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System identification of inverse, multimodal and nonlinear problems using evolutionary computing – Application to a pile structure supported on nonlinear springs

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ABSTRACT

This paper deals with the system identification of a mechanical structure supported by nonlinear springs subjected to an external load. If all mechanical parameters of the system were known, the displacement of the system subjected to this load could be easily calculated. However, the monitoring applications often deal with the inverse problem. The loads and displacements of the system are known and certain mechanical parameters of the system are sought. The solution of such inverse problems can be difficult, especially when they have a nonlinear and multimodal character, which often makes them appear intractable at first sight.

However, evolutionary computing can be applied to solve this inverse, nonlinear and multimodal problem. Sometimes a prior knowledge exists on certain system properties, which is difficult to implement into analytical or numerical solvers. This knowledge can play a decisive role in identifying the system properties and it can be easily included as a boundary condition when applying evolutionary algorithms. This article discusses how and under what conditions the unknown spring resistances can be identified. The practical application of this procedure is exemplified here with the mechanical system of a pile foundation.

1. Introduction

The multi-pod foundations with predominantly axially loaded piles (Fig. 1) are the most common type of foundation being used nowadays for the construction of offshore wind turbines in German waters. However, the current understanding assumes that these foundations may be at risk under the effects of the cyclic loading from wind and waves. This has prompted a line of investigations on the behavior of cyclic axially loaded piles and on the possibilities for their monitoring in the frame of two research projects [1] at the BAM (Federal Institute for Materials Research and Testing, in Berlin). It has been found that there is a pressing need in methods for the interpretation of monitoring data in order to assess the actual bearing capacity of a foundation.

The monitoring of constructions normally aims at measuring the actions and reactions of the system, which then permits the identification of certain properties or parameters of interest. This constitutes an *inverse problem* of system identification, such as the one being investigated here (see more details in Section 3). Furthermore, these foundations show a strong *nonlinear* character in the interaction between the pile and the soil, which should not be neglected.

However, the measurements are normally very costly (both in time and resources), particularly in the offshore environment. Therefore, it is often necessary to reduce the amount of instrumentation as much as possible. On the other hand, the amount of measurements should be enough to permit the identification of the unknown parameters of the system with confidence. If this is not the case, then the system will be indeterminate, which leads to the existence of different possible solutions for the system parameters of interest. Thus, the problem becomes multimodal.

Considering an axially loaded pile as depicted in Fig. 2 the most commonly measured variables are the force and the displacement at the pile-head. These are enough to measure the actual capacity if the pile is loaded until the failure criterion is reached, as for instance in a static load test (SLT). However, at first glance this does not provide any information on the distribution of the force along the shaft and at the pile tip. The axially loaded pile may be modeled numerically for instance by means of the Finite Element Method (FEM), as depicted in Fig. 2. The pile is here represented

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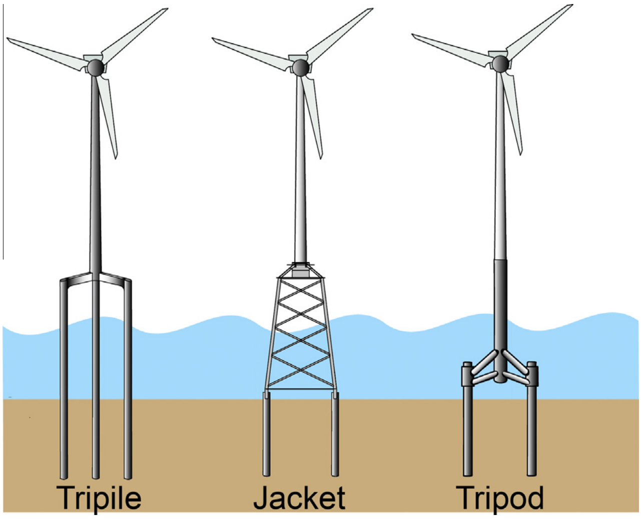

Fig. 1. Multi-pod foundation types for offshore wind turbines with predominantly axially loaded piles.

by a linearly elastic body and the soil–pile-interaction through the so-called *t*–*z* springs, which relate the friction resistance *t* at the pile–soil interface with the pile displacement *z* at each depth. Some technical standards [2] consider the pile for the design as a simplified rigid model (Fig. 2c). Elastic spring models (Fig. 2b) for the pile are increasingly used in case of more complicated issues as the influence of cyclic loading [3–5]. The difference between the diverse elastic models is the description of the soil–pile interaction (description of the spring) and the different constitutive law used for that.

The question to be discussed in this paper is whether the properties of the single springs can be univocally identified when the action *F* (axial load on the pile-head) and the system reaction *u* (axial displacement of the pile-head) are known. Furthermore, it is of special interest to know whether the solution for ultimate capacity can be found whenever only an incomplete load–displacement (Fig. 7) relationship is measured, as it is usually the case for a real structure in service.

In general, the measurements provide a relationship between the loads and the displacements on the pile-head but the amount of unknown variables is too large to permit the determination of a unique solution for the single springs. Therefore, engineers presume usually that the system identification is not possible. This paper investigates the causality between the characteristics of the discrete springs and the load–displacement behavior at the pile-head, whereby the solution of the system identification problem is performed by means of *evolutionary algorithms* [6–10]. Thus, the possibilities and limits of this methodology will also be discussed. Then, the following sections present its application to a specific case and discuss the results. Even if the methodology is demonstrated by a pile structure, it could be applied to every physical problem that uses a similar model as shown in Fig. 2b.

The main section of this paper concerns the topics mentioned below:

- The definition of the described example as an optimization and a system identification problem.
- The investigation of the system property that must be used consciously in order to meet the system identification with success.
- Interpretation of the multimodal result.

These issues represent actually the novelty of this paper, where an inverse multimodal engineering problem that cannot be solved directly, has been solved by using evolutionary computing combined with “a priori knowledge” and engineering judgement.

2. Evolutionary algorithms

Evolutionary algorithms (EA) (e.g. [11–13]) serve as an excellent option for solving optimization problems. They try to imitate the biological evolution by using the principal “*survival of the fittest*.” The main operators are mutation (eventually by recombination), heredity, and selection. By applying few slight random modifications in the input model, new exemplars can be created (mutation). Then by using one quality function (e.g. Eq. (2)), the fitness of each new exemplar can be calculated. The fittest one can be selected (selection) and is the new input for the next generation (heredity), for which we modified with small changes again. This process is repeated (Fig. 3) until the predefined stop criterion is achieved (e.g. maximum or minimum of the quality function). Different algorithms vary in terms of the number of new exemplars and performed changes or the number of the selected fittest exemplars. In

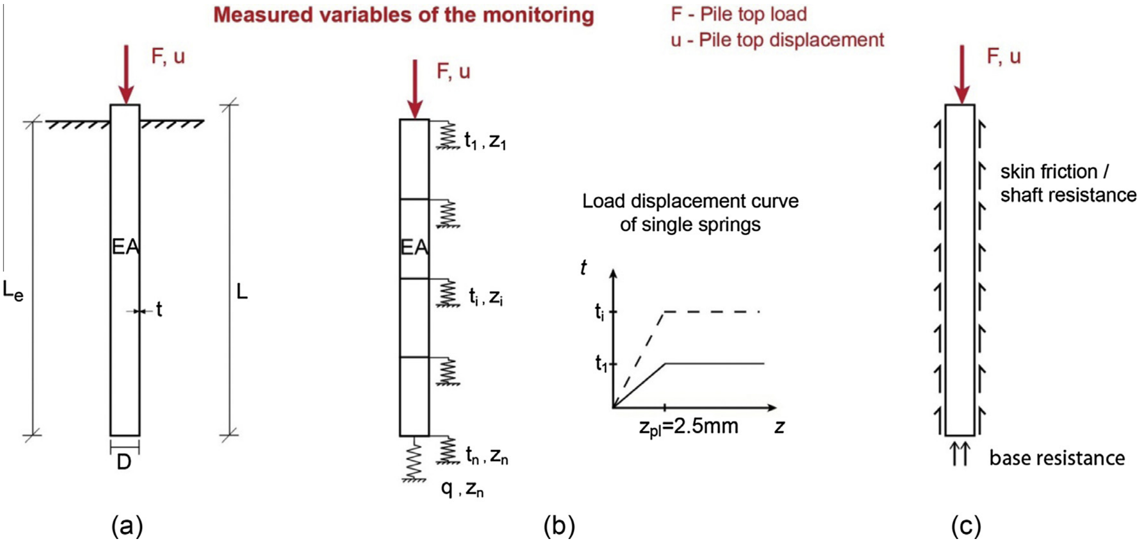

Fig. 2. (a) Load and displacement measurements at the pile–soil system. (b) Associated numerical model for the assessment of pile-head displacements (according to ISO 19902). (c) Simplified rigid model (according to [2]).