SSC Project Recommendation for FY 2016

Extraction of Real-Time, Full-Field Dynamic Stress and Strain using Finite Element Model Information and Limited Sets of Measured Data for Vessel Structural Health Monitoring

1.0 OBJECTIVE.

1.1 The objective of this project is to improve techniques that extract full field dynamic stress and strain from limited sets of measured data for the purposes of structural health monitoring (SHM) and damage prognosis of naval vessels. The results of this research will provide the marine engineering community with an experimental and numerical framework that utilizes finite element model (FEM) information to extract in-situ, the real-time operational deflection shapes (ODS) of a vessel subject to an unknown arbitrary loading.

1.2 The proposed approach eliminates the uncertainty associated with operational loads, by using a transformation matrix, established from a finite element model, to expand operational data collected at a limited set of points to a 'finite element scale' displacement field.

2.0 BACKGROUND.

2.1 While the procurement of a new vessel represents a large capital expenditure, general maintenance and downtime for unplanned repairs contribute significantly to total ownership costs. Consequently, the United States Coast Guard has initiated a Fatigue Life Assessment Program (FLAP) to aid in hull structure lifecycle management for the National Security Cutter Class [8.1, 8.2, 8.3]. Stambaugh et al. have shown that a considerable return on investment (ROI) can be achieved if fatigue life is considered early in a vessel's design. However, assumptions with respect to operational environment and in-situ loading affect the accuracy of the fatigue life predictions. In the case of the National Security Cutter, the vessel was found to operate in less severe conditions leading to an under prediction of the vessel's fatigue life at the design stage. While a more conservative fatigue life estimation may be desirable early in the design, a viable SHM program requires an accurate evaluation of the vessel's in-service response to operational loads to minimize sustainment costs and maximize vessel life. This evaluation needs to be performed regularly without the overhead of a complicated hydrodynamic loading analysis or model tests [8.2, 8.3]. Furthermore, in-situ measurement of a vessel's response to operational loads is limited to a set of sensors installed at accessible locations thereby limiting one's knowledge of the vessel's response and stress state at unmeasured locations. A robust SHM program also requires information of the operating response at structural locations that cannot be easily measured, but are important for assessing fatigue life.

2.2 The finite element method is commonly used to evaluate the response and integrity of a vessel to static and dynamic loads. The true nature of the applied forces and boundary conditions represents a major source of uncertainty in most finite element analyses. Accurate evaluation of a vessel's stress and strain requires a highly refined mesh, particularly in areas of stress concentrations. These highly refined models can be computationally intensive, further complicating the prediction of a vessel's response to operating loads. Therefore, the conventional use of a finite element model to determine the real-time response of a vessel to operating loads is not optimal. However, model reduction and expansion techniques exploit the limited modal nature of the dynamic response, condensing finite element data and limiting computational complexity. With an appropriately selected set of basis vectors, these methods can accurately capture the dynamics of the entire structure.

3.0 REQUIREMENTS.

All measurement and modeling efforts will be focused on demonstrating the extraction of full-field strain and stress from operating data collected on a single vessel.
3.1.1 The Contractor will create a full ship finite element model of a candidate vessel. Dynamic properties of the vessel (mode shapes and natural frequencies) will be extracted. An initial analysis of expected operational loads will be undertaken and the necessary dynamic properties needed to capture the response to these loads will be used to establish appropriate expansion transformation matrices.

3.1.2 The Contractor will utilize the full ship finite element model to synthesize operational data and conduct perturbation studies. These studies will be used to understand the acceptable limits of a given transformation matrix (i.e. modal basis) to capture accurately, the global dynamics of the vessel in a condition other than that used in to establish the modal basis (i.e. tank loads, outfitting, cargo, construction defects, etc.). The perturbed model should be reduced to a set of points representing simulated test locations. The accuracy of the expansion method should be discussed in light of the particular basis vectors included in the transformation matrix and the extent of the deviations between the models used to establish the transformation matrix and synthesized test data. The goal of this task is to quantify the robustness of a transformation matrix derived from a finite element model that is imperfect and uncorrelated to the structure whose operating data the transformation matrix is expanding.

3.1.3 Invariably, simplifications and assumptions must be made when generating a finite element model of a large structure such a ship. These simplifications and assumptions affect the accuracy of the modal basis vectors used in the expansion matrix. Finite element models of smaller localized structures can afford inclusion of finer details, potentially improving the accuracy of the basis vectors used in the expansion process. The Contractor shall repeat the tasks outlined in paragraph 3.1.2, utilizing basis vectors established from highly refined models of local ship structures. The viability of this method as applied to local structures vs. the entire ship shall be discussed.

3.1.4 The Contractor shall address the augmentation of the modal basis vessel with vectors capable of capturing static and quasi-static vessel displacements from localized loads. These static and quasi-static deflections can be characterized by higher spatial frequencies than those present in the lower order mode shapes.

3.1.5 The Contractor shall perform measurements on the actual vessel. As part of the measurement process, the Contractor shall discuss the types of sensors used (i.e. accelerometer, strain gauges, etc.) and comment on the selection of measurement locations such that the relevant vessel dynamics are captured. The Contractor shall also include additional ‘reference sensors’. Data collected from the ‘reference sensors’ will not be used in the expansion process, rather the data from these sensors will be compared to the expanded real-time operating data to assess the accuracy of the technique.

3.2 Two tasks are proposed, as follows:

3.2.1 The Contractor shall generate finite element models of a particular vessel. Imperfections and variations that simulate changes in tank loading, cargo, manufacturing defects, etc. will be artificially introduced and ‘synthesized’ test data will be generated from reduced versions of these models. The results of this task will establish the acceptable degree of variation between the finite element model used to generate the transformation matrix and the actual structure. The task will also compare the viability of the approach to local structures, finite element models of which can afford the inclusion of finer details that cannot be as easily captured in full ship models.

3.2.2 The Contractor shall evaluate the method for extracting full-field dynamic stress and strain by collecting operating measurements on the vessel modeled in task 3.2.1. The Contractor shall identify the appropriate sensor types and locations so that the relevant vessel dynamics are captured. Additional data shall be acquired but omitted from the expansion process. These data will serve as reference values and compared to data obtained from the expansion process. This comparison will be used to validate the proposed technique.

3.3 This effort will be performed in one calendar year from the date of contract award (‘contract inception’) as follows:

3.3.1 Develop full ship and local structure finite element models: 3 months
3.3.2 Complete numerical studies: 3 months
3.3.3 Prepare test plan for method validation: 2 months
3.3.4 Conduct operational test of the actual vessel: 1 month
3.3.5 Post-test data analysis and report generation: 3 months

4.0 GOVERNMENT FURNISHED INFORMATION.

4.1 Standards for the Preparation and Publication of SSC Technical Reports.
4.2 Access to a vessel for performing measurements. This vessel should be the same vessel analyzed during the modeling phase. All pertinent drawings and CAD models of the vessel should be made available. To limit the time required to generate the finite element model, it is desirable that the candidate vessel be approximately 150 feet or less in length.

5.0 DELIVERY REQUIREMENTS.

5.1 The Contractor shall provide quarterly progress reports to the Project Technical Committee, the Ship Structure Committee Executive Director, and the Contract Specialist.

5.2 The Contractor shall provide a print ready master final report and an electronic copy, including the above deliverables, formatted as per the SSC Report Style Manual as posted on the website http://www.shipstructure.org.

5.3 The Contractor will make available any finite element model developed during the course of this effort.

6.0 PERIOD OF PERFORMANCE.

6.1 Project Initiation Date: date of award.

6.2 Project Completion Date: 12 months from the date of award.

7.0 GOVERNMENT ESTIMATE. These contractor direct costs are based on previous project participation expenses.

7.1 Project Duration: 12 months.

7.2 Total Estimate: $99,700

8.0 REFERENCES

8.1 Stambaugh, K., Drummen, I., Cleary, C., Sheinberg, R., and Kaminski, M., "Structural Fatigue Life Assessment and Sustainment Implications for a New Class of US Coast Guard Cutters", Ship Structures Committee Symposium, Linthicum Heights, Maryland, May 18-20 2014.

8.2 Drummen, I., Schiere, M., Dallinga, R., and Stambaugh, K., "Full and Model Scale Testing of a New Class of US Coast Guard Cutter", Ship Structures Committee Symposium, Linthicum Heights, Maryland, May 18-20 2014.

8.3 Hageman, R., Drummen, I., Stambaugh, K., Dupau, T., Herel, N., Derbanne, Q., Shiere, M., Shin, Y. and Kim, P., "Structural Fatigue Predictions and Comparisons with Test Data for a New Class of US Coast Guard Cutters", Ship Structures Committee Symposium, Linthicum Heights, Maryland, May 18-20 2014.

8.4 Pingle, P., Avitabile, P., "Full-Field Dynamic Stress/Strain from Limited Sets of Measured Data", Sound & Vibration, August 2011.

8.5 Avitabile, P, Pingle P., Carr, J., Niezrecki, C., "Alternate Techniques/New Approaches for Identification of Full Field Dynamics Stress Strain from Limited Sets of Measured Data for Wind Turbine Applications", 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, AIAA 2013-1696.