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Design implications towards inspection reduction of large scale structures

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Abstract

Operational management is a key contributor in life cycle costs, especially for large scale assets which are in most times complex in structural hierarchy and with a large nominal service life. Decisions on the operational management may concern the number of inspections or maintenance strategies which may allow full utilization of structural capacity or sacrifice residual life in order to avoid an unscheduled intervention. Design of such assets is often governed by design standards which offer the designer the flexibility to take certain decisions that may affect the CAPEX to OPEX ratio such as that of building a more robust structure which may eliminate the need for costly inspection operations. This paper is investigating this approach, taking the example of offshore wind turbine support structures as the reference case, and examines the relevant provisions of the DNV-Os-J101 Standard with respect to the design implications that such a decision may have to the overall life-cycle cost of the structure. Assessment of the structural properties under different design conditions is evaluated through a combination of detailed cost model and an iterative optimization algorithm. The approach which is followed and documented, can be applicable to other complex structural systems for decision making through evaluation of service life costs.

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Keywords: offshore wind energy, monopile, design optimisation, material safety factors, inspection and maintenance, cost model, genetic algorithm

1. Introduction

Complexity of structural systems, introduce a variety of factors that a designer should take into account during the design stage of the project which could in any way affect subsequent stages of the service life of an asset. Energy assets are in most cases characterized by increased complexity and hence decisions over their design and operation becomes even more demanding. Offshore wind energy structures is a representative example of this phenomenon, varying significantly from similar applications, such as those of the offshore oil and gas industry, in the sense that they are deployed in arrays of several units (this number can reach or exceed 100) hence the requirements in mass production, should be designed to accept higher risks due to their unmanned operation in normal conditions and the fact that they refer to a marginal business were profits are limited and highly uncertain. In particular, as of July 2016, 3,344 units were installed and grid connected across Europe, at an average distance to shore of 42 km and 25 meters of deployment depth, accounting of 11.5 GW of total capacity [1] with ambitious targets for the foreseeable future (18 GW to be deployed by 2020) [2].

In this paper we consider the example of the frequency of inspection and maintenance of offshore wind support structures, usually determined by Industrial Standards such as the DNV-RP-J101 [3], recommending fixed intervals between consecutive inspections and outlining the design structural requirements of the wind farm turbines. Since certification is essential for an offshore wind farm to be eligible for insurance, it is of paramount importance for the wind turbines to acquire the certification needed through compliance to the underpinning standards. Although standards are in general very prescriptive, they often allow designer the flexibility to change the length of the inspection intervals by modifying the design of the substructure. As such, the designer can overdesign the support structure through higher material factors in order to expand the inspection intervals yielding significant inspection and potential maintenance cost gains. As a consequence, increasing the material factor of the structure is expected to

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have an effect on the material volume of steel and therefore on the construction cost of the support structure.

This paper investigates the effect of material safety factors on fatigue design of offshore wind turbine monopiles and quantifies the cost implications associated with each case. Results of this work highlight the fact that design elements of offshore wind farms should be based on strategic decisions affecting the levels of CAPEX and OPEX over the lifecycle of an offshore wind farm.

Nomenclature

CAPEX	Capital expenditures
CVI	Close visual inspection
GVI	General visual inspection
OPEX	Operating expenditures
ROV	Remotely Operated Vehicle

2. Inspection of offshore wind turbines

According to DNV-OS-J101 (Chapter 13) [3] periodical inspections should be performed during the design life of the offshore wind farm in the following components:

- wind turbines,
- structural system above water,
- structural system below water,
- submerged power cables.

The present paper focuses on the inspection of the structural system below water. Costs of subsea structural surveys represent around 1% of the total maintenance costs according to a report compiled by Garrad & Hassan [4]. Nevertheless, the high level of expenditure devoted for such investments render their limitation a rather important business.

Typical offshore subsea survey components for the inspection of the structure for the periodical inspections consist of the general visual inspection (GVI) and the close visual inspection (CVI) usually carried out through a Remotely Operated Vehicle (ROV).

One of the main issues of calendar-based maintenance of the subsea structural components is the determination of the interval between consecutive inspections. According to [3] inspection for fatigue cracks should take place at least every five years. However, the frequency of inspections may be waived according to the design philosophy that has been used for the structural components in question. As such, when the fatigue design of the component has been performed by using safety factors corresponding to a condition of no access for inspection operations, the inspections on the specific part could be eliminated. When, however, material factors are smaller, more regular inspections need to be performed. The Guidance note of the DNV-Os-J101 Standard with regards to inspections for fatigue cracks (section 13.3.7.2) recommends that the interval between consecutive inspections can be expressed in relation to the material safety factor γ_m as:

$$\text{Inspection interval} = \text{Calculated fatigue life} \cdot \gamma_m{}^5/1.25^5 \quad (1)$$

Therefore,

- when γ_m=1.25, inspections for fatigue cracks can be fully eliminated,
- when γ_m=1.15, inspections for fatigue cracks are needed every 13 years,
- when γ_m=1.0, inspections for fatigue cracks are needed every 7 years.

It becomes, thus, evident that overdesigning a monopile substructure could potentially reduce calendar-based maintenance costs. However, increasing the material factor would result in a higher volume of the steel quantity used for the construction of the substructure with a subsequent increase in the manufacturing and transportation costs.

3. Development of lifecycle cost model

In order to estimate the effect of the different design configurations on the cost of energy, a lifecycle cost model was developed.

Existing literature on the lifecycle costs of an offshore wind farm indicates that the cost drivers fall into the 5 main phases of the offshore wind farm's life (as in [5-7]), characterized by different operating conditions and cost structures:

1. Development and consenting (D&C)
2. Production and acquisition (P&A)
3. Installation and commissioning (I&C)
4. Operation and maintenance (O&M)
5. Decommissioning and disposal (D&D)

Above cost categories are further broken down into their constituent elements, and accordingly a database is built with the related cost elements.

The cost of energy can be calculated by the following equation:

$$\mathrm{LCOE} = \frac{\text{Sum of lifetime discounted generation costs (£)}}{\text{Sum of discounted lifetime energy output (MWh)}} =$$

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{\mathrm{CAPEX_t + OPEX_t + D}}{(1+\mathrm{WACC})^t}}{\sum_{t=1}^{n} \frac{\mathrm{NET_t}}{(1+\mathrm{WACC})^t}} \quad (2)$$

Where $\mathrm{CAPEX_t}$ is the capital costs in the year t, $\mathrm{OPEX_t}$: operations and maintenance costs, D: decommissioning costs, $\mathrm{NET_t}$: net electricity production in the year t, WACC: weighted average cost of capital.

It is noted that the calculation of total lifetime expenses is based on discounting annual financial flows, taking into consideration the time value of money.

The cost model aims at capturing the impact of applying a different design philosophy by using varying safety factors to the structure on the CAPEX and OPEX. Therefore, the cost components that are explicitly impacted by the design of the monopile are: (a) the cost of monopile steel mass, fabrication, transportation and installation, and (b) the subsurface inspection costs for fatigue cracks. To this end, these are the elements, which are further investigated within the context of this paper.

The following assumptions were applied for setting up the model with regards to the above parameters:

(a) The cost of the monopile (CM_t) during the production and