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The effect of gravity on the dynamic characteristics and fatigue life assessment of offshore structures

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ABSTRACT

This paper intends to draw attention to the influence of gravity on the dynamic response and fatigue damage assessment of offshore structures. In traditional fatigue life calculation, the gravity loads of structures are assumed to only contribute to the mean stress of the structures. This paper examines the significance of P-Delta (P-Δ) effects and the stress “stiffening/softening” induced by gravity. This paper first explains the two aforesaid gravity-induced effects, with studies on their influence on both eigenperiod and fatigue life assessment. A modal analysis of a typical offshore structure with large degrees of freedom is followed, to identify the dynamic characteristics influenced by the gravity effects. It is discovered that gravity load can induce a tendency to cause additional compressive and tensile forces to coexist in various structural components, causing the eigenperiods to increase, decrease or even cross each other. Compared to the stress “stiffening/softening” effects, the P-Delta effects on tuning the structure's stiffness and eigenperiods are insignificant in mild sea states. Furthermore, based on the nonlinear dynamic response calculation and a type of efficient wave energy inputs, a procedure for calculating fatigue damage is adopted and a systematic investigation of fatigue calculation of the structure is performed. It is discovered that ignorance of the gravity loads can underestimate the fatigue damage by up to 24%. Finally, through a series of investigations, it is discovered that gravity can have significant effects on both the response statistics and frequency content of the structural responses.

1. Introduction

As modern engineering structures become lighter and more slender than ever, and are also subjected to more adverse dynamic loading as a challenge, this has caused an increase in vibration amplitude, moved the vibration frequencies of structures into bands that are more awkward to deal with, and reduced the elastic critical load of structures. Therefore, identifying dynamic characteristics and fatigue assessment have become increasingly important, and almost routine for maintaining the structures' integrity. Linearisation involved in structural analysis can lose important information concerning structural responses, and therefore increase uncertainty in the integrity assessment. Consequently, nonlinearities should be taken into account. In a broad definition, the nonlinearities in structural analysis are reflected in the loading (e.g. fluid–structure interaction), geometric (e.g. large deformation and membrane and so on), material (e.g. nonlinear plasticity) and boundary (contact) aspects.

For offshore structures, since frequency domain analysis can hardly account for the non-linear load effects induced from drag forces in Morison's equation [1–6], the variation of water surface causing the intermittency of wave loading, the variation of buoyancy forces on components in the splash zone [7–10], or large structural deformations, and also because the power spectrum of the critical stress due to the dynamic wave loading may not be narrow banded, time history analysis is a preferred method of reducing the aforesaid uncertainties. This is also used in the current paper to calculate the stress response for fatigue assessment.

In traditional linear spectrum fatigue calculation in frequency domain, the gravity loads of structures only contribute to the mean stress of the structures. This of course influences the ultimate limit state evaluations of offshore structures. However, due to the large deformation of the offshore structures subjected to waves, and the centres of gravity for structures also changing over time, the gravity loads of topside and its supporting structure exert additional actions on the structure. These additional actions vary with the variation of the structure's deflection, i.e. they also vary over time. The additional actions in turn change the stiffness of the structure; this is a type of P-Delta (P-Δ) effect [11]. P-Delta effects can play an important role in increasing the effective load on a structural bay. Ruge [12] first exams the P-Delta effects to estimate the change of deflection of a vertical cantilever beam supporting a weight. Jennings and Husid [13] first study the gravity effects on inelastic structural responses, in which they emphasise the significant contribution of the effect of gravity. Montgomery [14] states that the influence of P-

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Delta effects are important if the ratio of base shear to frame weight is less than 0.1, or if displacement ductility demands are above 2.0. In seismic analysis, Gupta and Krawinkler [15] study 1 (2000), pp. 145–154. the seismic response of multiple degrees of freedom systems to earthquake excitation. They state that P-Delta effects can exert significant influence on dynamic response, particularly for multi-storey moment–resistant frames that can develop large inter-storey drifts. However, P-Delta effects are normally ignored by offshore engineers in their daily engineering practice. The main reason for this is that previous research focuses on P-Delta effects with regard to the ultimate limit state assessment, which indicates that the effects are relatively small, especially for offshore structures in shallow to medium depths [16]. Another important reason is that the nonlinearities due to the structure's large deformation cannot be properly handled in conventional linear spectrum analysis, and engineers normally take it for granted that the additional actions due to gravity loads are too small to be taken into account. Unlike evaluations of ultimate limit state, fatigue damage is proportional to stress amplitude, with power typically in the range from 3.0 to 5.0; a slight variation in stress amplitude may induce significant change to the fatigue damage calculations, and the nonlinear structural deflections due to gravity loads may then be a significant contributor to influencing fatigue damage. In addition, the stress "stiffening/softening" effects due to the gravity loads also slightly change the structure's natural frequencies, which can influence the fatigue damage of the structures as well. Particularly for structures under compressive forces globally, the natural frequency normally decreases, and this can cause problems regarding vibration and fatigue. The earliest publication to address the stress "stiffening/softening" under axial load was written by Galef [17], who set outs a practical formula for calculating the natural frequency under compressive load. Based on Galef's work, Bokaian [18] investigates the applicability of Galef's formula under a set of support conditions and also extends his study to tension loads [19]. Using Galef's formula, Shaker [20] first investigates relevant practical problems in aerospace structures: a vibrating beam with arbitrary boundary conditions, a cantilever beam with tip mass under constant axial loads and a cantilever beam with tip mass under axial loads applied on the tip directed to the root. In addition, he also extends his analysis to tension loads. Virgin [21], Virgin, Santillan, and Holland [22] and Virgin and Plaut [23] also perform a series of research to investigate the dynamic behaviour of axially-loaded structures. By neglecting the large deformation of vertical cantilevers, Virgin and his co-workers [22] calculate their eigenfrequencies and validate the calculation through a number of modal testings. They experimentally proved that a beam with an "upward" orientation will experience de-stiffening effects and a beam in a "downward" orientation will be stiffened by the weight of the beam through the development of tension stress in the beam. By including the effects of large displacement equilibrium paths through a nonlinear moment-curvature relationship, Virgin and Plaut [23] further present a formulation to obtain the eigenpairs of vertical cantilevers. From a mathematical perspective, buckling and vibration are both eigen-oriented: buckling occurs when compressive stresses are large enough to lead to a zero resultant stiffness condition, i.e. the natural frequency of the structure reaches zero [24]. By performing a nonlinear time domain dynamic analysis, and calculating the fatigue damage, Jia [25] investigated the dynamic responses and the resulted fatigue damage of a typical flare boom subject to dynamic wind loading, from the calculation it is found out that gravity load generally gives more deviation of the kurtosis from a value of three, i.e. the gravity load increases the non-Gaussian trend of the response. In general, for the welded joints under study, the calculated fatigue lives by accounting for the gravity effects are significantly less than the ones without considering the gravity effects [26]. Several pieces of research [27–29] discuss the use of measured vibration frequencies obtained from non-destructive modal testing to determine approximate buckling loads. They all conclude that changes in the measured vibration frequencies during increased loading can be used to predict the buckling of a structure. With the aim of developing robust low-dimensional models, Mazzilli and his coworkers [30] use the nonlinear normal mode method to develop a rigorous derivation of non-linear equations that govern the dynamics of an axially-loaded beam; they also apply the equations for a study of dynamic characteristics of offshore risers.

However, research into fatigue damage assessment influenced by gravity effects is limited. Through the calculation of wind buffeting-induced fatigue for a high-rise flare boom structure, Jia [31] states that influence due to gravity loads is significant on certain parts of the flare boom. To address the situation of limited research work in this area, this paper first explains the two aforesaid gravity effects. Furthermore, the dynamic characteristics and gravity effects of a realistic offshore structure are studied. By using different numbers of discrete frequencies, as well as formulating the frequency spacing with uneven distances as a type of efficient wave energy input, and by calculating the nonlinear structural dynamic response in time domain, a procedure presented by Jia [32] and Jia, Ellefsen and Holmås [33] for calculating the fatigue damage of offshore structures is adopted to carry out investigations into gravity effects. Furthermore, their influences are also studied through a series of statistical and frequency checks of the structure's response.

2. P-Delta and stress "stiffening/softening" effects

Traditionally, the self-weight of a structure is considered to only cause a constant load (induces mean stresses) on the structure, which has almost nothing to do with the fatigue calculation of welded joints (not influenced by the mean stress due to the presence of residual stress). However, in reality two types of effect induced by self-weight are relevant: the P-Delta (P-Δ) effects and stress "stiffening/softening".

The P-Delta effects are due to the variation of a structure's lateral deformation in the horizontal plane, which changes the resultant action point of the structure's self-weight, and consequently induces additional actions on the structure and changes its stiffness. The change of stiffness further changes the force distribution on the structure. These effects are obviously nonlinear and can start a pernicious circle against the structural system because the influence of gravity loads increases as the lateral displacement grows, while at the same time the lateral displacement is magnified as a consequence of gravity loads acting on them [34]. For many moment-resistant frame structures, the P-Delta effects associated with component deformation are insignificant compared to the P-Delta effects on the displacements at the ends of the components [35]. In addition, the stiffness changes due to the P-Delta effects also alter the eigenfrequencies of the structure. However, this type of effect cannot be handled in conventional linear spectrum fatigue analysis. In this study, by adopting the implicit algorithm HHT-α method for the time integration in nonlinear dynamic analysis, both the stiffness and load matrix are updated at each time step — the large deformation-induced geometric nonlinearities can then be taken into account.

The stress "stiffening/softening" derives from the fact that the self-weight may introduce significant component force globally. For offshore structures, this typically causes compressive force, which alone does not contribute to the calculated fatigue damage for welded joints. Meanwhile, since it decreases the global stiffness of the structure, the eigenfrequency is therefore decreased (stress "softening" or geometric "softening"), thus influencing the dynamic responses of structures, consequently affecting the fatigue damage accumulation as well.

Eqs. (1) and (2) show the formulation of linearised buckling and vibration-generalised eigenproblem respectively.

$$(-K_N)\varphi = \lambda_b K_S \varphi \quad (1)$$

$$K\Psi = \lambda M \Psi \quad (2)$$

Where K is the linear stiffness matrix, K_N is the nonlinear strain (geometric or initial stress) stiffness matrix, K_S is the linear strain stiffness