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Complementary numerical–experimental benchmarking for shape optimization and validation of structures subjected to wave and current forces

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ABSTRACT

A new benchmark problem is proposed and evaluated targeting fluid related shape optimization problems, motivated by design related ocean engineering tasks. The analyzed test geometry is a bottom mounted, polygonal structure in a channel flow. The aim of the study is to analyze the effect of shape variations of the structure on the resulting horizontal forces. Steady current conditions, dynamic loading due to waves, and combined wave–current scenarios are considered. A clear focus is put on simplicity and reproducibility, allowing for efficient testing of related methods and codes. This is achieved by defining a simple test geometry, altered in one design variable only, and by designing the test case such that a two dimensional analysis of the flow fields is possible. The force sensitivities to changes in the geometry are determined both numerically and experimentally for a great bandwidth of different load cases. The experiments are carried out in a recirculating wave–current flume while the numerical simulations are based on Computational Fluid Dynamics (CFD). Data is also provided to analyze the effect of wave–current interaction on structural loads. Furthermore, a reference study is carried out that focuses on differences in load curves resulting from 2D and 3D flows. It is shown that the major trends predicted by the numerical simulations are also captured in the experiment, highlighting the potential of CFD as a powerful tool for shape optimization studies. The overall aim of the paper is to provide clear and thorough information for validation and verification of methods and codes used to analyze fluid related shape optimization problems.

1. Introduction

The utilization of numerical methods to solve fluid dynamics problems continues to be a topic of high interest in research and development. Despite rigorous and ongoing efforts in the field, physically accurate and efficient modeling of fluid flows remains to be a challenging task. Nevertheless, many of the developed methods are gaining in importance beyond pure research efforts, as they are applied industrially in various fields of engineering. As a result of developments in computer technology, improvements in the numerical methods underlying commonly used fluid software, and simpler handling of commercial and open source programs, numerical methods are increasingly utilized to solve complex design problems. However, the readiness to produce results does not always reflect the complexity of the problems and the knowledge required to apply the models appropriately. Therefore, as new methods and software packages emerge, verification and validation is ever more important.

For the purpose of testing new and established methods, a great variety of benchmark studies have been proposed and analyzed. Numerical and experimental results for a number of fundamental flow problems were documented by Freitas [14]. These include the two dimensional flow over a backward-facing step and the three dimensional flow in a shear-driven cubical cavity. Concerning flows around a structure, the cylinder is arguably the best documented reference problem, including studies at various flow conditions, orientations and aspect ratios (e.g. [48,9,40,18,41,55,56,3]). For computational wind engineering applications, the Silsoe cube, a 6 m cube exposed to a physical wind field, has been studied vigorously both experimentally and numerically (e.g. [25,46,21]). For the purpose of code refinements and validation of aeroelastic problems, NASA carried out a program that established the NACA 0012 air foil benchmark, which has been the subject of various experimental investigations (e.g. [37,50])

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and numerical studies (e.g. [44,10]). Fluid Structure Interaction (FSI) codes are frequently verified based on the so-called "Turek benchmark", consisting of an elastic object in an incompressible flow [53,54]. For free surface methods, a dam-break flow [43], breaking wave impact [19] and sloshing in tanks [29] serve as popular validation problems.

The aforementioned studies serve as an example of the multitude of different benchmark tests that provide excellent information for validation and verification of different fluid related solution methods and modeling aspects. However, only few studies have been carried out that specifically target optimization problems, where the primary concern is to capture the differences between the individual optimization runs and to attain a precise optimal solution. Even fewer studies focus specifically on shape optimization in ocean engineering related topics, which typically involve not only steady current flows but also dynamic wave loading. Those studies concerned with ocean engineering related applications have mainly targeted the shape optimization of ship hulls (e.g. [45,5,51]). As part of these studies, the results of the numerical optimization runs were validated by carrying out a few selected experimental reference tests. Although the approach was very successful, the complexity of the analyzed problems renders these studies not ideally suited as general benchmark problems for the validation of codes and methods. This pertains particularly to the complex three dimensional hull geometries that require a significant discretization effort when utilizing mesh based numerical methods. Furthermore, the solution of the ensuing three dimensional flow problem involves substantial computational costs. Complex optimization problems often also suffer from being highly none-convex, which may be problematic when testing certain optimization approaches.

This paper addresses the need for a simple optimization benchmark problem that can efficiently be applied as part of fluid related validation and verification studies. A successful benchmark should exhibit certain characteristics in terms of the degree of complexity and the required resources necessary to solve the benchmark problem. While an oversimplification of the problem to guarantee easy reproducibility may result in a lack of useful results, overly complex benchmark problems become superfluous if a solution cannot be attained with reasonable effort, or if the likelihood of producing invalid results is too high [13]. Therefore, the benchmark problem should be complex enough to reflect the essential characteristics of the application at hand, while simultaneously allowing for a solution of the problem within a reasonable amount of time and effort. In this particular case, the essential physical phenomenon chosen to be modeled and verified is the horizontal load-sensitivity to shape variations of bottom mounted structures subjected to inertia and drag forces during wave and current loading. These forces are of utmost importance in the design process of reliable offshore structures. The essentially very complex problem definition is simplified through two main limitations in the definition of the benchmark problem: First of all, only one parameter is chosen for variation of the structure geometry, reducing the modeled objective function to a 1D problem in terms of design variables. Secondly, the problem is configured such that the overall domain can be modeled in a 2D environment in terms of space coordinates, which significantly reduces the computational effort required to solve the problem. Under both of these problem definitions, the physical characteristics of wave and current induced inertia and drag forces can be retained, therefore preserving the initial characteristics of the problem.

The benchmark problem definition of this paper is distinctive in that it allows for testing of highly complex flow conditions in a two-dimensional framework. Typically, 2D benchmarks are presented for relatively simple flow problems, such as the aforementioned flow over a backward-facing step or the modeling of the von Kármán vortex street about a cylinder. On the other hand, more complex flow fields are usually given in the literature in conjunction with complex 3D models, such as the mentioned ship hull investigations. By presenting experimental reference results of a complex wave–current flow that can be modeled numerically in a 2D environment, a highly efficient problem setup is created that is ideally suited as an optimization benchmark problem solved by analyzing multiple geometry variations.

The paper provides not only an experimental reference solution, but also analyzes the potential of Computational Fluid Dynamics (CFD) as a powerful tool as part of shape optimization studies of structures. Both the experimental and numerical setup are described in detail in order to allow for and encourage future comparative validation and verification studies. A detailed description of the measured and simulated boundary conditions is given, including turbulence data for the considered flow conditions. Following, results for peak horizontal loads on the geometries as well as selected load time series are presented and analyzed. Objective function approximations are compared, showing the capabilities of numerical methods to predict changes in loading as a result of shape variations. Furthermore, data is provided to validate wave–current interaction studies. Finally, the study is extended to a consideration of 3D flow scenarios, as a reference for computationally demanding 3D validation studies. Overall, the presented work gives a comprehensive description of a reproducible benchmark problem for shape optimization, embracing a brought spectrum of different flow conditions, motivated by structural design requirements in ocean engineering.

2. Benchmark geometry specification

The body to be analyzed in the benchmark study is a bottom mounted, fully submerged structure that is varied in one design variable only. A clear focus is put on simplicity and reproducibility, in order to minimize preparation required to carry out comparison studies. The benchmark geometry consists of a polygonal shape that is parametrized using the design variable ϕ, the leading and trailing inclination angle of the geometries, as shown in Fig. 1a. The point coordinates p_3 to p_6 are parameters defined as a function of the design variable ϕ, according to the formulas given in Table 1. Here, the parameter r corresponds to the inclination length from points p_1 to p_3 and p_2 to p_4. Coordinates p_1 and p_2 are constant and remain unaltered during all shape variations. The geometry is subject to a the following constraints:

- cross sectional area $A = 250\ \text{cm}^2$,
- base dimension $b = 5$ cm,
- structural height $h = 10$ cm,
- gap size $s = 0.5$ cm,
- inclination angle $0^\circ \leqslant \phi \leqslant 26.57^\circ$.

The gap size s has practical implications, as part of the experimental setup described in Section 3. The base section of height s below the body does not hold any significance concerning the loads exerted on the structure. Forces recorded in this study pertain solely to the geometry enclosed by points p_1 through p_6.

According to the introduced definitions and constraints, the leading and trailing edge height of the structure is equal to the structural height h for $\phi = 0^\circ$ and diminishes to zero for $\phi = 26.57^\circ$. This shape evolution is shown in Fig. 1b, including the intermediate configuration $\phi = 20.56^\circ$, for which the leading and trailing edge height is equal to $0.5h$.

The benchmark is specifically designed to allow for a validation based on 2D simulations. This is made possible by restraining the