Global elastic and local plastic/fracture response of structure.
2. Inherently involves capturing local structural detail and compartment level response
3. Need to capture both shock propagation, fragment effects, and post-detonation combustion
4. Short to medium time scale- milliseconds for external blast, hundreds of ms for internal blast

Challenges:

1. Evolving FSI interface due to fracture including venting between compartments
2. Accurate but efficient models for capturing late-time combustion
3. Capturing combined blast and fragment effects
4. Capturing complex local material and structural response

Approaches & Example Codes: DYSMAS, NESM, LS-DYNA, ABAQUS, SHAMRC, CTH.

Note: No method plot was generate for this use case during the event

A.2.6 Wave Slap and Secondary Non-Impact Pressures

Wave Slap and Secondary Non-Impact Pressures

Problem Description

1. Secondary loads on panels and grillages without slamming impact, greenwater loading on deck
2. Oil-canning, fatigue loading, permanent set, and sponson impact all important examples
3. Local pressures critical to multihull design

Research Objectives:

1. Accurate prediction of local pressures for design
2. Rapid assessment of fatigue strength
3. Prediction of secondary pressures for unusual hull geometry

Figure 23: *USS Comstock*

Important Physics & Phenomenology:

1. Longer timespan than true impact slamming tenths of seconds to a few seconds
2. Many locations are only intermittently in the water
3. Green water involves complex physics of water transitioning from wave field to a shallow-water flow with rigid bottom
4. Local free surface elevation and relative motions must be predicted accurately
5. Oil-canning involves snap-through buckling response of plates

Challenges:

1. Prediction of local free surface
2. Prediction of non-linear structural response for snap-through buckling
3. Modeling of green water dynamics on moving vessel

Approaches & Example Codes: Non-linear panel/3-D codes such as LAMP and AEGIR linked to FEA models; NavyFOAM, CFD-Ship Iowa linked to FEA models; Scale model experiments to representative pressures

Note: No method plot was generate for this use case during the event

A.2.7 Ice Impact

Ice impact

Problem Description

1. Prediction of ice impact forces on non-icebreaking vessels
2. Mainly light ice, drifting growlers, and accidental impacts

Research Objectives:

1. Development of design pressures and loads for vessels operating in light ice
2. Assessment of suitability of existing vessels for near-polar navigation

Figure 24: *USCGC Healy* in thin ice

Important Physics & Phenomenology:

1. Three-material challenge ice, water, and vessel structure
2. Ice as a brittle, but variable material
3. Impact scenarios are dynamic, but total impact time is often on order of seconds
4. Plastic deformation of hull structures is normally tolerated
5. Interaction and movement between vessel and ice can be significant if masses are similar

Challenges:

1. Difficult structural modeling — brittle ice and plastic hull structures
2. Multi floating body problem, especially when ice weight is similar or smaller than vessel
3. Dynamic impact

Approaches & Example Codes: Custom codes

Note: No method plot was generate for this use case during the event

Future Research Goals for Local Loading FSI

5 Years

Research:

- Understanding and using large life-cycle data sets
- How to deal with uncertainty in FSI modeling/exper.
- High temporal, special, and statistical measurements of water free surface, flow field, structural deformation, motion, and water-structure interfaces conditions
- Two-phase LES free surface flow
- Coupling convergence rates, error bounds, etc.
- Scaling concerns
- Validation of coupling at full-scale
- Non-intrusive measurements
- Quantitative pressure and shear map on surfaces new methods (non-invasive)? Validation quality
- Tools for wave slamming and high pressure at short time scales
- Wave impact on compliant/active structure to study effects
- Coupling CFD/CSD in effective/efficient way
- Range of applicability of CFD/CSD
- More efficient 3D potential flow code for slamming

10 Years

Research:

- Probabilistic design tools from life cycle tools
- Repeat 5 yr. research vision 9
- Improving plastic deformation in coupled codes
- Quantitative pressure and shear meas. On curved flow for CFD validation
- 1/10 s scale pressure and shear measurements (non-intrusive)
- Multi-phase flow measurement for high void fraction measurement
- Accurate life time fatigue modeling
- LES/CSD Validation
- DNS/CSD coupling
- Full-scale V&V of state-of-the-art FSI tools
- Improved understanding of scale effects

15 Years

Research:

- Advance design tools that account for the integrated cyclic
- Integrated uncertainty quantification for CFD/CSD
- Smaller LES cut-off scales
- Computational abilities w/ advanced V&V
- Improved turbulence model
- Multi-material anisotropy structural model
- Accurate fracture modeling
- 1/100 s scale pressure and shear measurements (non-intrusive)
- Better resolution of flow structures
- BIG DATA

Future Application Goals for Local Loading FSI

5 Years

Application:

- Life-cycle data for maintenance, scheduling, FSI fatigue monitoring
- Best practices for non-invasive instrumentation
- Scaling experiments for fluids and structures
- Small boat slamming one-to-one validation
- Integration of all of the disciples for design space exploration
- Life cycle modeling
- Hybrid virtual experiment tow tank
- Hydrofoil assisted vessel for slamming/slapping
- Best practices for characterizing FSI uncertainty
- Full-scale structural response for slamming motions
- Active structure for sloshing

10 Years

Application:

- Accurate life-time fatigue modeling
- Maintenance scheduling based on life-cycle, structural weight reduction
- Slamming effects over time
- Use life cycle data
- Statistical description of loads on vessels over the life time
- Adaptive hull forms to mitigate impact loads while maintaining..
- Informing maintenance from full-scale ship data
- Informed sensor placement
- Environmental responsive control surface (active/passive) sloshing/small boat slamming
- Morphing hull for reduced impact loading small boat/planning
- Multi-phase compressible air VOF/level set tightly coupled CFD/CSD
- Monolithic approaches for FSI Coupling stability criteria, convergence rates, error bounds on multi-method theoretical context for CFD/CSD

15 Years

Application:

- Life-time fatigue and life-cycle estimates and extension
- Deformable materials for impact mitigation
- Additive manufacturing of ship structures
- Integrated FSI approach
- Active control flexible structure

A.3 Propeller and Appendage FSI

A.3.1 Propulsor and Appendage Dynamics

Propulsor and Appendage Dynamics

Problem Description

1. Advanced materials, composite materials in particular, are an attractive alternative to conventional NiAlBz for naval propulsors and appendages
   (a) Stronger fluid structural coupling
   (b) More complex failure mechanisms
2. FSI is a critical issue for structural integrity, vibration, and acoustics for a wide range of operating conditions and loads

Research Objectives:

1. Enhance understanding of FSI physics (hydro, structural, acoustics) of propulsors and appendages
2. Improved V&V and uncertainty quantification

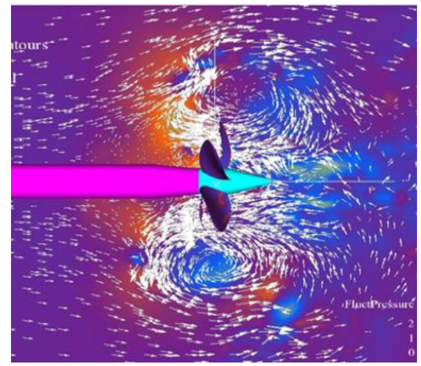


Figure 25: Propeller Simulation

Important Physics & Phenomenology:

1. Turbulence and mean flow harmonics with wide range of length- and time-scales
2. Non-uniform & vortical wake stemming from interactions with hull boundary layer and appendages, ship motion, and maneuvering in waves
3. Accurate description of operational environment
4. Cavitating flows & air ventilations
5. Significant added-mass and hydrodynamic damping effects
6. Nonlinear, anisotropic materials
7. Hydro-elastic instabilities and fatigue
8. Structural acoustics and vibrations
9. Hydrodynamic interaction among blade rows and between blade rows and duct at angles of attack
10. Scaling of fluid and solid properties and mechanisms

Challenges:

1. Multi-physics, multi-scale, multi-fidelity & multi-material problems involving highly nonlinear coupled mechanics
2. Highly stiff coupled CFD/CSD equations with disparate time scales
3. Gridding and large amplitude motions
4. Computational model fidelity for sound and vibration
5. Constitutive laws for fluid and solid
6. Experimental data to address scaling effects
7. Techniques for simultaneous measurements of hydrodynamic, structural dynamics, and acoustics

Approaches & Example Codes: High-fidelity numerical prediction of FSI based on accurate, fast, robust, and scalable coupling strategies and algorithms; Benchmark experiments involving simultaneous FSI measurements; Experimental measurement of FSI

Future Research and Application Goals for Propulsors and Appendages Dynamics

5 Years	**10 Years**	**15 Years**
Research: • Simultaneous hydrodynamic, structural, and acoustic measurements • Physics based reduced order modeling for FSI suitable for design • Predictive tools for cavitation, erosion, hydrodynamics and acoustics • Turbulence modeling for multiphase flow • High fidelity FSI simulation for shock and impact loads • Propulsor FSI during maneuvering • Failure model for composite propulsors and appendages	**Research:** • Simultaneous hydrodynamic, structural, and acoustic measurements • Fatigue modeling for composites • Real time structural health monitoring for composite prop • Active/passive control technologies • Mitigation technologies for adverse effects	**Research:** • Simultaneous hydrodynamic, structural, and acoustic measurements • Hybrid coupled numerical and experiential modeling
Application: • Coupled DES/RANS+FEA in design (noted during poster session - what research is needed to achieve this is 10—20 years?) • Cavitation damage, noise, and operating profiles	**Application:** • Coupled LES+FEA in design • Composite propeller	**Application:** • Coupled DNS+FEA in design

A.3.2 Unconventional Propulsors and Appendages

Unconventional Propulsors and Appendages

Problem Description

1. Design and analysis of "designer" appendages and propulsors taking advantage of FSI
2. Passive and/or active controllable deformation and properties
3. Static and dynamic noise and vibration control

Research Objectives:

1. Strongly coupled multi-DOF FSI
2. Active FSI for real time sensing and actuation

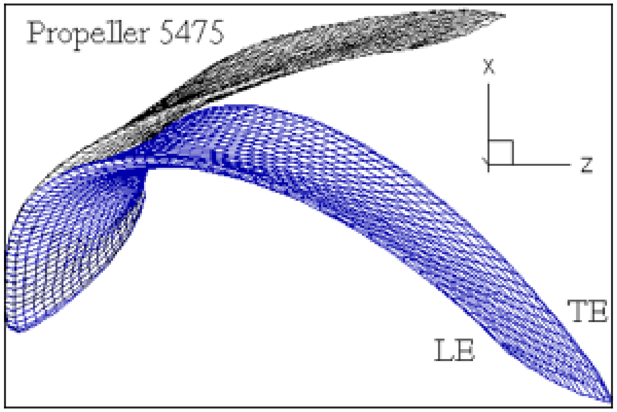


Figure 26: FSI Response of a Propulsor

Important Physics & Phenomenology:

1. Energy transfer, storage, and harvesting in space and time
2. Large structural deformation and FSI
3. Soft materials and flexible structures
4. Smart materials
5. Vorticity and flow control using FSI
6. Complex flow structure interaction at fluid structure boundary

Challenges:

1. Very fast actuation and morphing
2. Constitutive modeling of smart materials
3. Predictive and design tools for large scale deformations
4. Multi-phase FSI
5. What kind of (large) deformations we want and how to achieve it

Approaches & Example Codes: Tightly coupled scalable FSI; Optimization and reduced order modeling; Integration of newly developed materials into FSI

Future Research and Application Goals for Unconventional Propulsors and Appendages

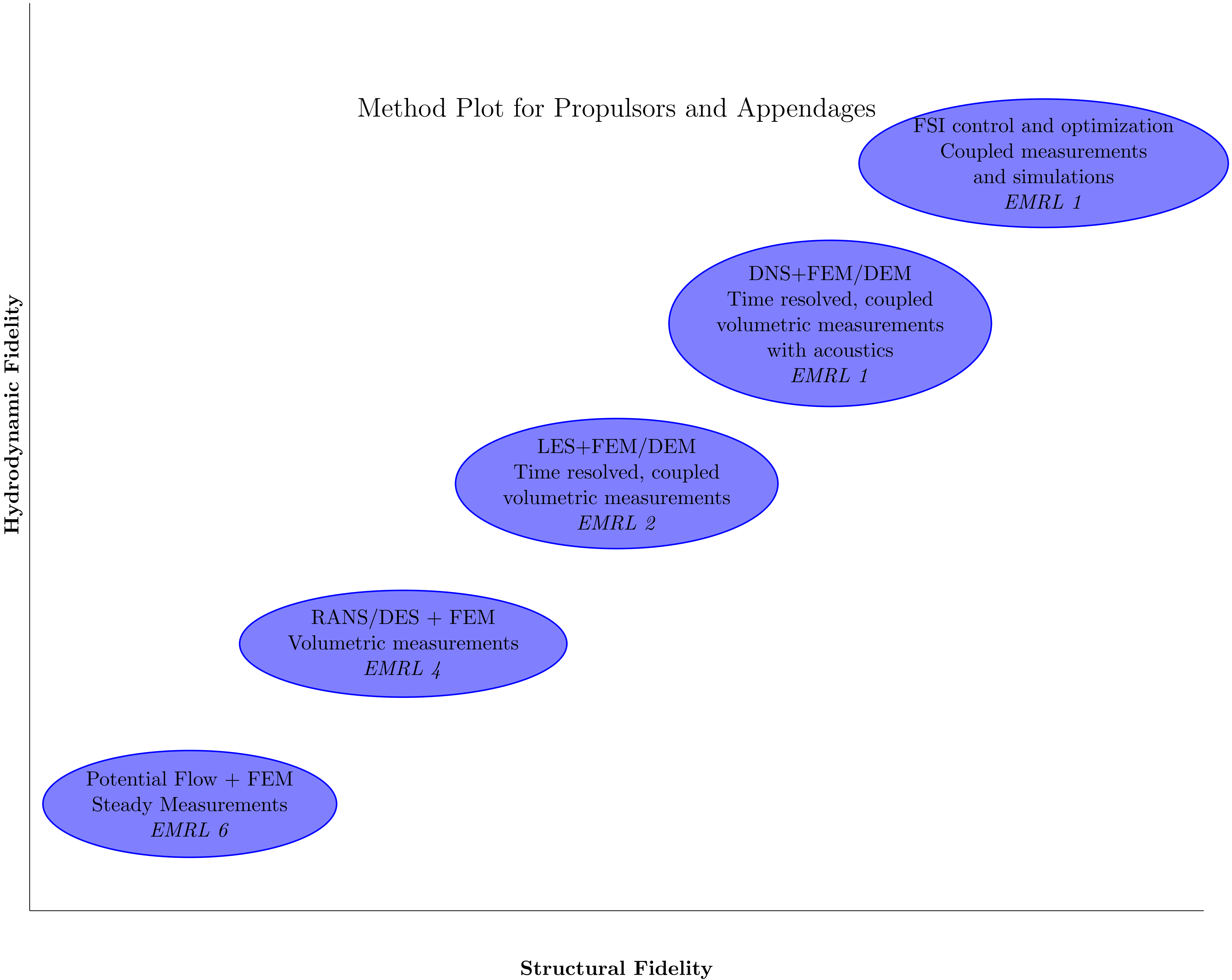
5 Years	**10 Years**	**15 Years**
Research: • Constitutive modeling for composites • Coupling for composite FSI • Reduced order modeling	**Research:** • Design and control of large deformation FSI • Scalable FEA • Multi phase FSI	**Research:** • Smart materials and distributed actuation and damping
Application: • Composite appendages/propellers	**Application:** • Passive large motion flexible materials/structures • Active small motion materials/structures	**Application:** • Active large motion • Smart appendages/propellers

A.3.3 Acoustics of Propulsors and Appendages

Future Research and Application Goals for Acoustics of Propulsors and Appendages

5 Years	10 Years	15 Years
Research: • Couple hydrodynamic and acoustic simulations • Couple hydrodynamic and acoustic experiments • Noise generation due to multi phase flows and vibration	**Research:** • Coupled hydrodynamic, acoustic, and structural simulations and experiments • Sound propagation in complex media • FSI of maneuvering platforms • Methodology for mitigation of adverse effects	**Research:** • Real time noise monitoring and suppression
Application: • Inform propulsor and appendage design • Inform validation of numerical simulations for VV&A	**Application:** • Inform design of advanced materials for propulsor and appendage • Improved predictive models • Enhance realistic simulation • Mitigation strategies	**Application:** • Enhanced environmental awareness

A.3.4 Methods for Propulsors and Appendages



B Research Questions

B.1 Overview of Day 2 Questions

1. **How can we better utilize machine learning and data processing to improve the generation and understanding of large experimental and computational data sets?** Topics such as storage, searching, visualization of large experimental and computational data set, methods to process and map large amount of data between code (one-way coupling), automated mesh refinement during simulation from on-line algorithms, and intelligent grid generation to reduce analysis turn-around time.

2. **What are the current limitations of fluid simulation methods for FSI problems and how can we reduce them?** What fundamental improvements in physics models are required to better capture the type of flows of interest for future FSI problems? All uses cases, plus other navy applications are in scope. This may include methods that better represent multi-phase physics, turbulence etc. or methods that increase computational efficiency at current accuracy levels.

3. **What are the current limitations of structural mechanics solution methods for FSI problems and how can we reduce them?** What fundamental improvements in physics models are required to better capture the type of structural responses of interest for future FSI problems? How do we move beyond primarily elastic structural analysis in FSI problems? All uses cases plus other navy applications are in scope. Multi-scale models, material/geometric non-linear models, and models dealing with fracture and failure are all of interest.

4. **What are the current limitation of coupling approaches to FSI problems and how do we address them?** What are the needs in developing more robust coupling models? Is there a role for monolithic codes or loose coupling? What V&V requirements are needed for our current coupling approaches? How do these methods currently scale?

5. **What physics and applications require us to address the full 2-way coupled FSI problem? When can we use other approaches?** Is it possible to know ahead of time when each coupling technique is needed? When will using a 2-way coupled FSI solution change requirements? Does global response require 2-way coupled FSI solution for extremely flexible vessels?

6. **What are the current needs for Verification and Validation? What uncertainty quantification developments are needed?** How do we address V&V of complex codes coupled together? How do we handle uncertainty quantification for these codes when used in design or analysis settings? What are the primary sources of uncertainty that are not well understood?

7. **What experiments are required to advance our understanding of FSI?** What benchmark experiments are needed to support future FSI development? What experimental facilities and techniques might need to be developed to carry out these experiments? How repeatable are these experiments?

8. **What are the key problems with user training and human interaction with complex FSI numerical simulations?** Given the complex physics being simulated by most FSI approaches, and the complex IT requirements of running practical FSI problems, how do we

address user training for these codes? How should we document and prepare codes for use? How should the results of these codes be presented to non-technical experts? What software development models open-source, shared-source etc — would effectively allow concurrent development and application of these codes?

B.2 Question 1: Improving generation and understanding of large data sets

Prompt: *How can we better utilize machine learning and data processing to improve the generation and understanding of large experimental and computational data sets? Topics such as storage, searching, visualization of large experimental and computational data set, methods to process and map large amount of data between code (one-way coupling), automated mesh refinement during simulation from on-line algorithms, and intelligent grid generation to reduce analysis turn-around time.*
Group Response:

- Objective and Goals for 5-10 years
  - Decision making through physics
  - Improvement of validation based on big data
- S & T Challenges:
  - Automation - complex grids, etc.
  - Data compression
  - Model/dimensionality reduction
  - Multi-fidelity/dimensionality modeling
  - Pattern recognition and automated cost function
  - Machine learning and adaptive surrogate modeling for FSI simulations and experiments
  - Distributed data and system identification

Comments from Walking Poster Session:

- How to exploit legacy data both experimental and numerical?
- In machine learning area, noise is always problem. How do you identify and filter our noise?
- How much data is enough to allow machine learning and modeling of the correct physics?
- Machine learning expertise is needed to improve our basic understanding of where it might pay off
- Identify key data to be passed, possible algorithms to interpolate intermediate data

B.3 Question 2: Limitations of current fluid simulation models for FSI

Prompt: *What are the current limitations of fluid simulation methods for FSI problems and how can we reduce them? What fundamental improvements in physics models are required to better capture the type of flows of interest for future FSI problems? All uses cases, plus other navy applications are in scope. This may include methods that better represent multi-phase physics, turbulence etc. or methods that increase computational efficiency at current accuracy levels.*

Group Response 1:

- **Slamming Problems:**
  - 3-D Potential Flow (expensive but current workhorse)
    * Adaptive refinement approaches needed
    * Hybrid zonal approaches
    * Use with HPC resources
  - Viscous RANS Flows (limited current use)
    * Free surface contact zones
    * 6-DOF coupling
  - LES
    * How important is LES? What additional physics do we need to capture?
    * Current limitations around multi-phase, compressibility, and free surface/turbulence interaction
- **UNDEX Problems**
  - Challenge of full compressibility
  - Equations of state and bubble formulation
  - Near surface effects: shock impact, cavitation
  - Range of time scales
  - 3 distinct events: formation, propagation, and impact

Group Response 2 (Propeller/Appendage Focus):

- Propellers
  - Issues
    * Multi-material
    * Crashback simulations
  - Limitations
    * Tip vortex and blade cavitation
  - Research topics
    * Improving algorithm efficiency
    * Model reduction
    * Reduce calculation cost or time
- Acoustics
  - Issues
    * Near-wall coupling
    * Unsteady predictions
  - Limitations
    * Unsteady near-wall modeling
  - Research topics

    * Near wall physics
    * Unsteady coupling

- Erosion
  - Issues
    * Range of length scales — micron-scale bubbles through large scale fluid/air
  - Limitations
    * Physical modeling
    * Numerical modeling

Comments from Walking Poster Session:

- It is still unclear to me if we have a plan for extremes of simultaneous loads (multi-directional) of multi-hulls
- Incorporation of experimental data
- CFD limitations for rare event simulation
  - Need extreme value distribution
  - Need pressure map in addition to integrated loads a time of extreme event
- Unsteady boundary layer formulations
- Time zonal methods that effectively use different fidelity in time as more physics is needed: i.e. in waves as approaching a slam event linear →non-linear →VOF/RANS/Euler →linear again
- Consider detailed FSI computations and limited experiments to developed structural/material specific characterizations of slamming impact response (stress, transfered forces etc.) models for use in time domain seakeeping in lieu of current Wagner/Lewis approach.
- New algorithms needed that address long time solutions (UNDEX)

B.4 Question 3: Limitations of current structural simulation models for FSI

Prompt: *What are the current limitations of structural mechanics solution methods for FSI problems and how can we reduce them? What fundamental improvements in physics models are required to better capture the type of structural responses of interest for future FSI problems? How do we move beyond primarily elastic structural analysis in FSI problems? All uses cases plus other navy applications are in scope. Multi-scale models, material/geometric non-linear models, and models dealing with fracture and failure are all of interest.*
Group Response 1:

- Grid resolution mis-match and multi-scale models (5-10 years out)
  - Structures and fluids use different grid sizes
  - Structural grids often much finer (e.g. near welds)
- Use of course mesh with automatic mesh refinement (e.g. around damage) (5 years)

- Fracture and failure improvements (10 years)
  - Want to be able to identify fragmentation/material separation
- Performance and scalability remain challenging (5-10 years)
- Remesh after damage in FSI problem (5 years)
- Gather/scatter bottleneck in parallelization approaches needs to be resolved (5 years)
- Internal fluids inside tanks currently cannot be handled with tools — particle approaches?
- Other items not discussed in detail but areas for improvement:
  - Composite delamination
  - Stability of solutions
  - Use, risk, acceptability of non-converged meshes
  - Joint mechanics, especially stiffness and damping

Floor Questions for Group 1:

- What do we need to learn to understanding damping? Answer: Probably mainly in joints for many structures
- What is capability with composites? Answer: Good capability for layups, harder at joints with steel/other materials or after delamination/damage
- What about inflatable structures? Answer: Some capability if fully inflated

Comments from Walking Poster Session:

- Need to develop intermediate structural models for fast and simple structural responses models of multi-hulls for elastic responses and FSI calculations in time-domain seakeeping, esp. for advanced, light, unmanned vehicles
- Need a lower fidelity option for multihulls other than 3-D FEA models
- Implement material failure into FEA beyond mesh-sensitive element deletion
- Modeling of distinct damping mechanisms (e.g. hysteresis/structural, acoustic, radiative, viscous) esp. for non-metallic materials

B.5 Question 4: Limitations of current coupling models for FSI

Prompt: *What are the current limitation of coupling approaches to FSI problems and how do we address them? What are the needs in developing more robust coupling models? Is there a role for monolithic codes or loose coupling? What V&V requirements are needed for our current coupling approaches? How do these methods currently scale?*

Group Response 1:

- Research goals for next 5 years
  - Convergence and conservation of the coupling

- Experiments for validation of the coupling problem
  - More detailed measurements of field variables d/u/p at the interface
  - Different classes of problems
  - Both unit (canonical) and component problems
- Best practices for stability, accuracy, and efficiency (problem dependent)
- Time stepping/sub-cycling strategies
- Parallelization and scalability
- Interpolation and gridding strategies

- Research goals more than 5 years out
  - All of 5 year goals on more complex structures
    - Cracks
    - Sliding structures
    - Adaptive gridding
  - Time resolved volumetric measurements for fluid and structures
  - Discrete to continuum modeling both fluid and solid, related to coupling
    - Bubbly flows
    - Fragmentation
    - Particle methods
  - Influence of uncertainty

Comments from Walking Poster Session:

- Clear measures and metric for energy and moment conservation
- Unified application programming interface for FSI - Pressure, Velocity, Displacement and what else?
- Immersed boundary uses average cell pressure and boundaries. Maybe there are better ways to calculate the fluid pressure at the boundary
- How is uncertainty addressed in coupled problems? What is measure? Variables?

B.6 Question 5: When is two-way coupled FSI required

Prompt: *What physics and applications require us to address the full 2-way coupled FSI problem? When can we use other approaches? Is it possible to know ahead of time when each coupling technique is needed? When will using a 2-way coupled FSI solution change requirements? Does global response require 2-way coupled FSI solution for extremely flexible vessels?*

Group Response 1:

- Physics that matters for decision:
  - Large deformation
  - Fluid-structure density

- Ventilation, separation
- Cavitation
- Flutter/stability
- Compressibility

- 5-year S & T Goals:
  - Identify and explore canonical problems needing 2-way coupling algorithms to compare with theory and experiment, then more complex geometry
  - Evaluate importance of physics for different applications
  - Continue to develop 2-way algorithms for improved stability and efficiency
  - Uncertainty quantification for criteria to evaluate difference between 1-way and 2-way
- 20-Year landscape:
  - Advanced materials
  - Active control of compliant and flexible structures
  - Unmanned
  - Multi-fidelity, multi-physics
  - Design and optimization
  - Emerging heterogeneous computer architecture — GPUs, Parallelization
- S&T needs:
  - Potential flow still important to find extreme events
  - CFD
  - URANS/DES/LES
  - Coupling algorithm
  - Adaptability of algorithm

Group Response 2:

- Re-defined the problem
  - When is it sufficient to use 1-way vs. 2-way FSI coupling?
    - What kind of physics do you want to capture?
    - Will the numerical scheme be able to capture the desired physics? Why and why not?
    - How will the numerical solution (in terms of accuracy and stability) be affected by the coupling scheme?
- Near-term S&T Goals:
  - Define in parametric space in terms of dimensionless governing parameters (relative mass/density ratio, relative stiffness ratio, bend-twist coupling ratio, Re, FR etc.) when full 2-way FSI coupling is needed for canonical problems in terms of:
    - Physics

        - Relative time and length scales of the fluid and solid phenomena
        - Steady-state vs. dynamic (phase and amplitude of harmonics)
        - Instability and bifurcation (e.g. divergence, flutter, parametric resonance)
        - Problem regimes: Single phase internal vs. external problems (plates/foils in closed vs. open domains); Free surface flows (slamming of plates/wedges); Static, periodic vs. impulse type of problems (on plates); Viscous flows (vortex shedding, transition, TBL of flexible plates)
      * Numerics
        - Stability and accuracy
        - Dependence on coupling and integration schemes
        - Analytical derivations vs. numerical examples: Grid size and time sensitivity, re-meshing and interpolations schemes
      * Derive reduce order models based on these canonical experiments and numerical studies

- Greater 5 years S&T goals
  - Defined best practices for when full 2-way FSI coupling problems is necessary for complex problems and determine when ROMs are sufficient
    * Complex flows - (multiphase flows, breaking waves, and whipping, maneuvering, crashback of smart propulsors, UNDEX response of morphing structures, complex FSI-induced vibrations and acoustics)
    * Complex geometries (full vessel with appendages, propulsor, and free surface)
    * Complex solids
      - Anisotropic, fiber/matrix, composites
      - Plastic, creeping, and rate dependent materials
      - Erosion, cracking/delamination, and material failure in general
    * Complex structures (morphing structures, smart structures with active/passive control)
    * Multi-scale problems — local (e.g. localized material damage, erosion, crack propagation, cavitation, sprays) vs. global response; FSI approaches needing both discrete and continuum approaches
    * Seakeeping and maneuvering of adaptive structures
    * Dependence on numerical coupling and integration schemes, and effect on efficiency, stability, and accuracy. Numerical are also complicated by miss-matched mesh between fluid and solid, large deformations, removal of solid elements due to material damage, fluid particle out of domain.
    * Sensitivity to uncertainties
  - Use big data to bring together increasingly complex FSI problems to:
    * Define knowledge gaps
    * Develop reduce order models
    * Define new materials, smart structures, passive and active control strategies

Comments from Walking Poster Session:

- How to quantify the uncertainty based on the coupling fidelity? (Group 1)

- Non-linear structural response, both elastic and elastic-plastic (Group 2)
- Needs for coupling must tie to output quantities of interest. This is the only way to know if things are "good enough"

B.7 Question 6: Needs for V&V and Uncertainty Quantification

Prompt: *What are the current needs for Verification and Validation? What uncertainty quantification developments are needed? How do we address V&V of complex codes coupled together? How do we handle uncertainty quantification for these codes when used in design or analysis settings? What are the primary sources of uncertainty that are not well understood?*

Group Response 1:

- 5 Year Goals:
  - Set of canonical problems with isolated physics as well as combined for:
    - Fluid
    - Structure
    - Coupling
  - Trying to understand the source of uncertainty:
    - Coupling
    - Scaling
    - Facility bias
- Multi-fidelity studies
- Dynamic error estimators
- Using optimization methods to design the canonical problem (uncertainty reduction)
- 10 Year Goals:
  - Aleatory uncertainty: Validation of distributions (irregular waves) estimator
  - Designer wave
  - Consistent finite element solvers with consistent error bar estimation — Variational principles and Galerkin approaches
    - FE fluid solver
    - FE solid solver

Group Response 2:

- Well characterize simple geometry experiments, open, published
- Some large scale validation
- Computational/experimental collaboration (e.g. Design of Experiments execution)
- Statistics of test repeatability
- Experimental driven simulation — close work between CFD and experimental community

- Well characterized means:
  - Structural M, K, (no change) Damping.
  - Geometry
  - Flow boundaries
  - Boundary location f(t) - run experiments with fixed bodies and bodies with motions intentionally induced
  - Velocity distribution
  - Pressure distribution
  - Raw data databank
- Collaboration on test matrix, especially sensitivity to quality of instrumentation
  - CFD valuable to interpret the experimental results
  - CFD can explore conditions for testing
  - Fluid, structure, computational needs discussed from earliest stages
- Tools needed:
  - Non-intrusive, reliable, pressure sensors
  - Deformation measurements
  - Continue taking advantage of imaging and signal processing
  - Miniature gauges in large numbers

Comments from Walking Poster Session:

- How to validate stochastic, non-linear, dynamical systems? (Group 1)
- Collect selectively existing FSI benchmark experimental data for naval relevance (e.g. for 4-5 users cases relevance) and develop a data library for FSI research to use for V&V and UA purposes (Group 1)
- Investigation into "intrusive" methods for UQ may be warranted to get leaps in efficiency for UQ in this domain (Group 1)
- Error norms? Energy norms? L^2, L^∞ norms (Group 1)
- Cross solve codes - FE CSD solvers coupled with FV fluids solvers coupling scheme — what are the appropriate error metrics? (Group 1)
- Simulation-drive experimentation (test at the limit of theory) (Group 2)

B.8 Question 7: Future experimental needs

Prompt: *What experiments are required to advance our understanding of FSI? What benchmark experiments are needed to support future FSI development? What experimental facilities and techniques might need to be developed to carry out these experiments? How repeatable are these experiments?*
Group Response 1: *This group focused discussion on requirements of benchmarking*

- Well defined and simple boundary conditions
  - Fluid
  - Structural
  - Material/Mechanical
- Repeatable conditions/measurement convergence
- Community with access to experimental data
- Appropriate spatial/temporal resolution
- Iterative design featuring:
  - CFD and CSD inputs
  - Pre-test simulations
  - Iterations to better understand experimental data
- Integrate sensor and signal processing development
  - Intrusive sensors can change response
  - Sensor development needed
- Need ability to effectively determine extreme events — 1 in 10,000 event.

Group Response 2:

- Needed experiments:
  - Component problems (ship models) for measuring local and global loads/responses
  - Unit problems (canonical geometries, e.g. plates) for detailed, repeatable studies of local loads/responses in extreme events.
  - How to "tie together" component and unit?
  - Measurement techniques for obtaining time-resolved field of normal pressure and motion at fluid-structure interface
- Research plan next 5 years
  - Fully submerged cases
    - Benchmark experiment
    - Lifting surface
    - Rigid →flexible →non-linear
    - Forced vs. natural oscillations
    - Coupled validation
  - Slamming cases
    - Sensor and technique developments
    - Non-intrusive pressure embedded piezoelectric sensor
    - Improve optical fluid measurements
    - Surface effects

- Research plan 5-10 years
  - Fully submerged
    - Introduce cavitation
    - Multi-phase problem
    - Surface piercing
  - Slamming
    - Benchmark experiments
    - Flexible wedge
    - Dam break
    - Rigid →flexible →non-linear
    - Dry structural characterization
    - Coupled validation

Floor Questions and Comments for Group 2:

- Need to consider modeling the mounting, or use free-running model
- Field variable from coupled solution is what is needed for validation
- Programmatic challenge — cultural challenge to get experimentalist and CFD communities together and change way to approach problem
- Need to develop methodology to make complete data available for download when needed, even after people retire or move on

Comments from Walking Poster Session:

- Plate panel, stiffened panel, or grillage (in response to Group 1's requirements)
- Better deployable sensing for full-scale data — measurement of the fluid and structural loads and motion at the interface (Group 2's needed experiments)
- Full-scale canonical experiments (Group 2's needed experiments)
- Multi-scale experiments (Group 2's research plan)
- Forced deformation for one-way coupled validation (Group 2's research plan)
- Piezoelectric or other sensors (Group 2's research plan)
- Importance of similarity laws in designing experiments (Group 2's research plan)

B.9 Question 8: Training and human interaction challenges

Prompt: *What are the key problems with user training and human interaction with complex FSI numerical simulations? Given the complex physics being simulated by most FSI approaches, and the complex IT requirements of running practical FSI problems, how do we address user training for these codes? How should we document and prepare codes for use? How should the results of these codes be presented to non-technical experts? What software development models open-source, shared-source etc — would effectively allow concurrent development and application of these codes?*

Group Response 1:

- Re-define the problem
  - What are ONR goals?
  - There exists a Valley of Death between S&T and production use with the Navy
  - Also, is important to involve industry?
  - Who are the users?
  - This a very general problem across community that includes a need for a standard validation process
- Ideal: unit testing, formal open-source standard not practical
- What specific research gaol will advance the issue of user training and human interaction for FSI?
  - Complex world of ip, competitive goals
  - How can we encourage a robust community?
  - Downselect ... either through collaboration or reduction
  - Focus on specific needs of FSI
- 5-Year plan
  - Establish consortium in particular areas of FSI
  - Fund blind-tests, numerics before experiments
  - Round-robin testing
  - Shared code ideals
- Goals more than 5 years out
  - Investigate the utility of a common database for networking and comparing results and sharing source
  - Work to support community tools such as Integrated Hydro Design Environment, Integrated Structural Design Environment to coordinate research efforts
  - Not contractually required ... but at least inform the research of user standards to ease later transition
  - Investigate ways to encourage at least minimal documentation
  - Encourage collaboration between industry, labs, end users

Comments from Walking Poster Session:

- How does a university S&T code become verified for support of a major Navy program?
- If it is not going to be, why provide user training etc?
- Testing end users to see how the may misuse the code and understand why
- As codes become more complex, and simulations tie together codes from different domains (fluids, structures) how are we sure that the team understands what they have built? Both the development team and downstream users
- How do we communicate modeling needs and modeling assumptions between design community and analysis community for ad-hoc support of specific programs?
- How do we compare users mental model of assumptions to actual assumptions of the code?

C Working group agenda and lessons learned on facilitation

The Ann Arbor event represented a different type of event from normal review meetings or conferences. Other than the introductory, overview talks, all the remaining content for the event was generated live by participants throughout the course of the two days. Organizing and planning this type of event was a challenge as few interactive technical events have been held in this fashion. Indeed, the morning of the event, the organizers agreed that the event would either be viewed as a great success or a complete failure. Fortunately, it seems that the event fell much more in the success category. This appendix outlines the approach taken, and some of the lessons learned from this event. It has been compiled to help in the planning and execution of similar events.

From the outset, ONR was looking for an interactive method of determining a landscape map of the FSI community. After significant debate, it was determined that a large, community-wide working session would be the most fruitful way of obtaining this information. A small steering committee, ranging between three and ten individuals developed and critiqued the activities planned. This steering committee also completed the initial background work - determining the state-of-the-art experts to ask for introductory presentations, assembling use cases from NAVSEA, and preparing read-aheads and slides decks. The event itself was broken into two parts, based on the perception that there was a strong and distinct application and research components to the FSI community. Day one would focus on application needs, and technical developments to support them, while day two would focus on research opportunities. One day could be seen as the application pull, while the other day was the technology push.

The break-out group structure for each day was inspired by advice received from European colleagues. To prevent a few loud voices from taking over the conversation, breakout groups were limited to five participants. Smaller groups meant that more than one breakout group would address each subject, giving many voices a chance to be heard. It also allows the organizers to compare outputs from different groups. Similar ideas generated by all groups can be taken as a measure of consensus around those ideas in the wider community. This small-group approach, coupled with 8-person round tables as far as practical for groups, did seem to produce a lot of discussion and back-and-forth.

To further enhance participation, multiple opportunities for input were given. Plenary sessions were held after each breakout in a hierarchal fashion. First, groups addressing the same topic met to compare notes and prepare a "union" presentation of all their ideas. Then, each topic was presented to the entire group. The first step in this hierarchy was skipped on the second day as no question had more than two groups working on it — in general, if time allows for all breakout groups to present, this simpler approach may be better. Additionally, all participants were handed a stack of post-it notes on registration. Several opportunities were given for input via post-it note, including a final walking poster session at the end of the event where participants were allowed to comment on anything from the first two days. This method of input was very successful at capture input that might have been lost in the time limits of a plenary session. Indeed, some of the most insightful comments came from these post-it notes.

The list below presents a summary of the lessons learned. Ultimately, the event seemed to function as intended. The majority of the participants were happy with the structure, and a large amount of information on FSI was recorded. With proper planning, interactive formats in technical disciplines need not be feared.

- Interactive events require the ability to provide near-real-time summaries and synthesized slide presentations from breakout groups. In turn, this required:
  - Each topic (which may have had two to three five person breakout groups working under them) had two technical leads who were briefed ahead of time on the agenda and expected outputs.
  - Dedicated scribes for each topic who were not technical participants. Their only role was to record and integrate.
  - Strong IT support in the form of slide (PowerPoint) templates for results, laptops for the scribes, and printers to quickly turn slides into posters for the final working poster session.
  - While scribes were largely professional support staff, students performed many of the printing, mounting, and organizing supporting work.
  - Leaving some time at the end to formally document the sub-groups opinion prose would be helpful. The raw notes reproduced in the appendixes of this document, while useful, can be difficult to interpret in terms of relationship between ideas and priority.
- The original Day 1 plan was far too detailed. In the use case breakout groups, groups were expected to review use cases, fill in the EMRL plots, and the future research/application ideas for 5, 10, 20 years. It was not possible to explain this level of intricacy in the introductory talks. A simpler recording template (and maybe a live demo) would have been better. On Day 2, groups were organized around a single question. This ran much smoother.
- In addition to technical leaders and scribes, three to four students were necessary to help organize tables, distribute supplies, and answer questions.
- A low-tech approach was taken at the breakout group level. Large, blank flip charts and post-it notes were used to gather information. This was inexpensive and accessible to all. However, a better recording and filing system for this type of output would have helped in post-processing the result of the working group. Efforts to label each piece of paper as it came in did not scale well enough, and there was a bit of puzzling over a few pieces of paper.
- Giving people opportunities for many forms of input was very helpful and well used. Post-it notes or other means of gathering input that is both:
  - Asynchronous in that the contributer does not have to be able to interject it into a plenary discussion
  - Asynchronous in that the contributer can come back and comment on something that happened a few hours or a day ago.

  proved very helpful.
- People will largely trust that group activities will work. To help build up this trust, solid read-aheads and clear agenda are recommended. However, with any large group activity there will be surprises, so do not be tied to the original agenda. In this event, the questions for Day 2 were planned based on the feedback from Day 1, and then the timings of Day 2 were adjusted to fit the final questions on the fly.
- Compiling the final report took far more hours than anticipated. If possible, this work should be distributed to the technical leads in each area, at least for the reporting of the discussion that occurred.

Fluid-Structure Interaction Working Session University of Michigan, North Campus, Ann Arbor, MI 48104 July 19th-20th Ford Presidential Library, 1000 Beal Avenue Ann Arbor, MI 48109			
Time		**Talk**	**Speaker**
Day 1 -19 July 2016			
0800	0830	Introductory overview of FSI and purpose of the meeting	Dr. Tom Fu, Dr. Paul Hess, ONR
0830	0900	Presentation of hydro theory, experiment, and codes	Dr. Joe Gorski, NSWCCD
0900	0930	Presentation of structures theory, experiment, and codes	Dr. Neil Pegg, DRDC
0930	1000	Presentation of coupling approaches	Prof. Chris Earls, Cornell
1000	*1030*	*Break*	*All members*
1030	1100	Breakout group logistics and use cases	Dr. Matt Collette, UM
1100	1200	Initial use case working group meetings - 5 person discussion circles	All members
		Theme Area A: Global ship loading and response FSI (3 circles)	
		Theme Area B: Local ship loading and response FSI (3 circles)	
		Theme Area C: Propulsor FSI (2 circles)	
1200	*1300*	*Lunch in main foyer*	
1300	1400	5 person discussion groups continue	All members
1400	1500	Roll up of 5 person groups into broader theme areas A,B,C	All members
1500	*1530*	*Break*	*All members*
1530	1700	Conclusion gathering with theme presentations from areas A,B,C	
1700	*1830*	*Informal walking dinner in foyer*	*All members*
Day 2-20 July 2016			
0800	0830	Overview of progress thus far, agenda for the day, description of issues and working group assignment announcements	Dr. Paul Hess, Dr. Matt Collette
0830	1000	Research challenges working groups	All members
1000	*1030*	*Break*	*All members*
1030	1130	Roll up research challenge working groups into theme areas A,B,C	All members
1130	*1230*	*Lunch in foyer*	*All members*
1230	1330	Brief out research challenge working groups	All members
1330	1430	Walking poster/issue session	All members
1430	*1500*	*Break*	*All members*
1500	1600	Research challenges evaluation	Dr. Tom Fu
1600	1630	Summary and way ahead	Dr. Paul Hess, Dr. Matt Collette

Figure 27: Pre-Workshop Agenda — Day 2 was adjusted the morning of to change timings slightly