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Passive Control of Vortex-Induced Vibrations: An Overview

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Abstract: Vortex-Induced Vibration (VIV) is a possible phenomenon in situations where a bluff body interacts with a fluid flow. There are many potential areas where this phenomenon could be observed such as in heat exchanger tube bundles, marine structures, bridges, power transmission lines etc. Due to VIV, the structures could be subjected to very large transverse vibrations which may lead to their fatigue failure. Hence, controlling vortex-induced vibrations or if possible, suppressing them is of paramount importance in practical situations, particularly in a situation like marine deep water environment where the fault diagnosis and repair would be extremely difficult. This could be achieved by passive and active control means. In this paper, a review of the passive control of VIV through various means is presented particularly emphasizing some recent inventions patented in this area. The review indicates that, in practical applications especially in marine engineering situations, passive control measures such as employing a streamline fairing or a helical strake, prolong the life of offshore structures by protecting them from vortex-induced vibrations. The paper includes recent patents on this topic and concludes with a note on the current and future developments expected in the passive control of VIV.

Keywords: Vortex-induced vibrations, passive control, damping, streamlining, add-on device, surface modification, boundary layer control, control cylinder.

1. INTRODUCTION

Flow-Induced Vibration (FIV) is a phenomenon arising out of fluid-structure interaction. Not all structures are subjected to flow-induced vibrations. Generally, ‘bluff’ structures from which flow separates from a wider section of the body tend to experience such vibrations when they are exposed to a fluid flow. Most of the practically used structures are bluff in nature (eg., bridges, buildings, heat exchangers tubes, cooling towers, aircraft control surfaces etc.). Primarily, these structures are meant to resist loads, contain fluid flow or to provide heat transfer surfaces and hence, usually they are not aerodynamically stream-lined at the design stage. As a consequence, as mentioned earlier, if they are sufficiently flexible and light, they could be subjected to flow-induced vibrations otherwise called fluid-elastic excitations. These vibrations could be some times large enough to cause structural damage and catastrophe. Particularly in structures like buildings (inhabited by humans), occurrence of these vibrations could cause alarming concern to public comfort and safety. Hence, reduction of these vibrations is fundamentally important from practical point of view. In this paper, a selective review of various aerodynamic passive control measures which could be adopted to reduce vortex-induced vibrations (most general type of flow-induced vibration) is presented along with some of the relevant inventions patented in this area. Also, it is pointed out that, this review is mostly focused on VIV control in marine applications.

Four classes of FIV are commonly identified, viz., vortex-induced vibrations, galloping, flutter and buffeting. Mechanism of vortex-induced vibration is discussed in detail in Section 2. Galloping is a fluid-elastic self-excited phenomenon characterized by low frequency, large amplitude vibrations. This kind of structural instability occurs mainly in the direction normal to the flow direction with a continuous increase of amplitude with flow velocity. This phenomenon was first noted in ice-coated power transmission lines subjected to strong winds. Even though very similar to galloping, flutter exhibits coupled modes of vibration and hence, not essentially one-dimensional (unlike galloping). Flutter of aircraft wings and turbo-machinery blades could be cited as examples to the occurrence of this phenomenon. It may be noted that all non-circular sections are prone to galloping and flutter instabilities. Buffeting is basically a kind of excitation induced by turbulence contained in the fluid flow. To cite some examples, this phenomenon could be observed in the wind-induced vibration of buildings and bridges. It may be pointed out that, all these excitation mechanisms are important from practical point of view. However, in this review, the scope of discussion is restricted to the phenomenon of Vortex-Induced Vibrations (VIV) which is seen to be the most common type of flow-induced vibration.

2. VORTEX SHEDDING AND INDUCED VIBRATIONS

When a bluff body is subjected to a fluid flow at sufficiently large Reynolds numbers, the flow separates from a wider section of the body giving rise to periodic vortex shedding from either sides of the body. This alternate vortex shedding characterized by definite periodicity would cause fluctuating pressure forces on the surfaces of the body due to which the body undergoes vibrations, if it is flexibly mounted. In this process, a coupling develops between the oscillating body and the flow field around it. The oscillations would influence the flow field and the flow field in turn would influence the oscillations forming a mutually coupled non-linear oscillatory system. Additional non-linearities could influence the system such as those arising from the variable stiffness and response-dependent structural damping [1].

Fundamentally, the body excitation amplitude is controlled by the flow velocity, fluid and flow properties, dimensions and geometry of the body, damping and also on the orientation of the body to the flow direction. Hence, in general, by controlling one or more of these factors, the flow induced oscillations could be markedly influenced. But, in situations where some of these factors could not be controlled or unpredictable (for example, tall buildings exposed to extreme wind flows) or in situations where these factors are set at certain values to achieve certain other engineering objectives, other controlling measures have to be adopted to contain the flow-induced vibrations within safe limits or to suppress them. Resorting to these measures, particularly passive control strategies require a thorough understanding of the mechanism underlying the process of vortex formation and shedding. Fig. (**1**) illustrates the mechanism of vortex shedding proposed by Gerrard [2]. When a vortex starts growing (say the upper vortex) being fed with vorticity from the respective shear layer, it draws the shear layer on the opposite side across the wake (lower). This drawn shear layer (forming lower vortex) carries fluid with oppositely signed vorticity along with it and thus annihilates and cuts the vorticity supply to

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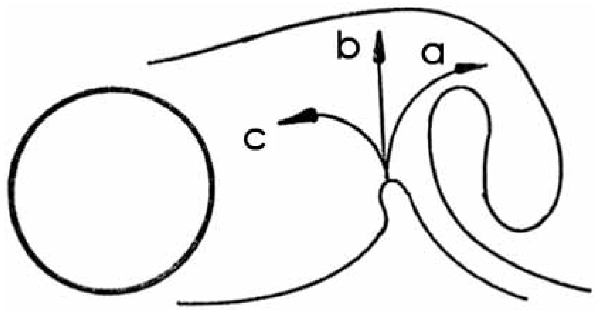


Fig. (1). Mechanism of vortex formation by Gerrard [2]. a,b-fluid entrainment c-reverse flow.

the upper vortex resulting in the shedding of the upper vortex. In the next turn, this lower vortex when grown sufficiently, would pull the upper shear layer across the wake (carrying fluid with oppositely signed vorticity) and due to vorticity annihilation, lower vortex would be shed downstream. This process repeats itself leading to alternate shedding of vortices from either side forming a vortex street downstream of the body. Thus, two factors are centrally important in the vortex formation and shedding (a) the shear layers should roll up to form vortices of sufficient strength (b) the shear layers should interact closely with each other. If any one of these factors (or both of them) is disabled or disrupted, then, it would prevent proper roll up of shear layers and thus, the vortex shedding phenomenon which would ultimately suppress the Vortex-Induced Vibrations (VIV). Besides the two factors (a) and (b) mentioned above, entrainment of irrotational fluid is found to be necessary for the growth of vortices in addition to rotational fluid supplied by the separated shear layers [3]. Switch of ‘confluence point’ (which marks the region where two entrainment layers coming from opposite sides would meet and interact) from one side of the wake axis to the other has been found to be integrally associated with the phenomenon of vortex shedding [3]. Hence, preventing this switch of confluence point could be expected to suppress vortex shedding. Basically, vortex-induced vibrations could be controlled using passive and active control measures. However, in this paper, the discussion is limited to passive control of VIV. In general, this could be achieved by modifying either the structure or the flow as follows.

3. PASSIVE CONTROL OF VIV

Vortex-Induced Vibrations could be controlled by various passive control means such as by increasing damping, by avoiding resonance, by stream-lining the structural geometry and by providing add-on devices. These commonly adopted measures are discussed in this section.

3.1. By Increasing Damping

One of the means is to increase the reduced damping (Scruton number, k_s) of the fluid-structure system. If the reduced damping exceeds a value of 64, then the peak amplitudes at resonance would come down to within 1% of the cross stream dimension of the body [4]. The Scruton number is given by, $k_s = 2.m.\delta/\rho D^2$, where m is the mass per unit length of the structure, δ is the logarithmic decrement, ρ is the fluid density and D is the cross stream dimension of the body. Hence, reduced damping could be varied by varying either one or more of these parameters. Additionally, motion-dependent fluid damping (viscous damping) could also influence the structural vibratory response quite significantly, which arises out of the viscous shearing of the fluid at the surface of the structure and flow separation [5]. Fluid damping becomes predominant at low reduced velocities $(U/(f.D) < 3.0$, where U is the approach flow velocity and ‘f’ is the structural natural frequency).

To weaken or even to suppress VIV, higher damping could be introduced by utilizing scrapings of materials having high internal damping such as visco-elastic materials between structural members or by using external dampers [4]. To cite some of the applications, Stockbridge damper has been used to reduce VIV of power transmission lines [6]. Dulhunty [7] has patented an invention on Stockbridge vibration damper for power lines (Fig. (**2**)). Stockbridge damper provides damping through two mechanisms (a) by exerting a force out-of-phase with the power line vibrations, and (b) by dissipating the vibrational energy through inter-strand friction in the messenger cable. Usually, the messenger cable consists of two or more layers (preferably, three) of helically wound strands of high tensile steel wire [7]. Nhan Nguyen [8] has patented an invention on visco-elastic damper to control the blade vibrations in axial compressors, turbines, or fans without affecting their aerodynamic performance. These could be used as root attachments of turbo-machinery blades which are expected to suppress the bending and torsion mode blade vibrations arising out of unsteady aerodynamic forces during operation. By suppressing the aero-elastic vibrations, they prolong the blade lifetimes and also reduce noise. Visco-elastic dampers are made out of materials such as polymers, rubber, and rubber like materials which provide very high energy dissipation per unit volume. Such dampers could be used to dampen wind-induced excitation of buildings as well [9]. Figure (**3**) typically shows the application of visco-elastic shear damper applied to a building framework. For tall buildings exposed to strong winds, Tuned Liquid Sloshing Damper (TLSD) has been identified as a suitable passive control device to subdue wind-induced dynamic excitations [10, 11]. TLSD mitigate the building vibrations by utilizing the inertia of the liquid column [12] wherein the frequency of the oscillating liquid column is tuned to the structural natural frequency. TLSD could be of two types, shallow-water type and deep-water type [10] and the damping is achieved by means of energy dissipation by the action of internal fluid friction and also from wave breaking action (by employing PVC beds or so).

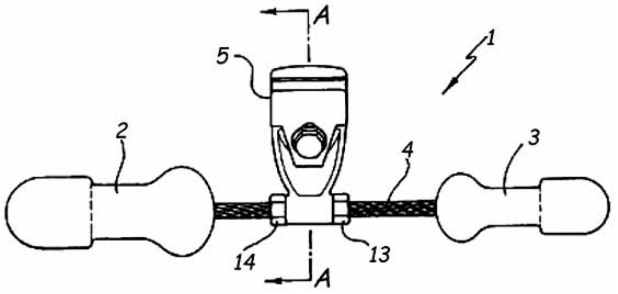


Fig. (2). Stockbridge damper for overhead power lines invented by P.W. Dulhunty [7]. 1-Stockbridge damper, 2&3-damping weights, 4-stranded steel cable, 5-clamp 13&14-claming points on the cable.

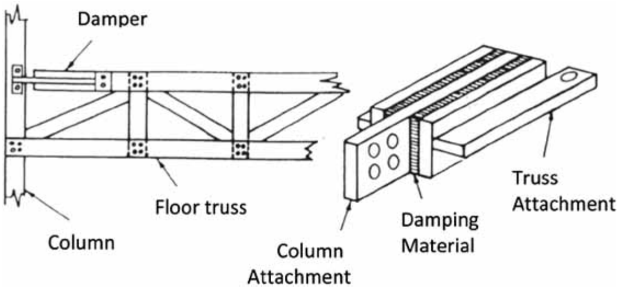


Fig. (3). Visco-elastic shear damper installed in diagonal bracing of building framework [4].

3.2. By Avoiding Resonance

Structural failures due to excessive vibrations usually occur at resonance conditions where the structural natural frequency coincides with the external forcing frequency. In case of VIV, forcing frequency is the frequency of vortex shedding. Hence, avoiding the occurrence of resonance condition is a possible means to reduce the excitation level and to ensure structural safety. This could be achieved by stiffening the structure (by increasing its natural frequency).

3.3. By Stream-Lining the Structural Geometry

As indicated earlier, vortex formation and shedding giving rise to pressure fluctuations is the primary cause for the occurrence of VIV and occurs in structures with bluff sections. Hence, streamlining the structure (reducing the bluffness) is another option for controlling VIV. When vortex shedding is weakened or suppressed, the drag also would be reduced. For streamlining, a tapering of 1:6 is normally provided to the structure in the flow direction. Streamline fairings (also called tear-drop fairings) are one of the effective streamlining devices generally used to mitigate vortex-induced vibrations. They are found to reduce VIV by about 80% with a drag coefficient of about 0.1 to 0.3. They are short, aerofoil shaped sections that swing freely about the body of the structure and they align with the currents to streamline the water flow around the structure so that the forces induced due to vortex shedding are minimized (see Fig. (**4h**). The fairing sections are separated by thrust collars, which also allow the sections to swing. They are widely used in marine environment particularly to curb VIV effects in marine risers and tendons (for tension leg platforms) in deep water situations. Usually, they are designed for a chord to thickness (cylinder diameter) ratio greater than two with a circular leading edge profile. Streamline fairings are also used in applications such as piers [13], oil pipes [14] to reduce vortex-induced vibrations. But, fairings even though effective in reducing vibrations, have a disadvantage that they are expensive (large installation costs), quite large in size and difficult to handle. Also, they could be subjected to a change of geometry due to the buildup of marine growth (such as barnacles) and thus, could lose their streamline shape. There is a possibility of increased surface roughness also due to which the effectiveness of fairings could reduce with service. Streamlining is most effective in cases where the direction of flow is fixed relative to the structure and structure has sufficient stiffness to avoid flutter [4]. But, in practical situations, change in the flow direction could be expected to occur due to which the effectiveness of fairings would be adversely affected, for fixed fairings. Rotatable fairings (adjustable with flow incidence angle) developed later compensates for this lacunae [15].

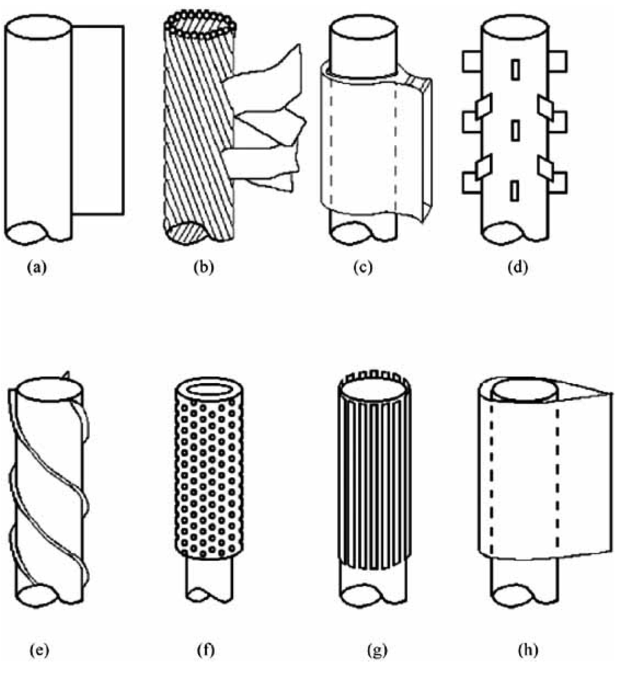


Fig. (4). Passive control devices for suppressing VIV [4, 25].

It is interesting to note that a couple of inventions have been patented developing a variety of streamline fairings mainly for marine applications. Allen and Henning [16] have developed and patented an ultra-short fairing for suppressing VIV in cylindrical marine structures especially suitable for subsea pipe lines, drilling and production risers, tendons for tension leg platforms, legs for traditionally fixed and compliant platforms, cables and other mooring elements for deep water platforms. They have the advantage of generating less drag than longer fairings together with weight reduction. Also, they enable easier marine pipe handling process. Fig. (**5**) shows some preliminary details of ultra-short streamline fairing system applied to a marine riser [16]. The inventors [16] have found that there is a significant reduction in the dynamical characteristics such as drag and the response amplitude when the fairing is attached to the cylinder as shown in Fig. (**6**), for a wide range of Reynolds number. As Fig. (**6**) shows, faired cylinder exhibits only feeble vibrations and also reduced drag.

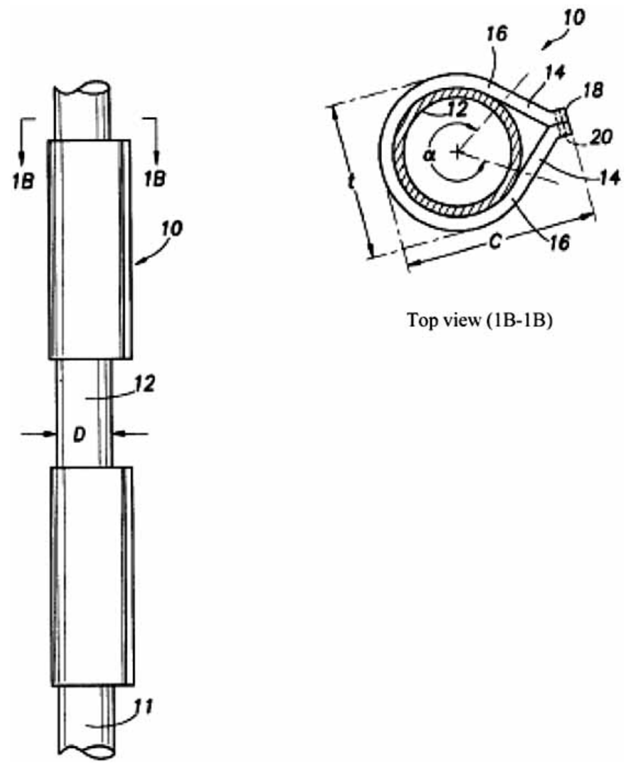


Fig. (5). Ultra-short streamline fairing invented by D.W. Allen and D.L. Henning [16]. Part10-fairing,11-marine riser,12-cylindrical marine element (D-diameter),14-sides of fairing, 16-point of departure of fairing from the cylindrical surface,18-tail ends of fairing connected with fasteners, 20-fasteners; α-angle of fairing

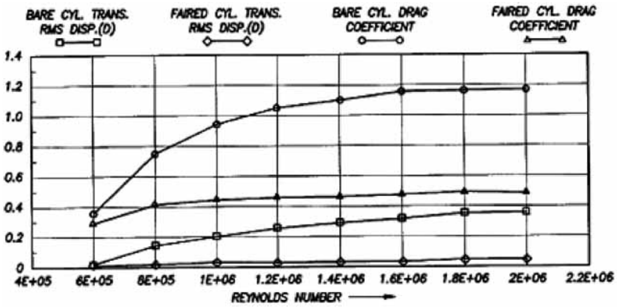
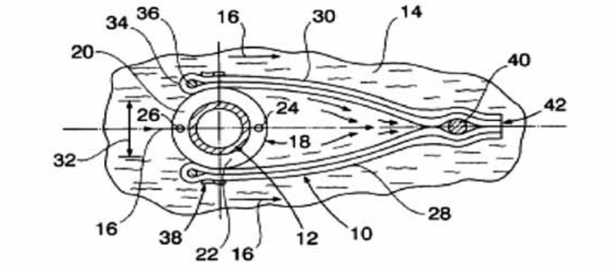
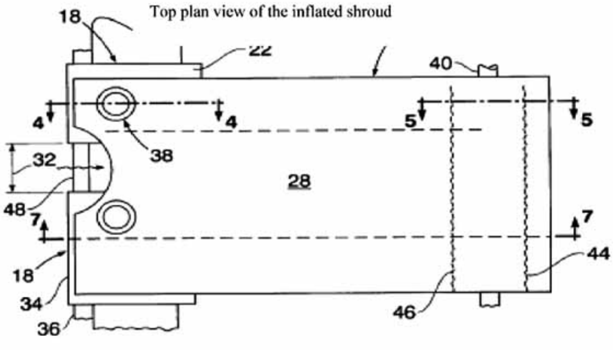


Fig. (6). Vibration suppression due to fairing [16].

A number of ultra-short fairings could be installed as fixed fairings in the marine cylindrical element in different orientations and thus could alleviate vortex-induced vibrations for a wide range of flow angle of attack. This is achieved in another invention of these investigators [17], but adopting an array of staggered fixed fairings along the length of the structure to accommodate a wide range of flow incidence angle. These ultra-short fairings are made with a chord to thickness (cylinder diameter) ratio of about 1.1 to 1.2. Another interesting patented invention is on inflatable fairing (Fig. (**7**)) by Coakley and Knutson [18]. Here, the fairing is made out of flexible plastic sheets and are attached to the marine structure in such a way that, they undergo inflation due to the dynamic pressure of the approach flow achieving the desired streamlined shape in the flow direction and thus weakening vortex shedding and consequently the induced vibrations.



Top plan view of the inflated shroud



Side elevation view of the fairing shroud

Fig. (7). Inflatable vibration reducing fairing invented by Coakley and Knutson [18]. Part 10-fairing shroud,12-vertical marine cylindrical pipe,14-sea water,16-flow direction, 18-hinged bushings, 20&22-cylinder-forming sections hingedly interconnected by a hinge pin 24-hinge pin,26-locking pin, 28&30-flexible components made of fabric material attached to the bushings,34-leading edge,38-fasteners,40-stiffening rod,42-trailing edges, 44&46-parallel spaced stichings (enable attaching the flexible components to the trailing edges),48-rectangular opening at leading edges (34).

As mentioned earlier, rotatable fairings have the advantage that, they could be operated over a wide range of flow angle incidence without the aerodynamic performance getting affected. Generally, short rotatable fairings (low chord to diameter ratio) are very likely to be subjected to an instability called galloping (or fluttering). To compensate for this problem, they could be made sufficiently longer (long tail fairings). But, this would end up in an increase in the overall weight and also the drag. Also, it would become more expensive to install and to maintain. Hence, for practical employment, short rotatable fairings are better, even though they may suffer from the said drawback of galloping instability. This drawback is compensated in the fairing (rotatable) invented by Halvor Lie [15] (Fig. (**8**)). This is made possible by providing an attenuation unit (an energy dissipating pump) for counteracting the possible instabilities (such as galloping) which could set up in the fairings during operation. Streamline fairing is in fact an add-on device. Other commonly used add-on devices are discussed in the following section.

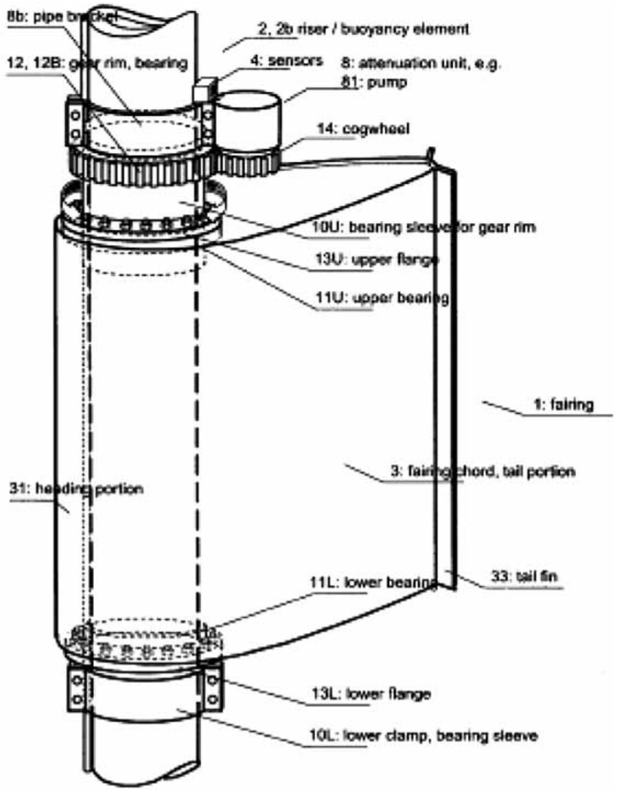


Fig. (8). Rotatable streamline fairing with accessories invented by Halvor Lie [15].

3.4. By Introducing Add-on Devices

Introducing Helical Strakes or ribs is one of the proved and widely used control measures in various industrial and offshore applications to contain VIV. Fig. (**4e**) shows typically how the helical strakes are mounted on to a cylindrical structure; strakes are helically wound on the structural member in a definite fashion. Basically, they adversely affect the shear layer roll up and disrupt the vortex formation and shedding process. Thus, the induced vibrations are curtailed. Sharp-edged helical strakes were invented by Scruton and Walshe [19] which are very widely used for chimney stacks, towers, suspended pipes and cables etc. This

Scruton patent reports that round stacks/chimneys do not require strakes higher than D/8 (D is the diameter of the stack) to eliminate wind-induced oscillations, even when minimum damping is provided. Usually, 3 equi-angularly spaced strakes are provided with a projected height of about 0.1D and a pitch of about 15D (optimum). Fig. (**9**) shows the helical strakes as designed by Scruton and Walshe [19]. Even though employing helical strakes is effective and economical, the disadvantage is that they give rise to higher drag coefficient which would give rise to large inline forces on the structure. Another disadvantage is that the effectiveness of strakes decreases with increasing turbulence intensity of the free stream and also with increasing reduced velocity [3]. Recently, a partial helical strake system has been developed and patented by Allen *et al* [20]. They have adopted a system where strakes are wound only partially on to the circumference of the body (about 50%). One problem which could arise in case of metallic strakes is the structural damage due to corrosion and marine growth build-up (fouling). To take care of these problems, Blair *et al* [21] have invented flexible elastomer wraps for submerged pilings, marine risers and pipes. These are formed with two layers, an inner layer and an outer layer. The outer layer which is directly exposed to the marine environment is embedded with a filler material to inhibit marine growth (biocides). The inner layer is intended to increase the resistance to mechanical damage which is likely to occur during installation or service.

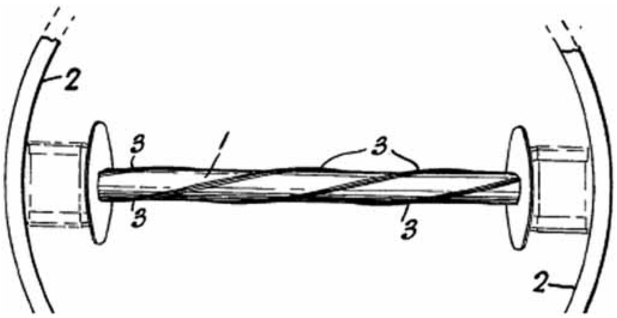


Fig. (9). Helical strakes invented by Scruton and Walshe [19]. 2-Wind tunnel body, 3-helical strakes (equi-angularly spaced and wounded on thecylindrical body).

Introducing perforated shroud is another way to curtail vortex-induced vibrations. Basically, this device is affecting the entrainment layers and thus the vortex shedding phenomenon [3]. Typically, Fig. (**4f**) shows perforated shroud mounted on to a cylindrical body. It consists of a relatively thin metal cylinder that is held off the main cylinder by struts. The outside diameter of the shroud is nearly 1.25D (D is the main cylinder diameter). Total perforated area would come to around 30%-40%. In this connection, the patented invention by Allen and Henning [22] is notable, wherein they have developed a shroud having a number of perforations, partially encircling the main cylindrical structure (Fig. (**10**)). Normally, perforations could be of 0.5 inch hole size. The extent of encirclement of shroud on to the main cylinder could vary from 45% to 55%. The main advantage of perforated shroud (with circular holes) is the lower drag it contributes [23]. A modified version of shrouds called ‘axial slats’ Fig. (**4g**) are also effectively used for reducing VIV in marine structures. The slat shroud outside diameter is generally kept at nearly 1.3D (D is the main cylinder diameter) with 40% percentage of open area. When compared to perforated shroud and helical strakes, slats are found to be better performing as a vortex suppression device [23]. The main disadvantage is that it is comparatively more expensive.

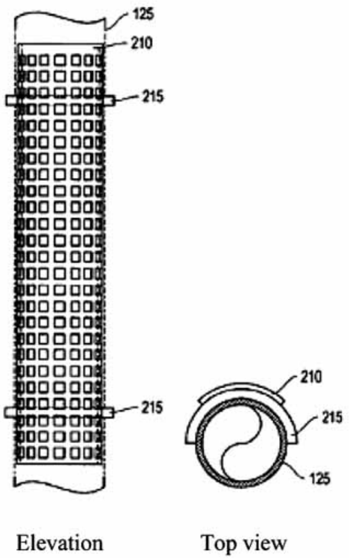
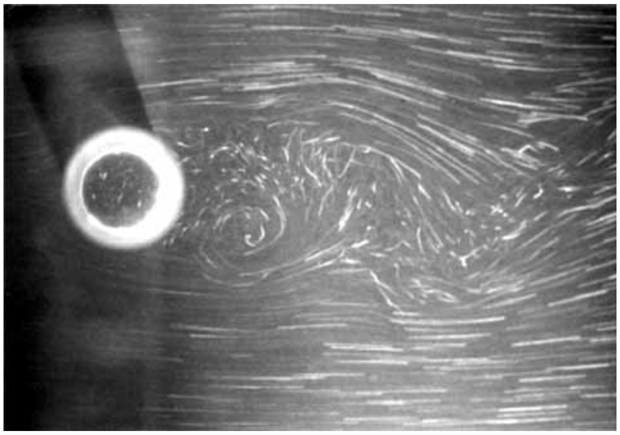


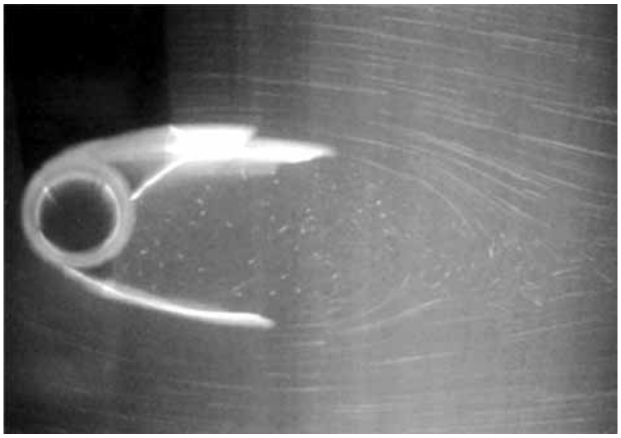
Fig. (10). Partial shroud invented by Allen and Henning [22]. Part125-cylindrical riser, 210-perforated partial shroud, 215-separation ring (separating shroud from riser).

Wake splitter is another efficient way to attenuate VIV in offshore engineering structures Fig. (**4a**). It is a flat plate attached on to the rear end of the body extending along its length. This device prevents the switch of the confluence point, thus act as a near-wake stabilizer controlling VIV [3]. A stream wise length of 4 to 5D is found to be effective for a wake splitter. For stabilizing the near-wake, methods like providing base bleed and introducing slits across the body [3] could also be adopted to curb vortex-excitation. Hwang *et al* [24] have observed that a detached splitter plate downstream of a circular cylinder would significantly reduce vortex-induced vibrations and reduce the drag force, by conducting numerical studies. Even though wake splitters are effective, they suffer from a disadvantage that, they could be used only in those situations where the fluid flow direction does not vary significantly. Flags which are very similar to wake splitters (but flexible) could also be used for VIV suppression. Actually flags are not as effective as wake splitters, but they could be easily wrapped around the cylinder and remain somewhat effective with varying flow directions. However, they are not much used in subsea applications primarily due to the fact that they would eventually get completely wrapped around the cylinder and become ineffective. Another disadvantage is the difficulty and expense in attaching them to the structure, along the length of the structure.

Another cheaper as well as effective method for controlling VIV is to provide ribbons or hair cables Fig. (**4b**). Generally, a ribbon width of 1 to 2D is employed with a length of about 6 to 10D, thickness of 0.05D and spacing of about 1 to 3D. Ribbons (add-on ribbons) made of polyurethane film are utilized in practice. Kwon *et al* [25] have reported results on the reduction of VIV using three ribbons attached 120 degrees apart to a cylindrical pipe, ribbons being self adjusting to the incoming flow direction. Fig. (**11**) typically shows the near-wake flow structures behind the cylinder without and with ribbons. As seen in Fig. (**11b)**, they are found to prevent organized vortex formation in the wake of the cylinder see Fig. (**11a**) also for comparison). This type of vortex suppression device has many advantages over other devices like helical strakes. They include simple design, ease of fabrication, convenience of handling the assembled structure, low maintenance and overall reduction in cost. The authors have also reported that a reduction in the aerodynamic drag could be achieved apart from suppressing VIV.



(a)



(b)

Fig. (11). Flow field behind a cylindrical member (a) without ribbons (b) with ribbons (Kwon *et al* [25]).

To mitigate VIV in structures, guide vanes could be used Fig. (**4c**). It is similar to a stream line fairing but with the trailing edge relatively bluff, also having a shorter body. The design of a typical guide vane would include a plate length (beyond the rear of the main cylinder) of 1D with a lateral separation between trailing edges of 0.9D. Such guide vanes are found to be effective in completely suppressing vortex-induced vibrations [4]. Yet another passive device is an array of spoiler plates mounted on to the cylindrical member Fig. (**4d**). Stansby *et al* [26] have found that spoiler plates reduce resonant vortex excitation by nearly 70%. They disrupt vortex formation and shedding and thus, suppress the induced vibrations. Figure (**12**) shows detailed spoiler plate arrangement typically provided on a cylinder [26]. Edfeldt [27] have invented a pipeline spoiler wherein a plurality of spoilers is placed on a conduit longitudinally and radially at different positions to reduce vortex-induced vibrations and this device was found to prevent upheaval buckling and also minimize future repair work Fig. (**13**). They found that, as spoiler height (above the outside diameter of the pipe, D) increases, the coefficient of drag also increases, whereas, the fluctuating lift force due to vortex shedding decreases once spoiler height crosses a value of 0.05D. In general, spoiler would give rise to considerable drag forces on the structure. For example, providing a spoiler height of about 0.1D would give rise to a drag coefficient of about 2.5. Hence, whenever spoilers are used, the structure has to be designed for greater mechanical strength to bear higher inline forces developed due to drag.

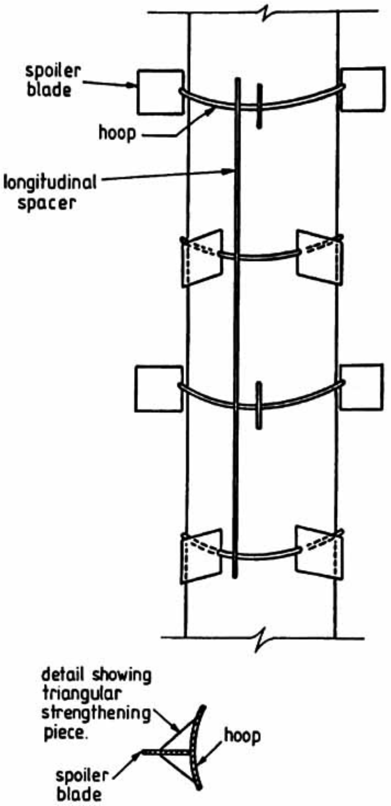


Fig. (12). Spoiler arrangement on a cylinder (Stansby *et al* [26]).

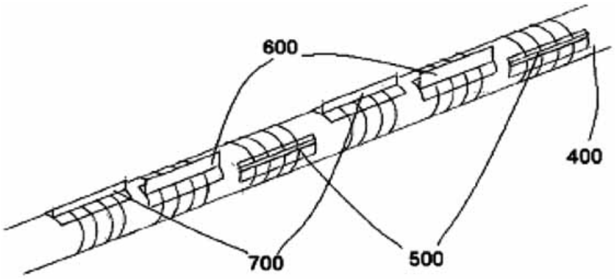


Fig. (13). Submarine Pipeline Spoiler invented by Edfeldt [27].

Part400-pipe line,600-first set of spoilers

500-second set of spoilers at +20o from 600

700-third set of spoilers at -20o from 600

It is interesting to note another add-on device to control VIV, namely the stepped cylinder. This is a modified form of shroud wherein long buoyancy modules (pipes) are attached to the main marine cylinder at intervals thus creating a stepped cylinder. Brooks [28] has reported that no VIV is found to take place in such stepped marine pipes used in deep water applications. Further, Walker and King [29] found that, basically, the span-wise correlation of vortex shedding is suppressed in such pipes and thus, reducing the induced vibrations.

It may be noted that, the degree of reduction in VIV achieved in a marine structural member by installing these add-on devices depends on the amount of system damping and also on the presence of other structural members situated close to it. Helical strakes, perforated shrouds, ribbon cables, spoilers and axial slates could reduce VIV by nearly 70-90% [4]. Streamlined fairings or guide vanes could be expected to reduce vortex-excited response amplitude by 80% or more and also could give more than 50% reduction in the drag.

As mentioned in Section 'Introduction', Vortex-Induced Vibrations occur in many practical applications such as in heat exchanger tube bundles, buildings, bridges, offshore structures etc. Most of the add-on devices discussed above are very relevant particularly to marine engineering applications. For producing hydrocarbons or the like from subterranean deposits which exist under a body of water, the drilling and production equipment have to be invariably subjected to strong water currents and hence, evidently there is a strong possibility of VIV. Equipment exposed to VIV include structures ranging from the smaller tubes of riser system, anchoring tendons, or lateral pipe lines to larger underwater cylinders of the hull of a mini-spar or spar floating production system. A riser system principally consists of cylindrical pipes carrying fluids between a drilling vessel and a well bore and also to guide a drill string to the well bore. For example, in the drilling of a submerged well, a drilling riser usually consists of a main conduit through which the drill is lowered and also through which the drilling mud is circulated from the lower end of the drilling string back to the surface. In addition to the main conduit, usually auxiliary conduits extending parallel to it are also provided to enable additional services. Due to VIV, besides large resonant amplitudes, considerable stresses also would be levied on these structural members critically affecting their performance and life. Especially, for very deep drilling processes, much longer risers are required due to which there is a possibility of bending also, the structure being more slender. The riser could be subjected to alternating stresses induced due to vortex shedding in the cross stream direction and also due to drag force in the stream-wise direction. Typically, a riser pipe with a diameter of 0.3m placed in a water current with a velocity of 1.5 m/s could be subjected to oscillatory amplitudes of about one riser diameter in the cross stream direction with an oscillation frequency of about 1Hz Fig. (**14**). At high velocity conditions, the vibratory amplitudes and also the induced stresses could be alarmingly large and could lead to an unacceptably short fatigue life of the structure. Also, a long riser (typically say 2000 m long) when subjected to strong water currents may act as a string vibrating at several higher harmonics (even 50th oscillatory mode could be excited) further activated by sharp velocity gradient along the riser pipe. Taking in to consideration all these possibilities of structural failure due to VIV, it is always advisable or rather it is a necessity to employ one of the add-on devices discussed above to suppress or at least to subdue the intensity of vibrations due to vortex shedding. This would be of immeasurable help to offshore production systems, where system component failures (such as due to VIV) would bring unacceptably huge financial loses.

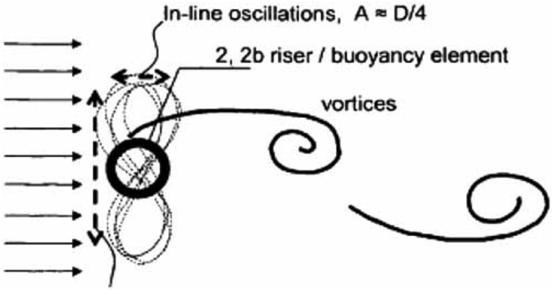


Fig. (14). Modes of oscillation and magnitudes of a typical marine member (Halvor Lie [15]).

4. OTHER PASSIVE CONTROL MEASURES TO REDUCE VIV:

In Section 3, measures such as increasing damping, avoiding resonance, stream-lining the structural geometry and introducing add-on devices have been discussed for controlling VIV. However, there are other passive control means which does not seem to fit these classifications. Hence, these are separately discussed under this section.

4.1. Through body surface modifications

Owen *et al* [30] have reported that providing hemispherical bumps reduces vortex-induced oscillations (up to 47%) and drag (up to 25%) in cylindrical structures. Fig. (**15**) shows the view of the circular cylinder with hemi-spherical bumps. By providing bumps, the flow separation lines are forced to become sinuous. They also found that, the dependence on the angle of incidence could be removed by attaching the bumps in a spiral pattern.

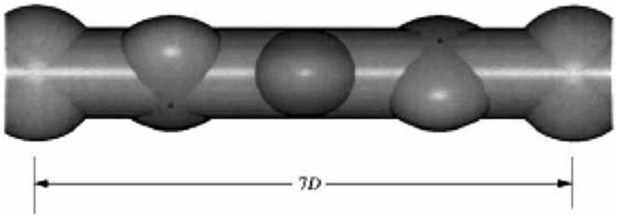


Fig. (15). Circular cylinder fitted with hemi-spherical surface control bumps (Owen *et al.* [30]). Angular separation=45deg, longitudinal pitch of spiral=7D.

Further, the same authors have patented a similar invention [31]. They have found that providing smoothly curved protuberances on to a cylindrical structure (ellipsoidal shape) would significantly reduce drag and vortex-induced vibrations Fig. (**16**). They further suggested that, height of protuberances shall be in the range 0.25D to 0.5D. It is to be noted that, the protuberances are radially distributed (in the range 30deg to 90deg.) so as to provide effectiveness in a wide range of flow direction. The inventors suggest that, more pronounced protuberances (greater height) are required when used in denser liquids to become effective in controlling VIV. The main advantage of providing protuberances is that it is simple and relatively inexpensive. But, application of protuberances would lead to loss of structural geometry which may not be acceptable in some situations. Practical applications of this invention include legs or risers of offshore platforms, underwater cables in sea currents, chimneys in wind flow and wind turbine support tower.

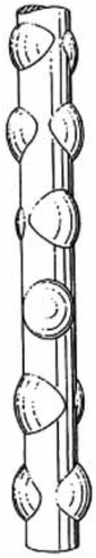
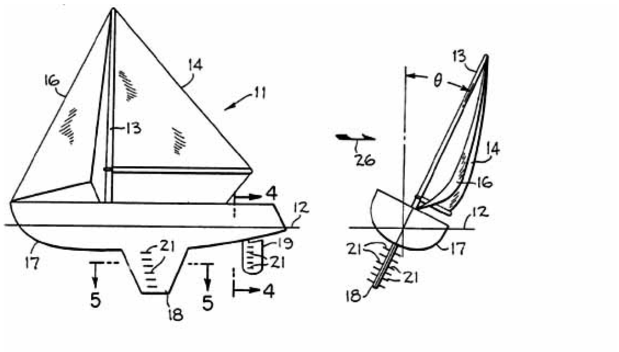


Fig. (16). Smoothly curved protuberances added to a cylinder (Bearman *et al* [31]).

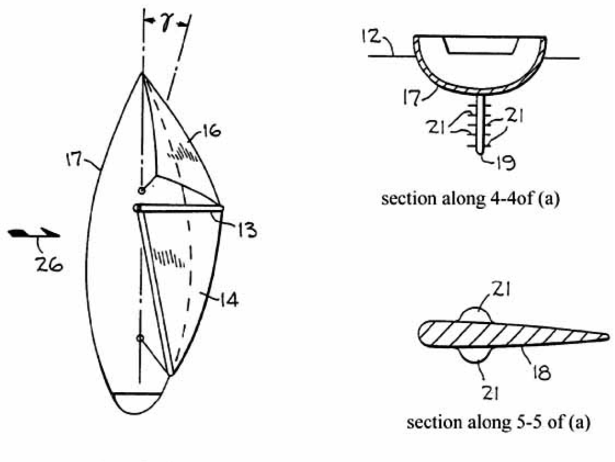
Another interesting method is to introduce wavy separation lines along the span of the body as suggested by Bearman and Owen [32]. They report that vortex shedding could be completely suppressed by this method and the drag could be reduced by at least 30%.

4.2. Through Boundary Layer Control

During 1948-1950, H. D. Taylor of the United Aircraft Corporation discovered that small mixing devices, now known as vortex generators could be used to increase the efficiency of diverging wall diffusers, air foils, axial flow fans, burner mixing, etc. Later, Slemmons [33] have invented a vortex control method for a sailboat keel using vortex generators energizing the boundary layer developed over the body (sailboat keel); Fig. (**17**). The energizing vortices are induced utilizing strips having forward and trailing edges with upper and lower surfaces. The upper and under surfaces intersect at an acute angle at the forward edge of the strip and several vortex generating foils extends from the upper surface of the strip and between the forward and trailing edges thereof. Further to this, Edmund Muehlner [34] has developed an apparatus and method for reducing vortices in the wake of marine members by utilizing the same principle, viz., controlling the boundary layer Fig. (**18**). Reduction of both drag and VIV is achieved by disposing one or more vortex generators on the surface of the body.



(a) Elevation view of sail boat (b) Bow view of the sail boat

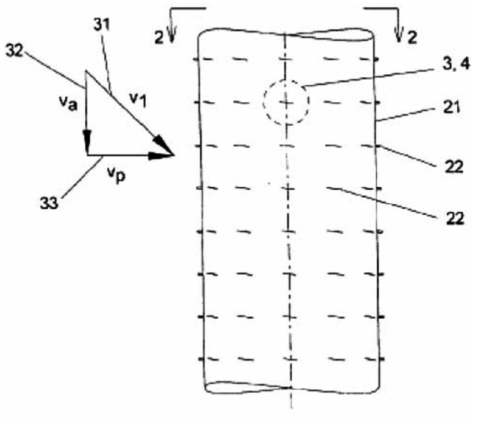


section along 4-4of (a)

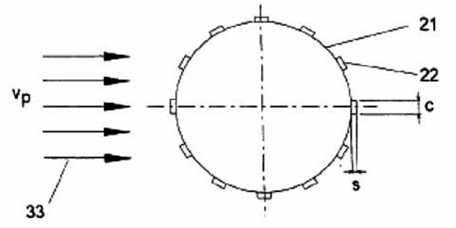
section along 5-5 of (a)

(c) plan view of sail boat

Fig. (17). Sailing Craft Keel and Rudder Flow Modifiers invented by Slemmons [33]). 11-sail boat,12-water surface,13-mast,14-main sail waft, 16-foresail waft, 17-hull,18-boat keel,19-rudder,21-vortex generators or foils, θ-angle of heel γ-leeway angle, 26-wind forces.



Side Elevation



Top View (2-2)

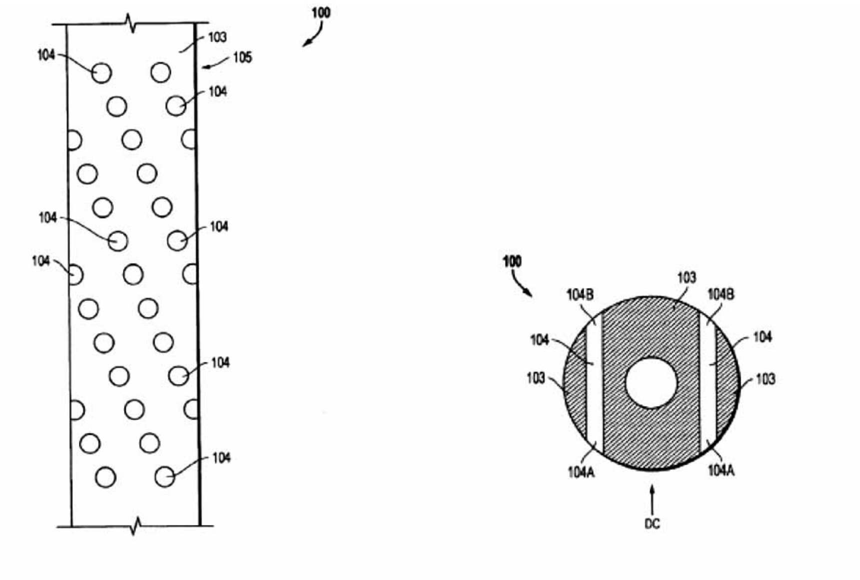
Fig. (18). VIV control Apparatus invented by Edmund Muehlner [34]. Part 21-cylindrical marine member,22-vortex generators,31-flow velocity V1 32-vertical component of V1,33-horizontal component of V1.

The vortex generators are small, wing-like devices placed inclined at a predetermined angle relative to the flow direction [34]. Due to the inclination, each vortex generator produces a small circulation field with an axis of rotation nearly parallel to the flow direction. The circulation field induced by the vortex generators provide additional kinetic energy to the boundary layer due to which flow separation would be delayed further downstream or, in optimal circumstances, is completely avoided. The patent discusses a variety of vortex generator configurations, installation angles, size ratios, and methods and means of operation and also the desirable operational characteristics. In addition to marine applications, vortex generators are commonly found on aircraft, in power plants, and many other technical devices utilizing fluid flows. Typical applications include diverging diffusers, curved air vents, turbine blades, and airfoils.

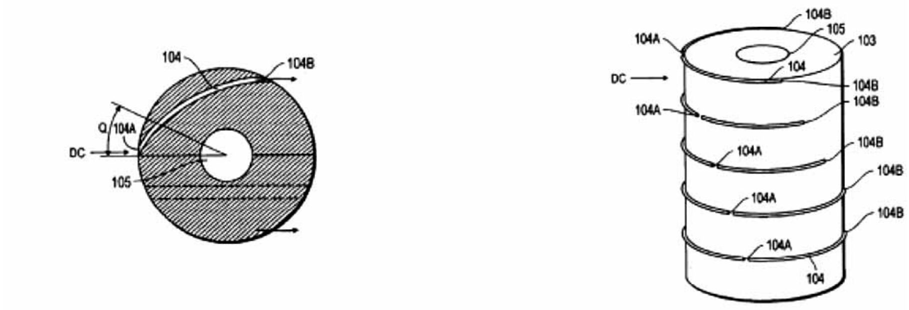
By utilizing the principle of energizing the boundary layer, Shu and Allen [35] have developed and patented an invention to control vortex-excited response of structures Fig. (**19a**). Their method comprises of providing a fluid passage through the structural member (which is to be protected against VIV) with the inlet positioned at the upstream region and outlet positioned at the downstream region. This is found to reduce/control the vortex-induced oscillations, drag, low frequency oscillations due to the action of random waves and low frequency wind-induced resonant vibrations [35]. Fig. (**19b**) shows a typical marine environment in which this invention could be applied, viz., a Tension Leg Platform (TLP).

4.3. By Using Control or Interfering Body

Lesage and Gartshore [36] report that a small circular rod called the 'control rod' placed upstream of two two-dimensional bluff bodies could reduce the drag and the fluctuating side forces due to vortex shedding. Another interesting study made by Strykowski and



(a) side view of riser pipe (b) cross sectional view(fluid passage in line with flow direction DC)



(c) cross sectional view (fluid passage not aligned-with the flow direction DC) (d) fluid passages positioned outside the-buoyancy member

Fig.19 (a). Passive apparatus for VIV control invented by H. Shu and D.W. Allen [35].
Part100, system, 103-buoyancy member,104-fluid passage,104A-flow inlet 104B-flow outlet,105-riser pipe.

Sreenivasan [37] have revealed that a small control cylinder (or secondary cylinder) placed in the wake of a circular cylinder could completely suppress vortex formation by diffusing the concentrated vorticity in the shear layers behind the body. Ajith Kumar and Gowda [38] and Gowda and Ajith Kumar [39] have found that, the flow-induced vibrations of a square cylinder is suppressed due to the interference effects caused by another square cylinder (interfering cylinder) placed in the vicinity of the former at some typical positions, at certain values of reduced velocity. They have found that, for a variety of configurations (relative spacing arrangement between the cylinders), size ratios (between the cylinders) and reduced velocities, the upstream cylinder exhibits varied response characteristics. Figure (**20**) typically shows the features of the vibratory response (the dynamical characteristic) of the upstream cylinder at an interference position ‘A6’ (L/B=1.175, T/B=2.05; L is the longitudinal distance between the centers of cylinders, T is the transverse distance between the cylinder centers and B is the side dimension of the upstream cylinder). In Fig. (**20**), the non-dimensional amplitude of vibration (a/B, where ‘a’ is the vibratory amplitude) is plotted against the reduced velocity U/fB (‘U’ is the flow velocity and ‘f’ is the system natural frequency). It could be observed that except for b/B=0.5, for all other b/B ratios (b is the side dimension of the interfering cylinder, i.e., the downstream cylinder), the vibrations of the upstream cylinder are suppressed. Even though, control of VIV was not the objective of their study, one could infer that this could be a possible means of controlling vortex-induced vibrations. Basically, by introducing interference (using a secondary or interfering cylinder), the near-wake characteristics of the primary cylinder are altered such as by inducing ‘gap flow’ which curbs the possible vibrations of the cylinder. Shao and Wang [40] have used a narrow strip to control the mean and fluctuating forces on a circular cylinder. Their results show that vortex shedding from the cylinder could be suppressed if the strip (with its axis parallel to the cylinder) is installed in an effective zone downstream of the cylinder. Major disadvantage of these methods is that, they are position-specific, i.e., the effectiveness of the control rod or cylinder or strip depends on the position they occupy in the wake of the primary body. So, they may not perform effectively at all possible practical circumstances.

Out of many passive control devices reported in the literature (including patent literature), only a selected few have been discussed here. However, among the devices reviewed, rotatable streamline fairing seems to be the best option typically suited for

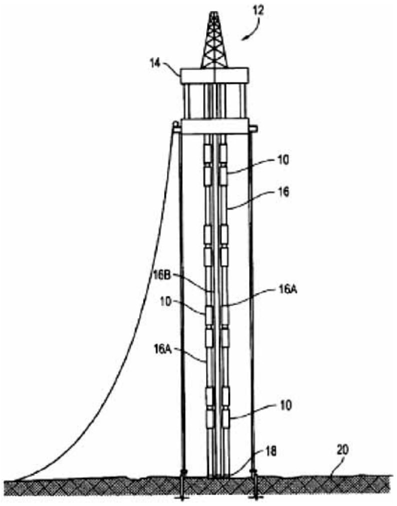


Fig. 19(b). Tension Leg Platform (Shu and Allen [35]). Part10-buoyancy member with fluid passages (energizing boundary layer),12-tension leg platform 14-surface facilities,16-riser pipes,16A-production riser,16B-drilling riser,20-ocean floor.

marine environment except for the higher initial installation cost possibly involved (Fig. (**7**)). Methods like boundary layer control and the use of control cylinder, even though effective in controlling the vortex-induced vibrations, appears to be not easily feasible options mainly because of the increased difficulty in engaging them with the structure to be protected. Surface modifications (such as protuberances) may not always be possible because there could be a need to retain the structural geometry due to design considerations.

5. CURRENT AND FUTURE DEVELOPMENTS

This review reveals that inventors have contributed a variety of passive control devices to suppress VIV, in the fields of buildings, bridges, marine engineering etc. However, it has been observed that, there is a difficulty in achieving a good blend of aerodynamic performance, cost and simplicity. For example, ribbon is very simple in construction and could be easily employed, but the drag coefficient is found to be relatively high. On the other hand, streamline fairing exhibits very good aerodynamic performance, but the initial cost involved is high. Because of this reason, it is felt that, still there is enough scope for the development of much more cost effective, simple and efficient passive control devices. Hence, fresh research attempts are expected in this area.

Another striking aspect noticed is that, almost all of the devices developed so far were for controlling the vortex-induced vibrations of a single structural member, whereas, in practice, structures could exist in groups, for example in heat exchanger tube bundles. It appears that, so far, no contributions have been registered for mitigating VIV in such situations. For structures in groups, the characteristics of excitation induced would be very different from that of single body excitation. At certain combinations of spacing (between the cylinders or structures), reduced velocity, relative size between structures and damping conditions, very large elliptical oscillations could result [41, 42] which could further lead to a possible catastrophe and structural failure. Another important aspect involved in interference excitation is the possible induction of negative aerodynamic damping. With the induction of negative aerodynamic damping, the total system damping could be reduced to a substantially low value magnifying the structural vibratory amplitudes several times. Since the fundamental mechanism of excitation could be very much different for interference excitation, understanding the physics involved, passive control devices are to be developed adopting suitable design strategies. Needless to say, this is a challenging task ahead for the inventors to break through and hopefully, enough contributions could be expected in the future in this area.

ACKNOWLEDGMENT

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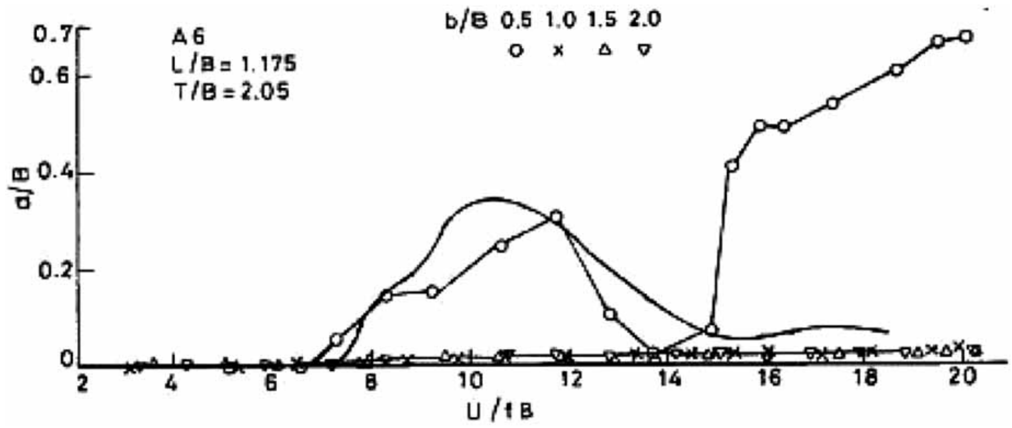

Fig. (20). Vibration suppression due to interference effects [39].

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