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Stochastic identification of imperfections in a submerged shell structure

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ABSTRACT

Accurate predictions of the buckling load in imperfection sensitive shell structures requires precise knowledge of the location and magnitude of any geometric imperfections in the shell (e.g. dents). This work describes a non-contact approach to identifying such imperfections in a submerged shell structure. By monitoring the acoustic pressure field at discrete points proximal to a shell structure excited by a cyclic membrane (i.e. in-plane) loading, it is noticed that parameters, describing small scale denting, can be identified. In order to perform the identification, a fluid-structure model that predicts the spatio-temporal pressure field is required. This model is described in detail and includes the predicted effects of the imperfection on the observations. A Bayesian, Markov chain Monte Carlo approach is then used to generate the imperfection parameter estimates and quantify the uncertainty in those estimates. Additionally: for cases involving the occurrence of an unknown number of dents, reversible jump Markov chain Monte Carlo (RJMCMC) methods are employed in this work.

1. Introduction

Since the publication of Koiter's seminal dissertation in 1945, it has become well known that initial geometric imperfections in shell structures may lead to dramatic erosions in ultimate buckling strength [2,8,28]. 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 [5] 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. However, the jump from this notional understanding, to the realization of a practically useful means for predicting the actual strength of in-service imperfect shell structures, is formidable. It is virtually impossible to rationally guess the precise imperfection field that may be manifest in a given shell structure. One might attempt to infer the imperfection field from observations, however practical methods for identifying the exact location and magnitude of the imperfection, from observed structural response data, are currently lacking. The problem is even more challenging if this identification is to be made *in situ*. Submerged shell structures (e.g. submarine pressure hulls), constitute a class of problem for which the methods discussed in this paper may prove useful.

The present work focuses on the *a posteriori* characterization of initial imperfection fields present in partially submerged shell structures. 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

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identification approach are (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 imperfections) on the observed data. The current research employs a sparse array of acoustic fluid pressure sensors (i.e. hydrophones) to help identify the imperfection field, simply by ''listening'' to the pressure waves induced by vibrations during the structure's service condition response. A model describing the fluid–structure interaction (FSI) and the influence of the imperfections on the model response is also developed, and is described in detail in Section (2.1). In an earlier work [24] this basic approach was used to generate *maximum likelihood estimates* (MLEs) of the imperfection location and magnitude. While MLE is a powerful approach to drawing 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 may arise from imperfections related to boundary conditions, material properties, and shell thickness [19–22]. The principal cause of this variation, however, is the presence of initial displacement fields, resulting in deviations from the assumed perfect shell geometry [27,28]. Initial imperfections may arise during manufacturing, fabrication, construction, or service conditions. The resulting differences between observed and theoretical ultimate strength make the developement of principled design specifications difficult.

A recent study [16] 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 geometric imperfections in barrel vault shell structures separating air from water. Furthermore, we wish to quantify uncertainty in the imperfection estimates. In a previous study, [24], a similar 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), a situation that violates the underlying assumptions of this approach. Our approach, described in Section (2.2) requires neither a single-peaked likelihood nor relies on asymptotic approximation.

Much of the research involving damage detection within the context of FSI and shell structures has focussed on structures that are filled (either completely or partially) with fluid, such as spherical storage tanks [4], composite fuel tanks [34], and cylindrical laminated composite shells [31,32]. The works by Curadelli and Ambrosini [4] and Zhou et al. [34] 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 [26]:

1. Level 1: Determination that damage is present in the structure,
2. Level 2: Determination of the geometric location of the damage,
3. Level 3: Quantification of the severity of the damage,
4. Level 4: Prediction of the remaining service life of the structure,

then [4,34] focus on level 1.

A more sophisticated approach to damage identification is provided by Yu et al. [31,32], which addresses the second level outlined above. In that work, a damage index is computed as the change (between the undamaged and damaged structure) in the energy spectrum of the decomposed wavelet signals of structural dynamic responses, and then used within the context of an *artificial neural network* (ANN) to identify the location and length of a crack in a laminated composite shell partially filled with fluid. While successfully able to locate the damage, this approach furnished a single solution to the inverse problem. Moreover, such ''data-driven'' approaches are only capable of identifying cases on which they have been trained i.e., previously unseen damage cases may or may not be classified. These types of approaches can be similarly confused by fluctuations in covariates (temperature, sensor noise, etc.) that were not present in the training data.

The works described above require some knowledge of the response of the undamaged fluid–structure model *a priori*, for the purpose of calculating damage feature indices. The current work, however, requires no knowledge of the actual undamaged structure's response (which is typically not known, and is impossible to observe once the structure has been damaged),