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Stochastic identification of the structural damage condition of a ship bow section under model uncertainty

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ABSTRACT

A accurate, quantifiable means of assessing structural damage condition are paramount for maintaining the structural integrity of ship hull forms. Toward this end, precise knowledge of the location and magnitude of any imperfections (i.e. geometric imperfections in the form of denting and corrosion patches) must be determined, along with concomitant uncertainties accompanying such predictions. The current paper describes a non-contact approach to identifying and characterizing such imperfections within the submerged bow section of a representative ship hull. By monitoring the pressure field local to the acoustically excited hull section, it is shown how the resulting data can be used to identify the parameters describing the structural damage field. In order to perform the identification, a fluid–structure model that predicts the spatio-temporal pressure field is required. A Bayesian, reversible jump Markov chain Monte Carlo approach is then used to generate the imperfection parameter estimates and quantify the uncertainty in those estimates. This approach is particularly appealing as it does not allow for the damage model to be explicitly known *a priori*. Convergence of the Markov chains is assessed, and estimates of the Monte Carlo standard error (MCSE) are provided.

1. Introduction

Advances in the state-of-the-art in naval architecture have led to the ability to field new hull forms that frequently are made from new material grades. These advancements precipitate increased uncertainties surrounding long term performance, due to a lack of experience within the design community. Essentially, new hull forms, made from new materials, are being fielded in response to performance demands and economic constraints of modern service contexts. Because of the uncertainties surrounding the performance of the new designs, it may be advisable to monitor the resulting hull structures throughout their life in such a manner that an accurate assessment of the condition of the state of the structure, at any point in time, is possible. Additionally, as decades of experience and data are not available for these new designs, a means for making a prognosis for the future state of the structure is desirable.

Since the publication of Koiter's seminal dissertation in 1945, it has become well known that initial geometric imperfections (e.g. denting) in shell type structures, for example ship hulls, may lead to dramatic erosions in ultimate buckling strength (Bazant and Cedolin, 1991; Featherston, 2003; Singer et al., 2002). Such imperfections may arise due to manufacturing, fabrication, construction, or service conditions. A recent and comprehensive survey of research developments during the period 1996–2006 (Edlund, 2007) highlights the fact that understanding the nature and effects of imperfections in shell structures continues to be a fertile line of inquiry to this day. In addition to dent-type imperfections as a source of reduced load carrying capacities, another geometric imperfection relevant to ship hull structures is corrosion. Corrosion erodes the cross-sectional area of structural components within the hull; thus reducing the ability of the hull to resist external loads (Akpan et al., 2001). However, the jump from the notional understanding that geometric imperfections adversely affect hull strength, to the realization of a practically useful means for predicting the actual strength of in-service ship hulls, is formidable. It is virtually impossible to rationally guess the precise damaged condition that may be manifest in a given ship structure. One might attempt to infer the damage field from observations, however practical methods for identifying the exact location and magnitude of the damage, from observed hull response data, are currently lacking. The problem is even more challenging if this identification is to be made *in situ*.

The traditional structural health monitoring (SHM) problem is fundamentally one that can be described as statistical pattern recognition (SPR), composed of the following four step process (Farrar and Worden, 2007):

1. Operational evaluation.
2. Data acquisition, normalization and cleansing.

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3. Feature selection and information condensation.
4. Statistical model development for feature discrimination.

In an SPR SHM approach, the goal is to determine the presence of (and in advanced cases quantify the values of) structural damage by statistically correlating features extracted from sensor response data with data features of known damage. However, this typically requires some *a priori* knowledge of how the structure will behave when it is damaged. The approach described herein is a *model-based* approach, in which a high-fidelity computational analog of the monitored structure (i.e. a finite element model) is parameterized with features describing the damage to be determined. The solution is then to quantify these damage parameters in the finite element model, so that the model generated response data “matches” the observed sensor response data.

Identifying localized damage in structures is a difficult problem, made so by the limited influence the damage typically has on observed response data from which the damage related parameters are to be estimated. The result is a challenging system identification problem for which an obvious solution is unclear. The two requirements for any system identification approach are the following: (1) a means of acquiring observations from the object of interest and (2) a model describing the influence of the parameters of interest (in this case, parameters describing the denting imperfections and corrosion) on the observed data. The present work focuses on the *a posteriori* characterization of the actual damaged condition (denting imperfections or corrosion) within the bow section of a representative ship (in this case a prototype of the Joint High Speed Sealift vessel) (Cusanelli and Chesnakas, 2007). The current research employs a sparse array of acoustic fluid pressure sensors (i.e. hydrophones) to help identify structural condition, simply by “listening” to the pressure waves induced by ambient vibrations occurring during the ship's service condition. A model describing the fluid–structure interaction (FSI) and the influence of the damage on the model response is also developed, and is described in detail in section 2.1.

In an earlier work (Reed et al., 2014), this basic approach was used to generate marginal posteriors of geometric imperfection damage parameters, enabling uncertainty quantification of the parameter estimates. This approach was also used in Reed et al. (2013) to generate *maximum likelihood estimates* (MLEs) of the imperfection location and magnitude. While MLE is a powerful approach to draw statistical inference about unknown parameters, the associated methods for quantifying the uncertainty in the estimate require either replication (many trials) or asymptotic approximations. The present research furnishes a Bayesian approach for estimating the parameters describing the imperfections, estimating the number of imperfections, and quantifying the uncertainty in those estimates. It will be shown that this can be accomplished through the solution of a stochastic inverse problem effected using dependent sampling techniques.

1.1. Background and motivation

Discrepancies between theoretical predictions and experimentally observed ultimate strengths in shell structures (e.g. ship hull structures, as considered in this work) may arise from imperfections related to boundary conditions, material properties, and shell thickness (Papadopoulos and Papadrakakis, 2004, 2005; Papadopoulos and Pavlos, 2007; Papadopoulos et al., 2009). The principal cause of this variation, however, is the presence of geometric imperfections, (e.g. denting and corrosion), resulting in deviations from the assumed perfect shell geometry (Singer et al., 1998, 2002). Structural damage (i.e. any condition that changes the material and/or geometric properties of structural systems) may arise during manufacturing, fabrication, construction, service conditions, or natural aging. The resulting differences between observed and theoretical ultimate strength make the development of principled design specifications difficult.

A recent study (Kristanic and Korelc, 2008) explored an efficient optimization-based approach for obtaining a worst case initial geometric imperfection field within a shell structure, as constrained by bounds on feasibility, as related to hypothetical deformations being explored by the optimization algorithm. The current research is different in that its approach aims to uncover the actual imperfection field present in the structure, as opposed to hypothetical, worst-case deformations. Such knowledge could allow for improved inspection protocols (e.g. physically inspecting the structure when there is evidence that damage exists, versus inspecting the structure at regular, timed intervals).

The goal of the present work is to model, and subsequently identify and characterize, dent-like and corrosion patch structural damage in a partially submerged ship hull bow section. Furthermore, we wish to quantify uncertainty in the damage estimates. In a previous study, Reed et al. (2014), a similar problem was solved using a Bayesian estimation approach to identify and characterize the parameters of a dent-like imperfection present in a simple, idealized submerged shell structure, where the damage model was assumed to be perfectly known. The Markov chain Monte Carlo approach employed in the previous work was able to successfully characterize the damage, as well as the uncertainty surrounding the parameter estimates. A reversible jump Markov chain Monte Carlo example was also provided in that work to demonstrate the efficacy of estimating the damage field when the damage model is not perfectly known *a priori*.

In another work, Reed et al. (2013), the same simple, idealized submerged shell structure damage identification problem was solved using a modified differential evolution (DE) algorithm. The algorithm was designed to quickly find the MLEs of the damage parameters, thereby providing point estimates of the imperfections. Such MLE-based approaches are attractive from a practical point of view (e.g. they may be employed as part of fast inverse solution algorithms), yet they can sometimes present challenges in terms of quantifying uncertainty. Typically one either repeats the MLE many times and uses the resulting spread of estimates to produce a confidence interval. Or, one could use an asymptotic approximation and base confidence intervals on the curvature of the likelihood function. However for many structural systems the likelihood contains numerous maxima with a very high degree of curvature (“spikey” likelihoods are not uncommon) (Reed et al., 2013, 2014; Stull et al., 2011), a situation that violates the underlying assumptions of this approach. The Bayesian formulation described in Section 2.2 neither requires a single-peaked likelihood nor relies on asymptotic approximation. Additionally, the reversible jump Markov chain Monte Carlo approach described in 2.5 does not require that the damage model be known exactly *a priori*, allowing for a robust stochastic inversion solution.

Much of the research involving damage detection within the context of FSI and shell-type structures has focused on structures that are filled (either completely or partially) with fluid, such as spherical storage tanks (Curadelli and Ambrosini, 2011), composite fuel tanks (Zhou et al., 2010), and cylindrical laminated composite shells (Yu et al., 2007, 2007). The works by Curadelli and Ambrosini (2011) and Zhou et al. (2010) explore the extent to which the presence of structural damage can be detected by monitoring changes in modal parameters between the undamaged (perfect) and a damaged, fluid-filled structure. If damage identification can be classified into four levels (Rytter, 1993):

1. Level 1: Determination that damage is present in the structure,
2. Level 2: Determination of the geometric location of the damage,