称号及び氏名	博士（工学） Rudi Walujo Prastianto	
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論　　文　　名	An Experimental Study on Flow-induced Vibration Characteristics of Flexible Cylinders	
論文審査委員	主査	大塚　耕司
	副査	池田　良穂
	副査	馬場　信弘
	副査	宇都　正太郎

Summary

Flow-induced vibration of structures, in general, is of practical interest to many fields of engineering such as a riser system of offshore structures, heat exchangers, clusters of buildings and stacks, etc. In offshore structures applications, one important aspect is multi-mode vortex-induced vibration (VIV) of flexible slender structures in fluid flow such as a petroleum risers system, especially for deep water application. From structural point of view, one important implication of such multi-mode VIV is the existence of higher harmonic frequencies in the response. Recent researches found a significant contribution of the higher harmonic frequencies to the total fatigue life of the risers.

Another important aspect related to the structure-fluid interaction of flexible structures is the dynamics of free-hanging type of riser, such as the riser system of ocean thermal energy conversion (OTEC) or CO_2 sequestration floating platforms. The riser's dynamic behavior due to the current, obviously, would be different from typical at-sea-floor-terminated riser type of oil or gas platforms, because of, e.g., the free-end condition of the risers.

So far, general characteristics of such phenomena, multi-mode VIV of long and dynamics of the free-hanging flexible cylinders subjected to water flow are not well understood in various parameters. Dynamic response characteristics of such interactive systems are very complex. Several factors influencing on such complexity can be the range of Reynolds number, characteristics of water flow, variability of pretension in the cylinders, aspect ratio, strong interaction between transverse and inline motion, bottom-end condition of the cylinders, etc.

Despite large number of studies dedicated to those problems, there have been no studies

on the VIV and wake-induced vibration (WIV) of free-hanging flexible cantilever cylinders in which the cylinders are allowed to freely oscillate in two-degrees-of-freedom, inline and transverse to the flow with free-end condition taken into account. Therefore, for the design purpose, a better understanding on such dynamics phenomena is definitely required, particularly due to additional specific parameters of the free bottom-end condition (creates three-dimensional effect on the flow around the bottom-end of the cylinder) and bidirectional motion aspects of the cylinders.

The present study is addressed to improve our understanding to such phenomena through simplified experimental models in a laboratory. The interaction between a long flexible riser and sea current is treated as an interaction between a small-long flexible horizontal cylinder and uniform water crossflows as a multi-mode VIV problem. Meanwhile, the VIV and interaction problem of the free-hanging risers with sea current are simplified into an interaction between a single and group of free-hanging flexible cantilevers and uniform water crossflows as VIV and WIV problems, respectively.

Chapter 1 deals with an introduction including the background, objectives, methodology of the study, and brief reviews of some existing related experimental works.

In *Chapter 2*, highly flexible silicon tubes are used as a small-long flexible cylinder which freely vibrates in inline and transverse directions subjected to uniform flows. Generally, by using image processing techniques, the experiment has succeeded to simulate a multi-mode vibration behavior due to VIV, until about 9th mode, even though only with a small-scale model. The same behaviors found in either the large-scale experiments or field measurements, such as lock-in response in transverse direction and inline response frequency of twice the transverse (Strouhal frequency) one can be identified. A new phenomenon of high frequencies response in inline direction is observed for the inclined (by 5^{o}) cylinder case even at a low flow velocity. It can be expected that these high frequencies of 2.5 times the Strouhal frequency, may have a significant contribution to the fatigue life as well as the 3rd higher harmonic frequency in transverse response as mentioned by other researchers.

Chapter 3 describes low-mode dynamics of a free-hanging flexible cylindrical cantilever due to VIV, including the induced hydrodynamic forces and the motion of the cylinder. In order to model the free-hanging riser of an OTEC or CO_2 sequestration platform, a polyvinyl chlorite (PVC) pipe with an aspect ratio (length-to-diameter ratio) of 34.4 is used. New findings are found in hydrodynamic forces acting on and motion of the cylinder. An extreme reduction occurs on the mean drag coefficient in the present case. At the same Reynolds number of about 10,600, the coefficient is very small; approximately 10 times smaller than that of the static cylinder case with similar bottom-end conditions. In addition, at high flow velocities, the 3rd higher harmonic frequencies of the transverse response become predominant that produce quite different motion trajectories of the cylinder compared to the other existing comparable works with two-dimensional bottom-end condition, even same in bidirectional motion aspect. These phenomena are due to the combination effect between the aspect ratio and factor of self-excited bidirectional motion of the cylinder.

Chapter 4 presents wake interference effects on the time-dependent forces and motion of a two-cantilever system in tandem configurations. The same pipe used in single cylinder case (Chapter 3) and another similar PVC pipe are used as test cylinders. As found in the single case, the drag-lift ratios for both the upstream and downstream cylinders are approximately constant at 2 within high reduced velocities. Characteristics of the forces acting on the downstream cylinder in the tandem configurations are completely different from that of the single cylinder case. Contrary to the single case, at high reduced velocity, Ur, ($Ur > 4.0$), the transverse amplitudes of the downstream cylinder in tandem cases are larger than the inline amplitudes for all gap, L_{UD}, values. Remarkable reduction of the response amplitude of the downstream cylinder in inline, A_x, and transverse, A_y, directions are identified if compared to the single cylinder case. As an illustration, for $L_{UD} = 12D$ at $Ur = 6.79$, the A_x and A_y drastically decrease from the single case values by approximately 93 % and 75 %, respectively. The response trajectory patterns of the downstream cylinder in the tandem configurations clearly change with the parameters Ur and L_{UD}. The predominant frequencies in transverse direction as large as their corresponding Strouhal frequencies are responsible to the figure-of-eight response patterns. It is interesting to note that the decrease in transverse amplitude of the downstream cylinder controverts another existing interference experiment carried out with a stationary upstream cylinder. The oscillating upstream cylinder in the present test creates larger wake area that significantly suppresses the motion of the downstream one. Additionally, the oscillation upstream cylinder causes the characteristics of the downstream cylinder are never approaching to that for the single cylinder one; although the gap $L_{UD} > 10D$.

Chapter 5 discusses the results of another two-cantilever system of staggered configurations. For the upstream cylinder, there is similarity on each curve pattern of the total drag and lift coefficients as a function of the Ur at different transverse gap between the cylinders, L_T, even different in magnitude. There is an opposite characteristics between these two coefficients as a function of the Ur at $Ur \geq 5.5$. The $L_T = 2.5D$ becomes “a critical value” at which the forces coefficients starting to jump into the higher values as the L_T increases ($L_T > 2.5D$). More complicated characteristics on the forces coefficients occur on the downstream cylinder. Due to the stronger wake interference at small gaps ($L_T = 1D$, $1.5D$, and $2.0D$), the total drag and lift coefficients characteristics in the domain Ur are definitely different than at larger gaps ($L_T = 2.5D$, $3.5D$, and $4.5D$) and the single cylinder case. Frequency of the drag force is found approximately twice the corresponding lift force frequency at the related Ur for all cases and linearly increases as a function of the Ur. It has been proven that the forces frequencies ratios are constant at a value of 2 and independent of the Ur and L_T parameters within the range used. The response amplitude at bottom-end of the downstream cylinder in inline, A_x, and transverse, A_y, directions linearly increase with the Ur and L_T. Again it can be seen that the influence of the wake interference on the amplitude of A_x and A_y are gradually getting weaker as the L_T increases. Beyond a stagger angle of 41.2^o ($L_T \geq 3.5D$), more than twice the angle in the case with a stationary upstream cylinder, the downstream cylinder similarly behaves as the single cantilever case. The trajectory of the response displacements are strongly dictated by the parameters Ur and L_T. In the present staggered configurations test, as the L_T increases (at the $L_T \geq 4.5D$), the trajectory patterns for all Ur step by step approach the characters of the single cantilever case.

Chapter 6 describes the WIV effects on time-dependent forces and motion for more complex three-cantilever systems of two different triangular configurations. The characteristics of the total drag and lift coefficients are strongly influenced by the *Ur*, with unique characters at three distinct regimes within the *Ur*. For small L_{UD}, at the moderate *Ur*, the configuration with dual downstream cylinders (called as Case B) produces higher total drag and lift coefficients on the downstream cylinders than the opposite configuration of only one downstream cylinder (called as Case A). The existence of such two downstream cylinders cause stronger wake interference between each other and in turn slightly reduce the total drag and lift coefficients of the upstream cylinder. The mean drag coefficients, $C_{D.mean}$, of the upstream cylinders almost linearly increase with the *Ur* and the oscillating drag coefficients are fluctuated as nonlinear functions within the *Ur* for both Case A and Case B. Meanwhile, for the downstream cylinders, the variation on the coefficients much more complicated which is characterized for instance, by a nonlinear relationship between the $C_{D.mean}$ and the *Ur* for small L_{UD} values. From the analysis of the total, mean, and oscillating drag and lift forces, it is found that the influence of the L_{UD} variation on the upstream cylinders is weak, but in contrast strong on the downstream cylinders for both Case A and Case B. For all L_{UD}, at higher *Ur* ($Ur \geq 3.0$), the drag-lift frequency ratios are constantly at 2; thus independent of the parameters of *Ur* and L_{UD} within the range used in the experiment. An exception, at low *Ur* ($Ur < 3.0$), the ratios are larger than factor of 2. Generally, the change on the amplitude of inline motion, A_x, as a function of the *Ur* and L_{UD} is more complicated than that of the Case B. At the $Ur \geq 4.0$, as the L_{UD} increases, the A_x drops and approaching the values of the amplitude of transverse motion, A_y. For the Case A, at $L_{UD} = 10D$, the A_x becomes smaller than that of the A_y values. The Case A produces larger reduction on the motion amplitudes of the downstream cylinder in both inline and transverse directions than the Case B, if compared to the single cylinder case. As an illustration, for $L_{UD} = 10D$ at $Ur = 6.79$, the A_x and A_y drastically decrease from the single case values by approximately 73 % and 51 %, respectively. Meanwhile, for the Case B, the reductions are only 42 % and 25 %, respectively. For both Case A and Case B, because at large L_{UD} and high *Ur* the predominant frequencies in transverse direction are the Strouhal frequencies, so that the amplitudes and trajectories of the motion become smaller and simpler, respectively; no longer approaching the characters found in either the single cylinder or the tandem cases.

Finally, ***Chapter 7*** presents a conclusion of the study in which the general discussion of all results and some new findings are drawn. Important results that relevant for the design process are underlined. Some suggestions for further relevant works to this field are described in the last subsection of this chapter.

審査結果の要旨

本論文は、海底石油／天然ガス開発・海底鉱物資源開発・海洋温度差発電等で用いられるライザー管や、二酸化炭素海洋隔離で用いられる液体 CO2 注入管等、柔軟な円柱形状をした構造物の流れならびに渦による励振特性を、流体力と運動の両面から実験的に研究したものであり、以下のような成果が得られている。

(1)小径のシリコン・チューブを用いて、大水深柔軟ライザー管を模擬した高次モードの励振特性に関する模型実験を行い、流速と渦放出周波数ならびに振動モードの関係について明らかにするとともに、振動周波数が渦放出周波数に同調する”lock-in”現象が生じる条件、さらに振動周波数が渦放出周波数の３倍になる”higher harmonic”現象が生じる条件を示した。

(2)下端がフリーな単独の塩化ビニルパイプを用いて、深層水取水管や液体 CO2 注入管を模擬した基本的な励振特性に関する模型実験を行い、下端がフリーな場合には、円柱全体に働く流体力が両端固定の場合に比べて大幅に減少すること、流速が速い場合には自由下端が８の字運動するモードが支配的となることを示した。

(3)下端がフリーな２本の塩化ビニルパイプを用いて、上流側パイプの流れのかく乱による下流側パイプの励振特性に与える影響に関する模型実験を行い、下流側パイプに働く流体力が単独パイプの場合に比べて大幅に減少すること、下流側のパイプの振動周波数が、上流側の渦放出周波数に支配されることを示した。また、上流側パイプに対して流れに直角方向に下流側パイプを離した場合には、その間隔がパイプ直径の 2.5 倍より大きくなると上流側パイプの影響が急激に減少することを示した。

(4)下端がフリーな３本の塩化ビニルパイプを用いて、２本の上流側パイプの流れのかく乱による１本の下流側パイプの励振特性に与える影響、ならびに１本の上流側パイプのかく乱による２本の下流側パイプの励振特性に与える影響に関する模型実験を行い、前者の場合による流れの遮蔽効果は後者の場合に比べて非常に大きく、下流側パイプの流体力が単独パイプに比べて大きく減少すること、下流側パイプの自由下端が８の字運動しにくくなることを示した。

以上の研究成果は、長大で柔軟なパイプの設計にとって非常に重要である励振特性について多くの有用な情報を提供したものであり、今後ますます重要となる海洋資源開発・二酸化炭素海洋隔離等の技術の発展に寄与するところ大である。また、申請者が自立して研究活動を行うに必要な能力と学識を有することを証したものである。