Ocean Systems Engineering, *Vol. 12, No. 3 (2022) 301-333*
https://doi.org/10.12989/ose.2022.12.3.301

Vortex induced vibrations and motions - Review, issues and challenges

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(Received August 12, 2022, Revised September 2, 2021, Accepted September 8, 2022)

Abstract. Herein, we report meaningful and selective review of the progress made on 'Vortex Induced Vibration (VIV)' and 'Vortex Induced Motion (VIM)' of 'Structures of Specific Shapes (SoSS)' subjected to steady uniform flow and of relevance to/in marine structures. Important and critical elements of the numerical methods, experimental methods, and physical ideas are listed and analysed critically and the limitations of the current state of art of VIV/VIM are discussed in-detail. Our focus and aim are to analyse the existing researches with respect to the application in analyses, design and production of marine structures and the reported reviews centre on these only. We identify the critical and important issues that exist in the current literature and utilise these issues to highlight the challenges that need to be tackled to design and develop new age marine structures that can exist and operate safely in the areas of dominance by the VIV/VIM. Finally, we also identify some areas for future scope of research on VIV/VIM.

Keywords: catenary riser; computer simulation model; current velocity; moored structure; semi-submersible; steel catenary riser; towing velocity; vortex induced motion; vortex induced vibration

1. Introduction

In the world of engineering fluid mechanics, the 'Vortex Induced Vibration (VIV)' is the motion that is induced on structures of specific shapes interacting with an external fluid flow and it is either produced by or is the motion producing, periodic irregularities on this flow. Examples of 'Specific Shapes (SS)' include cylinder, ellipse, and square/rectangle with sharp/rounded corners and the VIV shows heavy dependency upon the curvature, i.e., a sharp change in the curvature causes the separation of boundary layer and that is primarily responsible for the VIV. Table 1 lists 'Structures of Specific Shapes' and their application ranges.

A real fluid always has some viscosity and this effect of viscosity causes the flow around any 'Structure of Specific Shapes (SoSS)' to slow down while in contact with the surface of structure thus forming the boundary layer. Depending upon the change in the curvature, this boundary layer

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http://www.techno-press.org/?journal=ose&subpage=7 ISSN: 2093-6702 (Print), 2093-677X (Online)

gets separated from the structure and a vortex is formed.

This formation of vortex changes the pressure distribution along the surface and when the vortex does not form symmetrically around the structure's mid plane, different lift forces develop on each side of the body. Differential lift forces lead to a motion transverse to the flow and this transverse motion changes the basic nature of the vortex formation. Change in the vortex motion implies changes in the momentum and leads to a limited motion amplitude. Although the motion amplitudes are low and limited, these are highly repetitive and keep on repeating unless and until the flow rate changes substantially. A SoSS is highly common across many branches of engineering and because of this the VIV can occur in cables, heat exchanger tube arrays, marine structures, bridges, stacks, transmission lines, aircraft control surfaces, thermos wells, engines, heat exchangers, drilling and production risers in petroleum production, mooring cables, moored structures, tethered structures, buoyancy and spar hulls, pipelines, members of jacketed structures, and other hydrodynamic and hydro acoustic structures, etc.

Wider occurrence of the VIV indicates that it is important in many disciplines and its study incorporates fluid mechanics, structural mechanics, vibrations, 'Computational Fluid Dynamics (CFD)', acoustics, statistics, smart materials, etc. As the oil and gas exploration and production are moving towards deeper and deeper water depths because of the depleting reservoirs at the on-shore/low water depth offshore locations, the importance of VIV studies is becoming more and more critical to ensure the design and development of safe and economic marine risers and platform, e.g., a case of high industrial significance is long SoSS in water depths of more than 3000 m.

As has been noted before, the VIV results in to highly repetitive and periodic low and limited motion amplitudes, and these cyclic motions are the critical source of fatigue damage in marine structures, i.e., oil exploration/drilling/production risers, export pipe lines, Steel Catenary Risers (SCRs), and tendons or tethers, etc., for more details see Pallan and Sharma (2022). A long and slender SoSS experiences both the current flow and top-end platform motions, and these motions result in the flow-structure relative motions and cause VIVs. Flow around a SoSS is on the fundamental open flow problems and at low Reynolds numbers, the streamlines of the resulting flow are symmetric because of the dominance of potential flow, and later when the Reynolds number is increased the flow gets more and more asymmetric. This asymmetricity results in to Kármán Vortex Street and the vortex shedding give rise to the motion. Some studies have explored the possibility of utilizing this motion to generate power, albeit on a very low and impractical scale, for more details Soti *et al.* (2017). A basic understanding of the VIV exists and it is based upon the Strouhal number ($St = \frac{f_{st} D}{U}$ where f_{st} is the vortex/Strouhal shedding frequency of the SoSS at rest, D is the characteristic dimension of the SoSS and U is the velocity of the flow under which the SoSS has been placed. Normally, the Strouhal number for a SoSS is taken around 0.2 covering a wide range of flow velocities and the 'lock-in' happens when the vortex shedding frequency becomes close to the natural fundamental frequency of vibration of the structure. If it happens then large and damaging vibrations will result and these produce catastrophic damage to the structure.

Although, the basic understanding of VIV exists and the problem has invited wide range of attention from both the industry and academia, the translation of results into application does not exist, i.e. how to apply the results for better designs of SoSS and the structure in which they are parts, is surprisingly remains largely unexplored. Additionally, both the numerical and experimental investigations toward better understanding of the kinematics/dynamics of VIV have centered on the low-Reynolds number regime. This is because limitations exist on both the computational powers in numerical investigations and flow/towing velocities in experimental investigations. Also, the VIV

Table 1 List of Structures of Specific Shapes and their application ranges

S. No.	Structures of Specific Shapes	Length, diameter and slenderness	Range of the industrial applications
1	Cylinder	A - Long length, low diameter, highly slender	A - Marine drilling and production riser, stacks, transmission lines, thermos wells, marine cables, towed cables, mooring cables, moored structures, tethered structures, buoyancy modules, pipelines, cable-laying, and members of jacketed structures, etc.
		B - Short length, medium to high diameter, lowly slender	B - Bridges, columns and pontoons in marine structures (e.g. semi-submersible), aircraft control surfaces, engines, heat exchangers, and other hydrodynamic and hydro-acoustic applications.
2	Square with rounded/sharp corners	Short length, medium to high diameter, lowly slender	Columns and pontoons in marine structures (e.g., semi-submersible), aircraft control surfaces, engines, heat exchangers, and other hydrodynamic and hydro-acoustic applications.
3	Rectangle with rounded/sharp corners	Short length, medium to high diameter, lowly slender	Pontoons in marine structures (e.g., semi-submersible), heat exchangers, and other hydrodynamic and hydro-acoustic applications.
4	Ellipse	Short length, medium to high diameter, lowly slender	Columns in marine structures (e.g., semi-submersible), and in tube bundle configurations (i.e., heat exchangers, boilers, condensers, and nuclear fuel rods, etc.).

is not a small perturbation superimposed on a mean steady motion and it is an inherently nonlinear, self-governed/regulated, large, and multi degrees-of-freedom phenomenon. To further complicate the issue, it implies unsteady flow characteristics that are resulted because of the existence of two unsteady shear layers and interactions of lone and slender structures with large-scale structures.

From the industrial design application point of view, we need to know about: What is the dominant response frequency, the range of normalized velocities, the variation of the phase angle, and the response amplitude in the synchronization range as a function of the controlling and influencing parameters, etc. On all these parameters the applicable knowledge remains sparse and it is difficult (if not impossible) to predict the dynamic response of fluid-structure interaction problems because these require the input of the 'in-phase' and 'out-of-phase' components of the lift coefficients, in-line drag coefficients, correlation lengths, damping coefficients, relative roughness, shear, and wave and current velocities, etc. A lack of proper understanding results in to usage of large safety factors and these result in to costly and uneconomic designs, for more details see Son *et al.* (2011). We believe that basic and fundamental studies, large scale experiments, and their detailed analyses for deriving usable and implementable design guidelines can only lead to the understanding of relationships between the response of a structure and the governing and influencing parameters. Our own research centers on this.

Most of the existing research on the VIV focuses on the interaction of a rigid SoSS whose degrees of freedom have been reduced from six to one to study its transverse motion with three dimensional separated flow, dominated by large scale vortical structures, for more details see King (1948), Verley and Every (1977), Vandiver (1983), Jones and Lamb (1993), Placzek *et al.* (2009), and references there-in.

Our aim in this paper is neither to report an exhaustive summary of the research available on the VIV and 'Vortex-Induced Motion (VIM)' nor to report reviews just for the sake of review, for these one can refer to Sarpkaya (1979), Sarpkaya and Isaacson (1981), Bearman (1984), Sarpkaya (2004), Williamson and Govardhan (2004), Naudascher and Rockwell (2005), Sumer *et al.* (2006), Hong and Shah (2018), Liu *et al.* (2020) and references there-in. Our interests are in the analyses, design, and production of marine structures and we focus only on the VIV and VIM relevant to the marine structures. In the area of marine design and production, research resulting in design papers is rare and our researches normally address this, e.g., Sharma and Sha (2005). Even in the scope of marine structures, our focus restricts to semi-submersible only because in the deep water depths applications only three choices exist (either semi-submersible or drill ship or spar) for oil and gas exploration/drilling/production, for more details see Sharma *et al.* (2009a, b, c), Sharma *et al.* (2010), and Gosain *et al.* (2017). Among these three choices sem-submsersible is more popular than the other too, especialy for the drilling purposes. Also, we analyze the research results primarily from the applications' perspective and highlight the concerning areas where despite decades of research no applicable guidelines can be or have been derived from the research knowledge base.

The remaining of this paper is organized as follows: Section 2 presents the background and motivation; Section 3 analyzes the studies of VIV responses of marine riser; Section 4 discusses the existing research on VIM responses of semi-submersibles; Section 5 reviews the computer simulation model for the response analysis of semi-submersibles; and finally Section 6 concludes the paper and identifies some critically important areas of future scope.

2. Background and motivation

The VIM response of semisubmersible can be investigated experimentally either by towing the semisubmersible in a towing tank where water is in the still condition or in a current flume where the semisubmersible is subjected to the incoming current. We note that most of the available experimental investigations are from towing tank approach, and alternatively, the 'Computational Fluid Dynamic (CFD)' based analyses also exist. The towing of a marine structure is not representative of its actual operating condition, and the drag dominates it. In the actual operating conditions, the structure is subjected to the incoming waves and currents, and there is less drag. Hence, the testing of a structure in wave-cum-current flume is closer representative of the actual operating conditions. Each of these ways to find out the VIM response of semisubmersible has their advantage and disadvantages.

In this regard, many researchers have tried different options to study the VIM of various offshore structures. Because of its critical importance in bluff body hydrodynamics and offshore engineering, the VIV problems and their related effects, like the VIM, were explored as early as 1878 in their theoretical essence. For the first time and seminally, Strouhal (1878) reported an original study on the bluff bodies' vortex shedding. This work inspired a detailed analysis by von Karman (1912), and from that time onwards, the vortex shedding process behind the bluff bodies has been studied continuously and continues to date. The process of vortex shedding can lead to the VIV, and in this regard, the investigations have focussed upon: Spring supported rigid cylinders and flexible cables. The studies have been in both directions (i.e., experimental and numerical) because of their wide industrial applications, e.g., marine risers, cylindrical columns in offshore structures, and mooring lines in the offshore industry.

A marine riser is typically cylindrical and hence a bluff body. Thus, the concepts of spring-supported cylinders or flexible cables are commonly applied to study the marine riser. Furthermore, in the semisubmersible design, the columns are generally cylindrical, and because of the combined effects of VIV of marine riser and cylindrical columns, the semisubmersible can also face the VIM. In this paper, we review the important and relevant kinds of literature that pertain to the following:

- The VIV responses of marine riser,
- The VIM response of semisubmersibles, and
- Computer simulation model for the response analysis of semisubmersible.

3. The VIV responses of marine riser

In the offshore industries, the marine risers are flexible structures that go from the deck of the offshore platform to the seabed, and because of that, they are prone to significant vibrations due to the sea currents, e.g., CR and DR, etc. The effects of vibration because of current are significant for deep offshore locations like the Gulf of Mexico, North Sea, and Brazil offshore and get further complicated in waves and harsh marine environments.

To understand the physics of VIV, both approaches (i.e., experimental and numerical) have been adopted, and primarily, the studies have focused on spring-supported cylinders, pivoted cantilevers, flexible cables, etc. The studies have reported for both air and water to predict inline and cross-flow amplitudes, drag and lift coefficients, and fatigue in the material. The results of cylindrical structures are applicable in the design and analysis of marine riser as it is also cylindrical. However, there are differences in the boundary conditions and flow patterns in the field and created in the laboratory.

Hartlen *et al.* (1968) conducted experiments on cantilevers and reported that as the aspect ratio (i.e. length (L) to diameter (D) ratio) of the cylinder increased from 11.4 to 14.6 the vibration amplitude of the cylinder decreased for the same reduced damping.

Griffin *et al.* (1975) investigated the dependence of the maximum amplitude of vibrations on reduced velocity (U_r) and response parameter and in their formulation response parameter is a function of damping, natural frequency, m^* (mass ratio i.e., $m/\rho D^2$, where m is the effective mass of the structure and ρ is the density of fluid surrounding it and D is the diameter of the cylinder in the flow). The mass ratio is a measure of the relative importance of buoyancy and added mass effects on the model) and St. Through their numerical models, the response predictions have been carried out on taut cables and circular beams and they are in good agreement with available experimental results.

Starting with Griffin *et al.* (1975), Sarpakaya (1979) and later Blevins (1990) based upon the experimental results they computed the numerical expressions (i.e., semi-empirical formulations based upon regression analysis) for maximum resonant amplitude concerning the vortex shedding. Their experiments were based upon investigations on cable, a rigid cylinder, and a pivoted rod. It is well known from the bluff body fluid-structure interaction hydrodynamics, that a cylinder in flow is subjected to the forces of lift and drag, and as the drag is significant because of the low length/diameter ratio of marine structures the drag coefficient gains importance in the design.

Blevins and Burton (1976) presented a regression analysis (i.e. curve fitting) for the experimental results of Vickery and Watkins (1962) and Hartlen *et al.* (1968) and showed that as the amplitude of vibration reaches one diameter of the pivoted cylinder the equivalent lift coefficient tends to approach zero thus resulting into a pure drag problem in the bluff body fluid-structure interaction hydrodynamics. From the regression analysis, they derived empirical equations for the equivalent lift coefficient under three distinct mode shapes with different conditions (i.e., rigid cylinder, pivoted cantilever, and sinusoid wave motion). Also, using the same regression model they analyzed the experimental data of Dale *et al.* (1966), Feng (1968), and Scruton (1963) and reported that the damping starts to decrease as the amplitude of vibration reaches the diameter of the cylinder. Most of the experimental studies considered by Blevins and Burton (1976) are on spring-supported rigid cylinders, pivoted cantilevers, and cable (in sine mode).

Skop *et al.* (1977) reported experimental results and derived semi-empirical expressions for the prediction of the drag coefficient. Their method has been applied to the design of 'Seacon II delta cables' to predict the drag coefficient, for details see Kretschmer *et al.* (1975). They obtained drag coefficients that are 150% to 230% higher than the nominal stationary drag coefficients for a rigid cylinder.

Griffin and Ramberg (1982) presented experimental results of measurement of hydrodynamic force coefficients across a range of Re (Reynolds number i.e., $\rho UD/\mu$ where ρ is the density of fluid surrounding it, U is the velocity of the current, D is the diameter of the cylinder in the flow, and μ is the viscosity of water), i.e., 1000 to 10000. Their work focused on the application to marine risers and other tubular structures and they derived equations for the lift coefficient (based on maximum displacement amplitude) and drag coefficient (based on rigid cylinder drag coefficient). Their investigation also included the influence of VIV suppression devices (i.e., helical strakes, shrouds, and near wake stabilizers). In a similar line, Vandiver (1983) discussed measurements of the drag coefficients of a 75 feet long cable and cylindrical pipe and compared his experimental results with Skop *et al.* (1977).

Vandiver (1983) conducted experiments at the mouth of Holbrook Cove near Castine, Maine, on a 75 feet long flexible cable and cylindrical pipe, where Re up to 22000 has been considered. In their studies, the cables and pipes were oriented normal to the tidal currents and they measured the drag coefficients of long cable and cylindrical pipes. Furthermore, they compared the experimental results with Skop *et al.* (1977) and reported the empirical expressions for slightly modified drag coefficient based on the 'Root Mean Square (RMS)' displacement $A^*_{Y_{RMS}}$ (i.e., $A_{Y_{RMS}}/D$, where $A_{Y_{RMS}}$ is the 'Root Mean Square (RMS)' amplitude of the vibrating cylinder, D is the diameter of a cylinder) values across the flow. They discussed the actual field conditions where flow is not spatially uniform because of the presence of different vortex shedding at different locations that occur along the depth of cable and termed the vibration response under the non-lock-in condition as a Gaussian random process. As their experiments have been conducted at the mouth of a river their conditions closely resemble the actual field condition. However, the internal fluids (i.e. drilling and completion fluids) that are always present in the offshore operations with marine riser were not considered in their studies.

Khalak and Williamson (1996) reported an experimental investigation on two rigid cylinders whose aspect ratios are 10 and 8.5 with different mass ratios. Their results showed that the response consisted of two different branches, one is upper and the other is lower. The upper branch - upper bound - occurs at the $U_r < 6$ and the lower branch - lower bound - occurs at the $U_r > 6$. Also, they showed that the lower mass ratio results in a higher response.

Hover *et al.* (1997) reported an experimental investigation in the towing tank with a 62 cm long cylinder whose diameter is 3.175 cm with different damping ratios. Their results showed that the peak lift coefficient and the peak dimensionless amplitude start to decrease with an increase in the damping ratio.

Bearman *et al.* (2001) reported experiments on large diameter cylinders to compare the responses with full-scale prototypes and study the influence of scaling effects from the laboratory scaled data to the field data. In their work, the Re was varied up to 120000 for the inline response of riser and the response measurements for large prototype and small models showed a close agreement in the restricted set of parameters. This is an interesting result because it showed that the small model results at a laboratory scale can be used to derive efficient design guidelines. After all, scaling is possible and is efficient from a small to a large scale of the structure.

Vandiver (2002) presented a formulation of the universal damping parameter which can present the VIV response in uniform and sheared flow. He discussed the variation of the added mass and the natural frequency with the flow and the relationship between the universal damping parameter and lift coefficient. The research results of Vandiver (1983), Vandiver (2002), and other papers as listed in UG (2015) have resulted in the development of commercially available software for the VIV analysis, i.e., SHEAR7***TM v4.8a. This software is based upon the approach of universal damping parameter to measure the response of marine risers for sheared flow and other semi-empirical and numerical formulations developed by the research group.

De Wilde and Huijsmans (2004) studied the VIV response of a long riser with a rigid pipe in the towing tank and they concluded that the VIV response of a long riser is a complex phenomenon consisting of multiple modes and the dominance of modes is not strictly orderly harmonic. They considered a rigid steel pipe instead of a flexible steel pipe and that is a limitation in their study.

In recent years because of the modern advances in computational fluid-structure mechanics and computing power available in machines, recent research focuses on the development of computational models that compute numerical solutions in either time or frequency domains. The computing time for complete simulation is decreasing with available and ever-increasing computing speed. The simulation-based approaches are attractive because they offer cost-efficient development of optimal solutions something that is prohibitively expensive with a purely experimental approach. An efficient simulation-based approach when verified and validated with experimental results offers the ideal choice for developing analysis-driven design solutions.

In this line, Xu *et al.* (2008), and Xu *et al.* (2010) presented a numerical simulation approach based upon the wake oscillator model applied to an elastically mounted rigid cylinder and compared the numerical simulation results with existing experimental results and results from Facchinetti *et al.* (2004). Across a limited range of applications, the presented model was successful in predicting the response amplitude and showed good agreement with the available experimental data. In general, the simplified model of the wake dynamics that is verified and validated through simple experiments has been known to result in the development of a simple computational tool for the prediction of some aspects of vortex-induced vibrations of long flexible structures. However, in strongly coupled motions when the resulting partial differential equations get more complicated with higher-order derivatives and variables, the wake oscillator model is not applicable. The fully coupled and strongly non-linear partial differential equations will demand solutions through computational fluid dynamics, e.g., Direct Navier-Stokes Simulation, time or frequency domain approaches of FSI, etc.

Although these are computationally expensive and the solution time can vary from a few hours to days to weeks, they are able to capture coupling and higher modes of vibration accurately.

Meng and Chen (2012) presented a parametric study based on the finite element analysis approach and wake oscillator model of Facchinetti *et al.* (2004) by varying the internal fluid velocity and top tension of steel catenary riser and showed that the mode transitions occur at certain external flow velocity. The increase in internal flow velocity initially decreases the response but after a critical threshold value any further increase in the internal flow velocity increases the response and also the tension is directly proportional to the response till the rigidity sets in and after that it breaks.

Gao *et al.* (2015) reported an experimental investigation on long flexible risers using VIV suppression devices (i.e. helical strakes with different pitch and strake height) in uniform and linearly sheared currents and they observed that in comparison with the bare riser, the dominant frequency, dominant mode, displacement response, and fatigue damage were all reduced greatly by using the helical strakes. Furthermore, in comparison with the strake pitch, strake height has a greater influence on the VIV response displacement and fatigue damage in both uniform and sheared currents.

Wang *et al.* (2015a) numerically investigated the responses of steel catenary riser and their influence on vessel motions for the oscillatory flows and observed that the responses of risers because of vessel motions are easily identifiable with time-varying features. These time-varying features show that the vessel motions are strongly related to KC (Keulegan–Carpenter i.e., U_mT/D, where U_m is the velocity amplitude of flow that oscillates with the time period T, T is the period of oscillation, and D is the diameter of the cylinder in the flow). It is used to understand the relative importance of drag forces over inertia forces for bluff objects in an oscillatory fluid flow in the time domain and larger KC number results in large motion. In their work, the RMS amplitude number is within 0.2 to 0.4.

Wang *et al.* (2015b) numerically studied the lateral displacement of the marine riser in the installation with a floating drilling platform by varying the water depths, wall thicknesses, blow-out preventer weights, wave heights, and wave periods. The authors showed that except for the wave period all other parameters influence the lateral displacement of the marine riser.

Recent researchers have focused on either numerical or experimental investigations on issues of primarily either theoretical interests or scientific interests, e.g. understanding the physics/mechanism behind VIV, for more details see Hourigan *et al.* (2001), Mukundan *et al.* (2010), Bourguet *et al.* (2011a, b, 2012), Zou (2012), Eswaran (2013), Eom *et al.* (2014), Park *et al.* (20214), Zhang1a *et al.* (2014), Antony *et al.* (2015), Bourguet and Triantafyllou (2015), Cifuentes *et al.* (2015), Kamble and Chen (2016), Han *et al.* (2018), Zhao *et al.* (2018a and 2018b), Hu *et al.* (2019), Huang and Chen (2020), Tamura (2020), Konstantinidis *et al.* (2021), Jia *et al.* (2022), and references there-in. Undeniably, the theoretical and physical understanding of the VIV is important, but engineering and technology are all about the application of science (including physics of course) in deriving the approaches for analyses, design, and production of engineering structures. It is on this issue that most of recent researches fail to focus and do not produce any implementable and usable guidelines, what-so-ever.

In our researches (Domala and Sharma 2018), we have focussed on the experimental study on vortex-induced vibration response of marine riser with and without semi-submersible and our analyses were utilized to draw and derive design guidelines and operational ranges for the marine riser (with and without semi-submersible). Although the application domains were clearly identified and the results have been revealing, they are just the beginning and centres on the low but widely occurring Reynolds's number (Re) up to 5000, only. To strengthen our efforts in the area of VIV, to

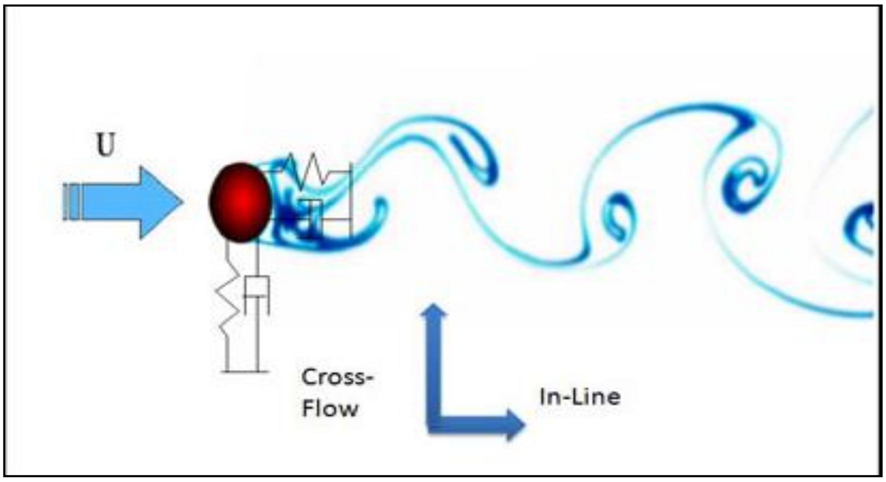


Fig. 1 A rigid cylinder flexibly supported with springs adapted from Van Dyke (1982)

develop deep and meaningful insights into the complex dynamic motion response related to the VIV, we need to investigate the moderate regime of Re, include more geometric configurations and shapes of columns/pontoons in the semi-submersible and focus on the design and development of an experimental set-ups for moored structures. The comparative listings on VIV response of marine riser and marine riser configuration are listed in Table 2.

2.1 Key limitations of the existing research on VIV of marine riser

In most of the existing research on VIV of the marine riser, the experimental investigations have been carried out in a towing tank where the riser is towed with the assumption that the towing velocity represents the current velocity and the rigid cylinder is flexibly supported at both the ends instead of fixed ends. The rigid cylinder flexibly supported with spring is shown in Fig. 1.

This type of condition is popular in experimental studies, but it does not represent marine risers' actual field conditions. It is well known that in a fluid flow, the cylinder is subjected to lift and drag forces, and if an experiment is performed in a towing tank then the flow becomes drag-dominated. In the real world, the flow around a marine structure is lift-dominated. Furthermore, since it is difficult to perform experiments with a CR, the literature is limited regarding CR. Additionally; the responses of DR and CR with internal fluids (i.e., representative of the actual field conditions) have not been studied so far. The studies on CR's response with semisubmersible are also scarce.

4. The VIM responses of semi - submersibles

Starting from the early stages of the design of semisubmersibles, it is important to understand the response due to waves, to develop efficient and economic designs. However, little is known about the response of semisubmersible because of the vortex-induced motions introduced by the cylindrical columns, the effect of the VIV of the marine riser on the vortex-induced motions of semisubmersible and the coupling of the VIV and VIM. These responses are critically important and for their better understanding, we need to understand the responses under both the conditions of

Table 2 Comparative listing of the marine riser configuration in experimental studies

Technical parameter of riser	References							
	Trim *et al.* (2005)	Lee *et al.* (2005)	Chaplin *et al.* (2005)	Xu *et al.* (2009)	Lie and Kaasen (2006)	DeWilde and Huijsmans (2004)	Gao *et al.* (2015)	Domala and Sharma (2018, 2020)
Riser length (m)	38 (DR)	36.6 (DR)	13.12 (DR)	8.5 (DR)	90 (DR)	12.6 (DR)	7.9 (DR)	4.5 (CR) and 1.2 (DR)
Riser outer diameter (mm)	27	63.5 & 38.1	28	47	30	16	30	14
Aspect ratio (L/D)	1400	576, 960	470	181	3000	787	263	157(CR) , 86 (DR)
Material	Fibre glass	Fibre Glass	Phosphor, Brozne	Coaxial rubber hose	Steel	NK	NK	SSBFH
Mass (kg/m)	0.761	0.761	NK	NK	2.27	NK	2.5	0.25
Tension (N)	4000 to 6000	NK	NK	420	3700	900	3000	33, 67 for DR
Modulus of elasticity (N/m^2)	2.25E+09	2.25E+09	NK	NK	2.10E+11	NK	1.08E+11	2.10E+11
TS/C (m/s)	TS: 0.4 to 1.5	TS: 2.4 to 5.5	TS: 1	TS: 0.1 to 1.0	TS: 0.16 to 2	TS: 1	TS: 0.8 to 2.8	C: 0.05 to 0.343
Mass ratio (m^*)	1.6	NK	NK	1.35	3.13	2.29	3.3	2.05 to 2.65
Discussed Results	A_Y^* with strakes	A_Y^* with fairing	Y/D and X/D with varying tension	A_X^*, A_Y^*, and velocity vector fields	Cross flow (CF) and inline displacement (IL), ILs should be included in fatigue calculations	Drag is measured and Single-mode response is not observed	A_X^*, A_Y^*, with strakes and fatigue of riser.	DR - A_Y^* with water, drilling fluid, stiffening, and different tension. CR - A_Y^* with semi-submersible

Most of the research results are reported in A_Y^* and they vary across the sections because of studies done with: either towing or current, either spring-mounted/supported cylinder or cylinder with ends fixed, and either cylinder with strakes or without strakes, etc.

NK – Not known. Towing speed – TS. Current – C, DR – Drilling riser, CR – Catenary riser.

individual and coupled. As the VIM can introduce significant oscillatory motions on the semisubmersible, its importance has been realized slowly, primarily in during 2000 to date.

Possibly for the first time on the problem of VIM, Waals *et al.* (2007) considered four configurations of floaters for the experimental investigation in a towing tank (i.e., 1-Deep Draft Semi-submersible (DDS), 2-TLP, 3-semi-submersible and 4 -semisubmersible with two pontoons). In their configurations, the major differences are in the mass ratios, where the 2-configuration has 32% less mass than the 1-configuration; in the column length, where the 3-configuration has 50% smaller than the 1-configuration; and the number of the pontoons, where the 4-configuration has two pontoons compared to the 1/2/3-configurations. Their results indicated that all the configurations have a maximum response at the 45-degree current heading and the peak response is found in between $5 < U_{rs} < 8$. The VIM did not reduce for higher values of the U_{rs} and the vortex shedding frequencies are not close to the motion periods and the galloping is observed for the 4-

configuration, i.e., two pontoon semisubmersible. Here in the experimental setup, the authors used equivalent mooring stiffness or a simplified mooring system (i.e., where horizontal springs are used instead of actual mooring lines) instead of catenary mooring lines for all the floaters, which is a limitation in their study.

Hong *et al.* (2008) reported model tests on the DDS under waves and current and they considered two current velocities and the Strouhal number test results were similar to mono column structure. If the current velocity is higher, then even for the smaller fluid particle velocity (i.e., lower significant wave height (H_s) and longer time period (T_p)) the VIM amplitudes are higher. Their results imply that a DDS is expected to experience a more significant VIM response in the regime of a stronger current.

Rijken and Leverette (2008) presented an experimental investigation on the VIM response of DDS with external dampers and the external damping device was utilized to provide the opposite force that is equal in magnitude to the motion-inducing force. This provided around 10% equivalent linear damping for the sway amplitudes and delayed the response of VIM to higher reduced velocities. Rijken and Leverette (2009) reported a detailed study on the field measurements of semisubmersible and presented results for two conditions: Lock in condition and post lock-in condition. They observed that the VIM amplitudes are significantly small for the prototype than the model test results. The field studies showed that even though inline and cross-flow amplitudes of vibratory motions are small but they are harmonic at the lock-in conditions and for the post lock-in conditions they are almost constant with little or no change. The primary reason for the lower amplitudes in the field is that the mooring lines and riser systems have significant mass, hydrodynamic loading, and drag.

But in the model tests mooring lines and risers are assumed as horizontal springs while neglecting their mass, hydrodynamic loading, and drag. The stiffness is the only property that is considered through the use of the concept of equivalent stiffness. Also, the boundary conditions are different at the ends in the case of the model and the prototype.

There exist some studies on marine structures that are based upon a deck resting on a single long cylindrical column, e.g., SPAR platform. Fujarra *et al.* (2009) and Gonçalves *et al.* (2010a, b) discussed experimental results on a model mono-column platform with hull appendages to check the VIM response subjected to different conditions, e.g., different drafts with the risers and the VIM suppression devices. In their results, the maximum VIM responses occur at the U_{rs} of 14 for both the inline and transverse vibrations at the 0 and 180 degrees current directions.

The change of current directions reduces the response of VIM due to the presence of hull appendages and the weak interaction between cross-flow and inline motions. The model of mono-column platform used by Fujarra *et al.* (2009) and Gonçalves *et al.* (2010a, b) consists of a scale model of the MonoBR floating unit and it is secured by a set of equivalent horizontal moorings in the towing tank. In the model test details, the 0 degree incidence is characterized by having one fairlead in front of the model and the 180 degree incidence is characterized by two fairleads in front of the model. Because of this arrangement of mooring lines, the point where the boundary layer separates keeps moving around the hull with the change in direction of current and increasing velocities; and this change results into the 'Vortex Induced Motion (VIM)' showing dependency upon the current even when the current is acting on an axis symmetric mono cylindrical column structure (like spar). The riser when connected to a platform provides extra damping and this decreases the cross-flow and inline responses. Furthermore, the waves with current decrease the VIM response only when severe heave motion is observed. In the range of low U_{rs} ($5<U_{rs}<10$), the VIM in the transverse direction present a small increase in amplitude and it is related to a simultaneous increase in the VIM in the in-line direction. At low U_{rs} the flow gets separated earlier causing the boundary layer separation followed by unsymmetrical vortex shedding. This results into an increase in the VIM responses (in the transverse and in-line directions) at low U_{rs}.

Wang *et al.* (2009) presented an experimental study with a bare cylinder and a cylinder with two helical strakes of different heights. They used two different mooring systems, i.e., 4 lines and 3 lines mooring system. Unlike the VIM experiments that are done in a towing tank, their experiment tends to replicate the real-world scene where water flows around the structure instead of the structure running/being towed through the water. Their results showed that the VIM response can be controlled by the strakes except at some of the particular current directions (i.e., 105^0, $225^{0,}$ and 345^0) and there the VIM response is not reduced. Furthermore, the strake with a higher height shows more effectively than with a less height and the strake also increases the sway natural period. The current direction and mooring line orientation also affect the VIM response of the cylinder.

Xu (2011) presented a semisubmersible design with optimization of the hull to reduce the heave motions and also the VIM. In his approach, the shape of the column was not altered and the large blisters of asymmetric shapes with sharp corners were attached at the lower part of the columns. The pontoons dimensions became thin at central part and elongated at the edges around the column and this shape was named ‘dog bone’ shape. He also reported model tests on conventional and new designs to check for the VIM performance under the 30 and 45 degrees current heading and the results showed that the blisters attached to columns had reduced the VIM response by breaking the vortex shedding by around 50%.

Rijken *et al.* (2011) presented experiment results on four different hull forms (A, B, C and D) of semisubmersible in a towing tank, i.e. A is a clean hull and the three others have varying hulls-appurtenances. They used horizontal springs for both the symmetric mooring without SCR and the asymmetric mooring with SCR. Their results showed that the VIM responses are similar even when the stiffness due to the mooring lines and SCR are different. These results are surprising and the explanation is that the mass of mooring lines and SCR are not considered in the model test. The VIM response is different or distinct when reversing the towing direction. Their test results were compared to the SPAR VIM response test results where similar vessel trajectories were reported. Increasing the details on columns affected the VIM response for 15 and 30degrees current heading, where the inline response was increased.

Martin and Rijken (2012) discussed model scale studies and investigated the effect of damping, hull surface and wave action on the VIM response of semisubmersible. They showed that an increase of damping by 50% decreases the response of VIM by 50% and the semisubmersible has very less response against the different sea states. For smaller sea states, the VIM response is very less and increasing the wave height reduces the response of VIM. The vortex induced yaw response can lead to the coupled sway-yaw response depending on the stiffness of mooring lines. The yaw response depends on current heading where 45 degree current heading has higher response compared to other current headings.

Gonçalves *et al.* (2012, 2013) reported experimental investigations on a semisubmersible and found that all the measured results are synchronized between the reduced velocities of 5 to 8 and the responses are harmonic between the mentioned reduced velocities. They also reported VIM responses for different drafts with waves and current in the same heading. In their results at the 45^0 current heading when no waves are present the VIM responses are higher and for regular waves with different waves heights there is no synchronization. Furthermore, for different sea state conditions with different frequencies the VIM responses are lower as compared with the no wave condition. They also reported results with different drafts where the VIM is higher at higher draft conditions as compared with the lower draft conditions.

Bai *et al.* (2013) presented experimental and numerical investigation on a DDS and their results showed that the sway response depends on current velocities, i.e., the maximum amplitude for surge and sway is obtained for the 135 degrees of current in between $6 \le U_{rs} \le 9$. However, because of the high characteristic length, the same is not observed for the 0 degree current and for the yaw response higher amplitude is obtained at the 90 degrees current at the higher reduced velocities. Their numerical results were for a 2 dimensional model while neglecting the hull appendages and pontoons and the response amplitudes were overestimated as compared with the experimental results, i.e. the higher amplitudes were obtained for the 135, 150 and 120 degrees current heading where lock-in was observed and the small amplitudes were observed for the 180 and 90 degrees current headings where no lock-in was observed.

Rijken (2014) discussed a CFD analysis based on the scale and mass ratios and reported the comparison between the two results. His results showed that the difference in VIM responses is low in between the model tests and CFD results and the change in mass ratio does not affect the VIM response as there is no change in the reduced damping (or Scruton number, i.e., $\delta_r = 2m(2\pi\zeta / \rho D^2)$, where m is the effective mass of cylinder and ρ is the density of fluid surrounding it, ζ is the damping ratio and D is the diameter of the cylinder in the flow. If the reduced damping is increases then the amplitude of vortex induced vibrations will decrease.).

Antony *et al.* (2015) presented an investigation of the VIM response of DDS with CFD analysis and they showed that the nominal vibration amplitude is of the same order for model and full scales. The sway periods are lower for full scale and the peak in nominal amplitude as a function of U_{rs} shifts to the left. In their studies, the damping is assumed for riser and mooring system and a linear damping model was assumed with the assumption of 10% and 20% damping. Their results showed a VIM response reduction with the increase in damping from 0 to 10% and later from 10% to 20% only a marginal reduction was achieved.

Chen and Chen (2015) reported the CFD simulations on a DDS for model scale of 1:70 and full scale, and compared the results with existing experimental results of Waals *et al.* (2007) and Rijken and Leverette (2008). Their comparisons of numerical results with the experimental results showed a good agreement within the restricted setting of parameters. They obtained the maximum sway amplitudes around the range of $5 \le U_{rs} \le 8$. They did not show any comparison for the yaw motion, possibly because the yaw response amplitudes are very small and hence any comparison will be difficult and erratic. Also, there is no interaction between the upstream columns and the rear columns are affected by vortices shed by upstream columns.

Irani *et al.* (2015) presented an experimental study on semisubmersible model to investigate the effect of varying draft, hull appendages and damping on the VIM. Their results showed that an increase in the draft results into the increase of the amplitude of vibration, an increase in the damping results into the decrease of the VIM response and with the hull appendages the VIM response decreases. They also reported comparison between the CFD results with model tests and field tests and the CFD results of full scale agree with field data within the restricted setting of parameters. However, the model test results are significantly higher than the field data and the process of computations of the U_{rs} are not very clear for their reported field data.

Gonçalves *et al.* (2015) reported the experimental results with different column designs (i.e., square and circular) and studied the VIM responses. They observed that the VIM amplitudes are higher in case of circular column semisubmersible as compared with square column semisubmersible. For the 0^0 current incidence the circular column has higher transverse response and yaw responses are similar, at 22.5^0 incidence both the structures have a similar transverse response and the yaw response is higher for circular column semisubmersible and at the 45^0 incidence the square column semisubmersible has higher transverse response and circular column has higher yaw response. All the responses have a lock-in range of the reduced velocities in between 5 and 8 and for the 22.5^0 and 45^0 a second peak is observed at around reduced velocity of 16 for semisubmersible with circular column. The second peak can be because of the coupling of either surge and heave, or sway and heave, or both.

Koop *et al.* (2016) discussed an important study that showed the VIM response difference between the field and model tests. They noted that when the square column roughness is increased there is no reduction in the VIM response as compared with bare hull. However, when the circular column roughness is increased the VIM response is reduced as compared with bare hull. This is because the response in the case of square like columns the sharp or rounded corners lead to fixed points flow separations (even when they are rounded) as compared to the circular section which is smooth. Hence, for a circular section any minor variation from the boundary smoothness can cause the flow streamline to separate from the body and thereby it will reduce the VIM responses.

This idea of altering the smoothness of section by using wires etc. to reduce the VIV and VIM responses has a long research history starting possibly in 2000s, e.g., Hover *et al.* (1997). Also, this idea can be extended further by utilizing the concepts of usages of '*chines*' in high speed crafts. In Koop *et al.* (2016), they also explained that the presence of small waves as found in the operational seas may not reduce the VIM behavior of the semisubmersible. But the lower VIM occurs for the higher wave heights. They also compared the CFD results of full scale and model scale and they reported that the VIM response occurs at lower reduced velocity as compared with model scale. But the peak values are same for both. Also they noted that the varying current velocity is not responsible for the VIM reduction in the field and for shear currents the variation of current velocity with the draft of semisubmersible is not large so the shear currents have little influence on VIM.

Liu *et al.* (2016) presented a study on four configurations of DDS for the experimental investigation of the influence of pontoon and column configuration on the VIM. Their variations are: 1 - DDS with four pontoons, 2 - DDS with two pontoons, 3 - four square column structure with no pontoons and 4 - four rhombic column structure with no pontoons. In their results, all the configurations showed synchronization between $5 \le U_{rs} \le 8$. The effect of pontoons on VIM responses are compared with Configurations 1 to 3 and they showed that the 1 - Configuration has lower response compared with the others and the pontoons decreased the VIM response. The VIM responses are high for the third and fourth configurations as compared with the other configurations and Configurations 3 and 4 have similar responses at the 0^0 and 45^0 current respectively.

Maximiano *et al.* (2016) reported the model test results for different drafts, different mass ratios and considered the different damping ratios for various draft conditions. They showed that in the shallow draft condition semisubmersible has lower VIM response as compared with the intermediate and deep draft conditions. The deep draft condition shows higher responses and increasing the mass ratio decreases the VIM responses. The increase in damping ratio decreases the VIM response and at the higher damping ratios the VIM responses can be controlled completely. They reported that the linear damping significantly reduces the VIM responses and it narrows the reduced velocities at which VIM occurs and shifts the peak values to higher reduced velocities. However, it is critical to note here that the increase in damping is a costly solution because either it is by addition of mass or altering the boundary conditions or changing the fluid flow around. And, all the options of increasing either the structural damping or hydrodynamic damping or both are prohibitively expensive.

In our researches (Domala and Sharma 2020), we have focussed on the experimental study on vortex-induced motion responses of a moored semi-submersible with and without riser and our analyses were utilized to draw and derive design guidelines and operational ranges for the semisubmersible (with and without marine riser). Remarkably, our results showed that the VIM response of semi-submersible reduces the VIV response of riser and that the motions in pitch and roll are likely to become critical and they demand a detailed analysis to be addressed in future to improve the operational range of semi-submersible and catenary riser in deep water depths under harsh marine environment of high current velocities. Here also, our limitations as noted before holds true, e.g., Centring on the low but widely occurring Reynolds's number (Re) up to 5000, only. To strengthen our efforts in the area of VIM, to develop deep and meaningful insights into the complex dynamic motion response related to the VIV, we need to investigate the moderate regime of Re, include more geometric configurations and shapes of columns/pontoons in the semi-submersible and focus on the design and development of an experimental set-ups for moored structures.

Based upon our review as reported above, we note the following critical observations:

- *(A)* A change in flow line on the boundary of body by using devices like strakes/wires, and blisters attached to columns, etc., can cause reduction in the VIM responses. However, they all have problems associated with them like severe algae growth, change of the effective span lengths, difficulty in manufacturing, increase in the cost, and increase of the in-line drag, etc. Our view is that they add more to the problems and less to the solution.
- *(B)* The deep draft of semisubmersible is more susceptible to the VIM as compared to the low or intermediate draft conditions. However, the use of deep draft is demanded because of underwater stability and payload.
- *(C)* Most of the studies show a large VIM response at 0^0 current directions for both the square and circular columns semisubmersible. For the square column semisubmersible 45^0 current direction is critical too. Also, the pontoons affect the critical current direction for both the square and circular columns semisubmersible.
- *(D)* Although, the existing results show that the VIM continues at the higher U_{rs} and does not reduce, the studies focused only on the lower range of U_{rs}.
- *(E)* The current velocity is important and at higher current velocities even for the smaller wave-induced particle velocity (i.e. lower H_s and longer T_p) the VIM amplitudes are higher.
- *(F)* In the field, lower amplitudes of the VIM are observed. Primarily, this is because of the mooring lines, riser systems of significant mass, hydrodynamic loading and drag. However, the current research still ignores the mooring lines because they focus on the tests in towing tank.
- *(G)* In the VIM responses sometimes multiple peaks are observed and they can be because of the coupling of: surge and heave, or sway and yaw coupling with the heave motion, or surge-heave-pitch.
- *(H)* Normally, shear rates do not affect the dominant vibration modes significantly. Overall vibration includes contributions from several modes, and each mode persists over a range of shear rates. This results into a traveling wave characteristic in the vibration. A larger shear rate shifts the position of the largest in-line time-averaged displacement more and more-closer to the end (i.e., location of the largest current speed). Additionally, an increase in the internal flow velocity and fluid density, results into the decrease in the maximal in-line displacement and increase in the maximum

Table 3 Critical comparative listings of VIM response studies on offshore platforms

References	Type of offshore structure	TT, CF and FT	Mass ratio of floating structure (m_s^*)	Mooring system	Important observations
Waals *et al.* (2007)	DDS	TT	0.83	Horizontal springs	Higher VIM can happen because of higher draft.
	TLP		0.57	Horizontal springs	Higher VIM can happen due to low mass ratio.
	Low draft semisubmersible		0.83	Horizontal springs	Lower VIM response because of low draft.
	2 pontoon semi-submersible		0.83	Horizontal springs	Similar to the DDS.
Hong *et al.* (2008)	DDS	TT	NK	Horizontal springs	*S* is similar to the mono column structure like SPAR and current and waves in coupled mode can induce higher VIM.
Rijken and Leverette (2008)	DDS with VIM suppression device	TT	NK	Horizontal springs	Sway response reduced and the VIM delayed to higher reduced velocities.
Rijken and Leverette (2009)	Prototype semi-submersible	FT	NK	NC	Significantly less VIM as compared to the model tests.
Fujarra *et al.* (2009) and Gonçalves *et al.* (2010)	Mono-column: SPAR with riser and hull appendages	TT	NK	Horizontal springs	VIM is higher for 0 and 180 degrees direction of current and the riser provided external damping which decreased the VIM response.
Xu (2011)	Dog bone shaped semisubmersible hull	TT	NK	Horizontal springs	Reduced VIM as compared with the conventional semisubmersible hull.
Irani *et al.* (2015)	Conventional semisubmersible with varying draft and damping	TT	NK	Horizontal springs	Higher VIM because of higher draft and VIM reduced with damping.
Domala and Sharma (2018, 2020)	Medium draft semisubmersible with mooring lines and CR	CF	1	Catenary mooring	Studies of VIM in the surge, sway, roll and pitch degrees of freedom.

Critical limitations of the existing observations: Most of the research results are reported in A_{YS}^* and they vary across the sections because of studies done with: either towing or current, either spring mounted/supported semisubmersible and either semisubmersible or TLP or SPAR or LDS or DDS, etc.

NK - Not known. NC – Not clear. Towing tank - TT , Current flume - CF, Field test - FT, Deep/low draft semi-submersible - D/L DS

displacement in cross-flow direction. The in-line deflections show an increasing trend with the increase of internal flow velocity and fluid density under the same external shear currents primarily because of the centrifugal force and the allocated energy. Shear currents show significant influence on VIM in the deep draft condition.

The critical comparative listings of VIM response studies on offshore platforms.are listed in Table 3.

4.1 Key limitations of the exsisting research on VIM of semi-submersible

It is important to note here that in actual practice any offshore structure with a marine riser will be in a moored condition. However, when an experiment is performed in the towing tank for the VIV/VIM tests, it is impossible to tow a model with riser and mooring lines. Hence, in a towing tank it is not possible to adopt any type of the mooring lines. In order to overcome this limitation, a simplified mooring system or equivalent stiffness system (i.e., spring stiffness is taken equivalent to the stiffness of steel catenary riser) being is adopted, i.e., spring mounted cylinder. A simplified SCR and mooring system that is normally considered in the existing VIM tests is shown in Fig. 2.

Additionally, in the actual field conditions a semisubmersible does not have the restoring forces in surge and sway degrees of freedom unless the mooring line offers the stiffness in the beginning itself. This does not happen in the beginning and happens only when the semisubmersible drifts through some large distance and the mooring line forces develop and try to restore the semisubmersible. In the towing tank, because of the uses of springs the stiffness is high since the beginning and the VIM responses are expected to be like a rigid cylinder with flexibly supported end conditions. Furthermore, in the towing tank tests some of the degrees of freedom are restricted because of the uses of springs and it seems that because of this reason the literature on VIM roll and pitch responses is very limited.

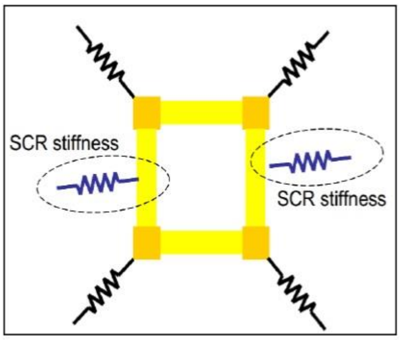
On the other hand, in the current flume a semisubmersible is moored with catenary mooring system and there is no restriction on the degrees of freedom. Also, in the towing tank tests, since a model is towed, the flow in towing tank is drag dominated and all the movements except in the direction of towing are either restricted or compromised. In the case of towing tank experiments because a model is towed, it is not possible to allow or accommodate large surge and sway motions. In the current flume a current is passed and the marine structure is moored and this give rise to a lift driven flow. This is closer to the actual filed conditions.

4.2 The VIM of spar in loop current and semisubmersible in strong current

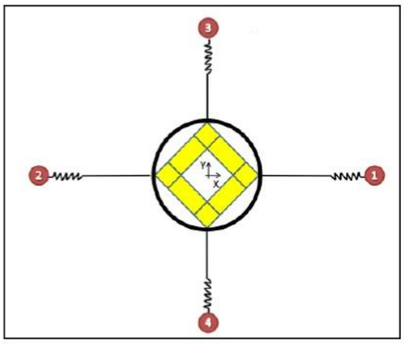
Following Paula *et al.* (2018), we note that the 'Loop Current' is a warm ocean current that flows northward between Cuba and the Yucatán Peninsula, moves north into the Gulf of Mexico, loops east and south before exiting to the east through the Florida Straits and joining the Gulf Stream. This current is an extension of the western boundary current of the North Atlantic subtropical gyre and it serves as the dominant circulation feature in the Eastern Gulf of Mexico. The Loop Currents are highly dominating, transports around 23 and 27 sverdrups and reach maximum flow speeds of around 1.5 to 1.8 m/s, for more details see Johns *et al.* (2002) and Gordon (1967). As the VIV and VIM both are current driven phenomenon, the Loop Currents affects both the VIV and VIM. As Spar is mono-column cylindrical structure it is adversely affected by the Loop Currents and a review can be found in Gonçalves *et al.* (2012a).

As noted before, both the VIV and VIM are adversely affected by higher currents and in regard to semi-submersibles, the VIM is primarily excited by high current velocities, variation of the current velocities across the column depths and vortex shedding around columns. Because of these reasons, the dimension of the column, especially the immerged aspect ratio and current velocities and variations are crucial in determining the VIM response of semi-submersibles. A strong current increases the average current velocities and tend to have a highly non-linear variation across the depth. Research results related to the studies of semi-submersible in strong currents can be found in Gonçalves *et al.* (2012b), Liu *et al.* (2017), and references there-in.

Clearly, higher current velocities (i.e., Eddy and Loop currents) and non-linear current variations across the depth results into larger transverse amplitudes in the VIV and VIM. In our opinion, flow control is the future in all the issues related to VIV, VIM and others like flow induced noise, etc. This area of flow control is gaining the importance slowly and new and novel ideas are being investigated. E.g. improved strake designs for better performance to minimize VIV for Spar, for more details see Maksoud (2005). Regarding the strakes, the current focus is on creating data on the



(a) Equivalent mooring system and SCR for semi-submersible adapted from Rijken *et al*. (2011)



(b) Equivalent mooring system and SCR for semi-submersible adapted from Goncalves *et al*. (2012)

Fig. 2 Simplified SCR and mooring system adopted for the VIM tests

effects of exterior equipment such as chains, fairleads, pipes and caissons, strake holes, modeling of mooring systems using springs. A comprehensive knowledge base of strakes can result into improved motions and arrival at simple and effective design guidelines, e.g., an increase in the strake width by 7.5 to 17.5 % of the hard tank diameter offers considerable benefits.

Other ideas to be explored and investigated are: Optimization of the strake layout for minimum openings and discontinuities, minimizing the size of the holes, and reducing the cost for passive mitigation means, all for the improved motions. Another idea is to mitigate the VIV and VIM using smart thrusters, for more details see Fisher *et al.* (2004).

One advantage of using an active control system is its low cost in comparison with the high cost associated with passive VIV/VIM mitigation means. The use of thruster forces proportional to spar velocities results into an efficient control and using these controls, the spar motions can be contained within 30 to 40 % of the spar diameter. Use of thrusters has a long history in the field of marine structures and although they are used quite often for multiple purposes (i.e., movement, position control, depth control, and buoyancy control, etc.), their operations are costly and associated with higher levels of noise and vibration. Additionally, their optimization for particular sets of requirements is not always either feasible or too computationally expensive to be adopted in practical designs or outside the permissible operational expenses.

In our opinion, the flow control mechanisms for the VIV and VIM need to focus on the design of marine from the stage of preliminary design and must extend to all the design stages. Shape, arrangements, L/D ratios, orientations, arrangements of columns to deck and pontoons, etc., influence the VIV and VIM, and their optimization can offer the most economical and efficient flow control mechanism for the VIV and VIM, for more details see: Gosain *et al.* (2017), Gosain and Sharma (2018).

4.3 The VIV/VIM as sources of marine hydrokinetic energy

An energy can exist in many forms and there are infinite options to capture energy and convert it into one form to another, e.g., movement of a body of water generates hydrokinetic energy. Any movement or noise or vibration can be utilized for energy generation and the hydrokinetic energy can be extracted from earth’s tides, waves, ocean currents, free-flowing rivers, VIV, VIM, and flow induced noise, etc. An early attempt was made through the invention of ‘Vortex Induced Vibration

Aquatic Clean Energy (VIVACE)' for extracting ocean current energy by Bernitsas *et al.* (2008).

All the bluff bodies (i.e., mooring lines, offshore structures, transmission lines, and chimney towers, etc.) that are slender in nature undergo large oscillations/vibrations due to boundary layer separation and formation of vortices, resulting in vibration and noise. These oscillatory motions, vibrations and noise can be extracted for power generation and the VIVACE was a demonstration of generating power from vortex-induced vibration of a cylinder. When the natural frequency of the structure is equal to the vortex shedding frequency at the resonance condition, the structure will experience large magnitude of vibrations/oscillations. In order to take advantage of these situations, the cylinder is mounted over springs with suitable stiffness so that the large sustained oscillations can be achieved. It was suggested that enormous power could be generated from an array of cylinders by Bernitsas *et al.* (2008) and a comprehensive economic viability study based on the laboratory tests was also reported by them.

In the similar direction, later Bernitsas *et al.* (2009) investigated another attempt of using the 'Vortex Induced Vibration Energy Converter (VIVEC)' for production of clean energy from water currents and streams. Afterwards, Ding *et al.* (2014) have studied the effect of different cross-section of the cylinder on the energy harvesting. They conducted a CFD analysis of the vortex pattern and maximum energy efficiencies of 45.7% and 37.9% were achieved for Q-trapezoid I and PTC-cylinder, respectively.

Kim and Bernitsas (2016) reported that multiple cylinders in proximity can synergistically work and harness more energy than the same number of single cylinders in isolation. Their estimations based on experiments, showed that a 4 PTC-cylinder converter could achieve 88.6% peak efficiency and they had used the 'Steady Lift Technology (SLT)' like turbines or 'Alternating Lift Technology (ALT)' like the VIVACE to harness the hydrokinetic energy. In order to evaluate the optimum regime to extract the hydrokinetic energy from the fluid by 'Fluid Induced Motion (FIM)', the power efficiencies of FIM for the cylinders with different cross sections were evaluated and a coupled formulation for modeling multiple piezoelectric energy harvesters based on vortex-induced vibrations phenomenon at arbitrary locations was presented and experimentally validated by Ramirez (2021).

Although, the above mentioned techniques have been major advancements in understanding and taking advantage of the VIV, VIM, noise and oscillatory motions and these have shown considerable potential through the laboratory model studies, their actual usages for industrial productions have never been initiated. There exists multiple reasons for that, e.g., high mechanical complexities, abnormally high costs of mounting these systems on any marine structures, extremely low scalability, issues related to transmission of power from sea to land, inherently unstable and unpredictable natures of marine water movements and the involvement of higher risks and low reliability in marine systems and structures dealing with tides, waves and currents.

We strongly believe that the marine hydrokinetic energy will remain at the research and development stages only in the near future and it will be difficult to design and develop a technology that can extract energy and is scalable with reasonable costs and lesser complexities. Researchers need to focus on these issues and need to aim towards these design and developments.

5. Computer simulation model for the response analysis of semi-submersible

The modern world is driven by the designs for efficiency and economy. The design through experimental processes is prohibitively costly but results into more accuracy. However, because of the high cost and time involved in the experimental investigations, recently more and more focus has gained into the design and development of computer simulation models that are efficient and economical to be used in the novel design development of modern marine structures.

A semisubmersible has low water plane area at the operating draft and because of this the motion responses of semisubmersible are low. This low motion allows the use of semisubmersible over a wider range of difficult weather and sea conditions. The motion response of semisubmersible depends on the weight, draft, distance between pontoons, size of columns, wave direction, wave height and other parameters. Because of their industrial significance the motion response of semisubmersible has been studied by various researchers and research has focused on variety of issues ranging from detailed computationally expensive numerical simulations to development of simple empirical formulations for the aid of design.

Kirk (1985) studied resonant heave response of semisubmersible and observed that the usages of square/rectangular shaped columns/pontoons with blunt edges in-place of circular/square/rectangular shaped columns/pontoons with rounded edges (either arc of a circle or ellipse) increases the drag coefficient but reduce the heave response. Furthermore, he observed that the non-linear drag force depends on column sizing and draft of the structure.

Later, van Santen (1995) proposed simple empirical formulas to compute the heave motion of semisubmersible and his results showed that the heave response depends on natural time period of heave and the submerged depth of pontoons or draft of the semisubmersible and on heave added mass.

Sunil and Mukhopadhyay (1995) reported a detailed parametric study by varying the depth and dimensions of the floaters (i.e. pontoons) of semisubmersible.

The computation of motion response of semisubmersible is critically important for operation, survival and to ensure that exploratory drilling (i.e., the main objective of using semisubmersible) continues with difficult weather and sea conditions, e.g., wave heights and periods. In the literature, some experimental results are available that have been performed on model scale semisubmersibles for prediction of the motions, e.g., Takagi *et al.* (1995) presented detailed model results for all six degrees of freedom and discussed the effect of wave height and wave direction on heave motion, roll and pitch motion. However, their results are restricted to regular waves.

The surge, sway and yaw degrees of motion are important in operational performance of semisubmersible because these do not have restoring force and therefore are critical in unfavorable environmental conditions. In the absence of a restoring force, the motion response gets heavily dependent upon mooring lines and its properties. In this regard, we focus on semisubmersible as a moored floating structure and aim to study the interaction between the semisubmersible and mooring lines. The natural periods of surge, sway and yaw are dependent on the mooring lines and properties of the material of mooring line. The popular choices available for mooring lines are: steel wire, Aramid, polyester, High Modulus Poly Ethylene (HMPE) and chains, etc.

Yilmaz and Incecik (1995) discussed surge response with mooring line damping, without mooring line damping, with thrusters and without thrusters in moderate weather conditions. In their results, for the first two simulations thrusters were not utilized and with the introduction of mooring line damping surge response reduction was found to be 43%. However, for other simulations when thrusters were utilized the surge response was not altered. These results suggest that the thrusters contribute more to the system damping than mooring lines. For extreme weather conditions surge response reduction is around 5-7% with and without thrusters. Although, the thrusters and/or structure's own propeller system - Dynamic Positioning System (DPS) - can be and are used for motion control and maintain an offshore structure's position, they add to system complexity, high initial and operating costs, high chances of running off position by system/power failures, and underwater accidental hazards from thrusters for divers and the ‘Remotely Operated Vehicles (ROVs)’. Hence, a solution based upon mooring lines seems to be a preferred choice for simplicity and economy and DPS seems to be a preferred choice for exact and fast motion response control.

Brown and Mavrakos (1999) presented a comparative study on motion analysis of a structure with options of chain mooring line and wire mooring line at different water depths for the harmonic and bi-harmonic waves using both the time and frequency domains methods for the prediction of maximum tension and mooring line damping. Their model was implemented in Ansys-AQWA**TM for more details see TMAA (2011).

Bowers *et al.* (1997) studied a multivariate, directional environmental force analysis on mooring lines to estimate the return period of mean mooring force.

Maeda *et al.* (2000) reported a time domain analysis on a very large floating structure with unidirectional and bi-directional irregular waves, and their experimental results were compared with theoretical results for vertical displacement and mooring line tension and they showed good agreement. However, it is important to note here that the time domain simulation is computational expensive than frequency domain simulation though it is more accurate. Also, a general simulation model needs to be verified and validated so that it can be applied to various design configurations.

Ye *et al.* (2003) reported coupled dynamic analysis of moored semisubmersible with SCR using Numerical simulation tool Ansys-AQWA**TM. They reported that the SCR and mooring lines have considerable effects on low frequency motions of semisubmersible and these motions have reasonable SCR fatigue damage at touchdown point of riser on seabed, but fatigue damage of SCR near the platform is high. This fatigue damage is due to the responses of semisubmersible in six degrees of freedom.

Hujis (2007) studied the heave and horizontal motions of semisubmersible with catenary mooring and steel catenary risers and observed that the reaction force from motions perpendicular to the plane of riser are in smaller order than the reaction force from motions in the plane of the riser.

Marcio and Celso (2007) reported a study on the behaviour of semisubmersible coupled with the drilling riser with dynamic positioning system and blow out preventer with current and waves.

In general, the mooring line dynamics are studied with Finite Element Analysis (FEA) based methods and rod theory, e.g., Tahar and Kim (2008) presented case studies on classical SPAR with polyester mooring lines and on tensioned buoy with polyester wire and their approach is based on non-linear elastic rod theory.

On similar lines, Song *et al.* (2010) studied the station keeping performance of semisubmersibles using different mooring materials such as HMPE, polyester and steel wires, and concluded that polyester mooring line are better option for deeper water.

Tie-bing *et al.* (2011) presented an experimental investigation on a large volume semisubmersible to establish relationship between air-gap distributions, wave parameters and wave run-up characteristics on the aft to observe response.

Madjid *et al.* (2011) reported an exhaustive code-to-code comparison for hydrodynamic motion of offshore wind turbine mounted on a SPAR platform, i.e. USFOS****TM and HAWC2*****TM, for more details see TMUSFOS (2015) and TMHAWC (2015). They focused on time domain simulations and their results - though computationally expensive with large running time - showed good agreements across code-to-code for motion and tension responses. However, they did not focus on presenting a general simulation model that can be applied to an offshore structure for motion and tension responses and instead focused on specific example and what are the strengths and weaknesses of available software solutions?

Yang *et al.* (2012) discussed the effects of mooring line inertia and damping, coupled dynamics response of truss SPAR in deeper water with mooring line and riser system.

Kurian *et al.* (2013) reported a numerical and experimental study on six columns semisubmersible and showed a good agreement between the results in their restricted settings.

Hujis *et al.* (2014) presented aero-hydro-servo-elastic time domain simulations on tri floater semisubmersible with 5 MW NREL wind turbine using Ansys-AQWA**TM coupled with PHATAS******TM software (for more details see Lindenburg (2012)) to study the wind loads on turbine and wave loads on semisubmersible. Also, in their work the aero-hydro-servo-elastic time domain simulations are compared with uncoupled frequency domain analysis.

In our researches (Domala and Sharma 2019), we have focussed on the design and development of an efficient modular 'Computer Simulation Model (CSM)' for response analysis of a moored semi-submersible. The computer simulation model was designed in two split models (i.e., computational and experimental models) and each of these models consists of various modules. The modules were developed from basic governing equations related to motion and modules are integrated and we aim for a seamless integration. The moored semi-submersible was represented mathematically as six degrees of freedom dynamic system and the coupling effects between the structure and mooring lines were considered. Results of the CSM were utilized to study the surge and sway responses with respect to the horizontal range of mooring lines and showed good validation with the existing experimental results. Presented analyses for utilized to rank different available design choices, e.g. the fibre wires showed minimum steady state response in surge and sway degrees of freedom as compared with the steel wires, but they have large drift as compared with steel wires. Developed CSM can help in detailed analysis of responses and results can be utilized for design and development of new age semi-submersibles for optimum performances for a given set of parameters. However, since it is a modular simulation model, different modules need to be expanded, strengthened and newer modules need to be added to represent real world design examples with all of the linear and nonlinear input parameters of importance.

5.1 Key limitations of the exsisting research on computer simulation model for the response analysis of semi-submersible

From the review of literature, as reported above, we observe that primarily the research on response analysis so far has focussed on either numerical studies or experimental studies both in restricted settings of parameters and focus has been on 'heave', 'pitch' and 'roll' degrees of freedom and less on the other degrees of freedom, e.g. surge, sway and yaw. Also, the relationship between the response of semisubmersible and its dependence on mooring line anchoring position has not been explored in-detail.

In our opinion the focus needs to be on developing a computer simulation model that is built module-by-module with each module having proper governing equations that are solved either analytically or numerically or in combination of the two, is general in its settings of parameters, is implementable in industrially standard software solutions, and is validated and verified with experimental results that are either available in literature or done for validation.

6. Conclusions

We reported meaningful and selective review of the progress made on 'Vortex Induced Vibration

Table 4 Summary of the review, issues and challenges in VIV/VIM

S. No.	Details of the parameter		Importance	Popularity/Focus in research	Possible approaches to address the challenges
1	Re	Low	High	Low	(A) Key challenge is to test at low to medium Re but representing moored structures by using springs along with load cells in the mooring line. This will allow the control of high surge and sway and these 'degrees of freedom' only limits the use of high current velocities.
		Medium	Medium	Low	
		High to very high	Not really important because actual marine structures do not operate in high range	High	
2	Marine Riser/ Structure	Un-moored, towed.	Low	Highly popular. Not representative of the real world scene and environment. But allows high Re.	In addition to (A), mooring lines need to be connected to springs and sensors to control and manage different 'degrees of freedom', primarily surge and sway.
		Moored with current velocity	High	Less popular. Difficult to test with high current speeds.	
3	SoSS	Cylinder	High	High	Square sections need to be investigated because they are used in marine structure and with angles of flow at 0^0 and 45^0, and ensuring proper orientation for in-line and cross flow motions.
		Square/Rectangle (Rounded/Sharp)	Medium	Rare. Not much is known in the context of Marine Structures	
		Ellipse	Low	- do -	
4	Design empirical models		High	Lacks focus	- Empirical predictive models to incorporate key design parameters (i.e., dominant response frequency, range of normalized velocity, variation of the phase angle for force versus displacement, and the response amplitude as a function of the controlling and influencing parameters) need to be developed. - Empirical predictive models to model and predict the dynamic response of fluid–structure interactions using/in terms of parameters (i.e. in-phase and out-of-phase lift coefficients, in-line drag coefficients, correlation lengths, damping coefficients, relative roughness, shear effects, wave velocity, and current velocities, etc.) need to be developed.
5	Numerical simulation model		High	Medium. Computational cost still remains high.	Efficient simulations are possible with closing and termination criteria based upon empirical knowledge base with semi-analytical approaches.
6	Flow control mechanism over the SoSS		High	Lacks focus	Marine structures are geometry dependent and hence significant flow control mechanism can be developed by modifying the geometry. E.g., using group of small squares/cylinders circumferentially in the close vicinity of SoSS.

(VIV)' and 'Vortex Induced Motion (VIM)' of 'Structures of Specific Shapes (SoSS)' subjected to steady uniform flow and of relevance to/in marine structures. We were able to identify and present some of the most important and critical elements of the numerical methods, experimental methods, and physical ideas that contribute in the design and development of modern state of art of VIV/VIM. Our focus and aim were to analyse the existing researches with respect to the application in analyses, design and production of marine structures and the reported reviews and extraction of relevant and implementable information from them had been discussed in detail. Finally, we identified the critical and important issues that exist in the current literature and noted the possible ways to move forward towards tackling them.

Table 4 summarizes the review, issues and challenges in VIV/VIM and some of our own researches are going in these directions.

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Acknowledgements

This research was supported by the internal research grants of IIT Madras through research scheme: OE14D213 for Mr. P. Sahoo.

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QM

Nomenclature

CR = Catenary Riser,
CoG= Centre of gravity with respect to water line,
CSM = Computer Simulation Model,
DDS = Deep draft Semi-submersible,
dof = Degree of Freedom,
DPS = Dynamic Positioning System,
ROVs = Remotly Operated Vehicles,
DR = Drilling Riser,
FEA = Finite Element Analysis,
FSI = Fluid Structure Interaction,
HMPE = High Modulus polyethylene,
KC = Keulegan–Carpenter,
Re = Reynolds Number,
RMS = Root Mean Square,
SCR = Steel Catenary Riser,
SSBFH = Stainless Steel Braided Flexible Steel,
TLP = Tension Leg Platform,
VIM = Vortex Induced Motion and,
VIV = Vortex Induced Vibration,
A_Y^* = Amplitude number of riser in y-direction,
A_X^* = Amplitude number of riser in y-direction,
A_{YRMS}^* = Root Mean Square (RMS) amplitude number of semi-submersible in sway dof,
A_{YRMS} = Root Mean Square (RMS) amplitude of the vibrating cylinder in sway dof,
D = Diameter of the marine riser (i.e. cylinder) in mm,
f_{st} = vortex/Strouhal shedding frequency,
H_s = Submerged height of the semi-submersible column,
L = The length of string,
m = The effective mass per unit length of string including added mass,
m^* or m_s^* = The mass ratio of cylinder or string,
S_t = Strouhal number,
T = Tension in the string (i.e. Drilling riser),
T_p = Time period
U = Current velocity in m/s,
U_r or U_{rs} = Reduced velocity,
U_m = velocity amplitude of flow that oscillates,
ρ = Density of fluid,
ζ = Damping ratio,

δ_r = Strouhal reduced damping,

μ = Dynamic viscosity of water.