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# Control of vortex-induced motion in multi-column offshore platform by near-wake jets

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ABSTRACT

Vortex-induced motion (VIM) poses a serious challenge in many engineering applications such as offshore structures, floating wind turbines, and high rise buildings. In particular, significant aspects of VIM have to be considered in offshore platforms subjected to high currents. The objective of this numerical study is to investigate the VIM suppression of multi-column floating platforms by injecting steady near-wake jets at the wake side of the columns. Before proceeding to the blowing-jet based flow control method, the transverse VIM amplitude of floating platform is validated with the model test data. We perform a systematic investigation of 3D scaled model with and without prescribed jet flows for varying reduced velocity ($U_r$) at a fixed mass ratio $m^*$=0.83, the damping ratio $\zeta$=0.01 and the Reynolds number $Re$=20,000. The numerical investigations are carried out for different near-wake jet configurations at reduced velocity $U_r$=10. We assess the response characteristics and flow profile patterns to identify a suitable configuration of blowing jet along the columns. We demonstrate that the semi-submersible with elongated near-wake jet configuration is efficient in suppressing VIM in comparison to other near-wake jet configurations and the uncontrolled no-jet case. The vibration amplitudes, the force coefficients and the flow patterns of semi-submersible with the blowing-based control technique are further examined for various mass flow rate coefficients. From our studies, we observe approximately 30% reduction of forces and the amplitudes for the offshore system with the prescribed jet flow compared to the system without near-wake jets. The optimal $V_{\mathrm{jet}}/U$ is estimated to be in the range of 2.5–5, for the effective VIM suppression, where $V_{\mathrm{jet}}$ and $U$ are the prescribed jet flow speed and the free-stream speed, respectively. To understand the underpinning of VIM suppression mechanism, the vortex dynamics and flow patterns in the near-wake region of a freely vibrating semi-submersible platform with the near-wake jet are explored. For this numerical study, we employ a stabilized finite element formulation with an explicit dynamic subgrid-scale model to simulate the fluid-structure interaction subjected to a turbulent wake flow.

## 1. Introduction

The floating offshore structures such as semi-submersibles are generally used in deepwater and ultra-deepwater regions for oil/gas production and exploration, floating wind turbines and ocean space utilization. The semi-submersible platform is a self-stabilized structure with improved motion characteristics and good resistance to the wind, wave and current in any directions [1] and comprises of submerged pontoon and four vertical columns, with square geometry cross-section. The vertical columns connect the submerged pontoon and the deck structure. The semi-submersible platforms have a relatively lesser sensitivity to the environmental loads due to winds, waves and currents, when compared to ship-shaped FPSOs (Floating Production, Storage, and Offloading). This stable characteristic of semi-submersible is beneficial for deep-water operations and hence it is widely deployed. Due to the existence of strong ocean currents, the structure undergoes flow-induced motions causing large transverse oscillations termed as vortex-induced motion (VIM). The phenomenon of VIM is similar to vortex-induced vibration (VIV) with regard to the underlying principle, which arises when the vortex shedding frequency matches the natural frequency of the structure. The VIM occurs for large floating bodies with large natural periods. Hence, the vortex-induced oscillation of floating structures is commonly referred to as VIM.

The semi-submersibles deployed in harsh sea conditions experience large unsteady loads and six degree-of-freedoms (6-DOF)

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motions due to complex nonlinear interaction with ocean currents and waves. In the recent years, investigations of VIM for semi-submersibles have gained importance due to the presence of strong currents in ultra-deepwater environments. In the VIM measurements of semi-submersible model by Waals et al. [2], the maximum transverse amplitude was measured to be 0.48$D$ and 0.41$D$ for 0° and 45° angle of incidence at $U_r$=11 and 7, respectively at $Re = 6 \times 10^3$ to $7 \times 10^4$. Here, $D$ denotes the characteristic column diameter, $Re = UD/\nu$ is based on this diameter, $U$ is the oncoming velocity and $\nu$ denotes the kinematic viscosity. The existence of lock-in and post-lock-in responses was exhibited from the field measurements of prototype [3]. The lock-in and post lock-in responses are defined as VIM and galloping regimes. Galloping is a self-excited instability which exhibits high-amplitude and low-frequency oscillation that typically occur in elastic structures with non-circular cross-sections [4]. Comprehensive studies of [5,6] have led to the development of a new generation semi-submersibles, followed by the measurements of Goncalves et al. [7], which provided insights into the flow dynamics of semi-submersibles. The flow profile on the wake side of the semi-submersible is more complex and wider when compared to circular cylinder [7]. This complexity of the flow profile is associated with the consequences of wake interaction of vortices shed from multiple columns.

Owing to the intrinsic presence of vertical columns for semi-submersibles in the fluid flow, complex wake flow patterns are generated. The flow interference and shielding effects of tandem and side-by-side square cylinder alter the wake patterns and hydrodynamic loads. Different types of regimes exist for tandem square cylinders depending upon the spacing ($L/D$) between them. The wake interference comes into the existence for two square cylinders in the tandem configuration for spacing ratio L/D=3 to 4 and becomes insignificant at $L/D = 27$ [8]. As most of the offshore structures are designed for $L/D \approx 2$ to 3, a clear understanding of the wake interference regime is necessary. The geometry of the semi-submersibles is generally square-shaped and therefore it is susceptible to VIM and galloping motions [9] and is essential to control VIM of floating platforms. It is well known that the frequency of vortex shedding is associated with switching of confluence point (saddle point) from one side to another side, with respect to the wake centerline of the square cylinder and only the analogy is represented for the floating platform. The saddle point is defined as the point where the two entrainment layers coming from opposite sides of the square cylinder meet and indicate the end of vortex formation region [10]. Zdravkovich [11] stated that, by disturbing the shear layers or preventing the switching of confluence points, the VIM could be completely attenuated.

Many flow control methods have been proposed in the last few decades to suppress VIM of bluff bodies. The flow control techniques are broadly classified into active and passive techniques. Each of these techniques is further classified and its details are presented in [12]. The key difference between active and passive techniques is that the former require auxiliary power to operate and the latter does not consume power. The manifestation of passive flow control techniques are appendages and auxiliary geometries over the bluff body. The prominent passive flow control techniques that are used in present scenarios are fairings, helical strakes, splitter plate, control rods, slits parallel to flow and surface protrusions [11]. Implementation of strakes to mitigate VIM for floating structures such as truss spars were already reported by researchers such as [13–16]. The effectiveness of splitter plate and its role in reducing vortex-induced forces were investigated by [17–19] for bluff bodies. Implementation of surface protrusions, small control rods, parallel slits over the cylinder surface and its influence over VIM and drag reduction were examined by [20–22]. Although the passive flow control techniques are most sought after due to its zero power input, the active flow control techniques are sometimes necessary for suppressing the VIM and the vortex-induced forces. The active flow control techniques such as blowing or suction from the wall surface, injection of micro-bubbles or particles, acoustic excitation, periodic rotation, wall motion are some of the examples.

Investigations related to the active flow control techniques, which includes rotating cylinders at the wake side [23] or at the shear layer side of the bluff body [24] were all carried out using finite element method with Petrov–Galerkin technique [25–27]. A number of studies, related to the injection of steady fluid for attenuating vortex-induced loads and VIM of circular cylinders has been reported earlier. Only a handful of investigators has focused on blowing technique for square-shaped columns. Measurements conducted by [28], for the porous cylinder at $Re$=8 × $10^3$ and 8 × $10^4$, observed that suction and blowing of fluid at the base side of the body influences the separation point. Through numerical computations, Dong et al. [29] demonstrated the elimination of the vortex streets of circular cylinders at $Re$=100 and 500 via a combined suction and blowing strategy. Intermittent breakage of vortices along the span-wise length of the cylinder was noticed in their studies. Suppression of VIM by acoustic means, conducted by [30], observed 30% reduction of drag forces at $Re$=9000. Significant changes in the wake velocity profile were visualized with the increase in the acoustic strength. Numerical investigations conducted by [31], for a circular cylinder with synthetic jets at the mean separation point, observed a remarkable attenuation of the transverse lift force. The injection provides additional momentum to the fluid surrounding the body, causing a net pressure increment on top and bottom surfaces of the body and lowering pressure on the front and rear side of the body [32]. Furthermore, from the numerical studies of [33], it was examined that the blowing jet increases the base pressure influencing the vortex shedding process and the drag force. The prominent effects of a splitter plate are to reduce the strength of the vortex formation region and to delay the interaction of free shear layers until the end of the plate [34]. As an analogy to a splitter plate, we will consider near-wake streamwise jets at the base side of the columns of semi-submersible since both the splitter plate and the streamwise jet tend to stabilize the near-wake region by delaying the interaction of shear layers [35].

The experimental investigations conducted by [32] for a square cylinder is the prominent work for $Re$ in the order of $10^4$. From their investigations, they observed that the pressure and drag forces around the square cylinder change significantly as the positions of the jet flow changes. The pressure deficit at the base side of the cylinder tends to get filled up with the injection of fluid [32]. The near-wake jet at the center position of the square cylinder prevents the shear layer interaction. Interaction of separated layers is also delayed due to the presence of near-wake jet at the center position of the square cylinder. Saha and Shrivastava [36]. have made these observations in their numerical investigations for a square cylinder with the near-wake jet at the center position of the body at $Re$=100. They also concluded that the near-wake jet mimics like a splitter plate, higher the jet flow velocity lesser the undulations of shear layers. The visualization flow experiments and pressure measurements of [37] have advocated the fact that injection of fluid in the near-wake region results in the pressure recovery at the base side of the body. Therefore, based on earlier investigations available in the literature it is evident that active flow control methods are efficient and applicable for the cases where passive flow control methods are not feasible.

Recent works on the implementation of active damping system in semi-submersible have achieved 75% of VIM reduction with 25% of critical damping coefficient [38]. Among various flow control techniques, the most prominent active flow control techniques are positioning of actuators in the sensitive regions, where the shear