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SLUG FLOW-INDUCED OSCILLATION IN SUBSEA CATENARY RISER EXPERIENCING VIV

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ABSTRACT

Slug flow appearance in a multiphase-carrying riser with a long tie-back distance and deeper water is inevitable, depending on the operational and environmental conditions. Several state-of-the-art technologies in mitigating the effects of internal slug flows might not be completely effective or cost-efficient. In addition to the slug excitation, the external current flows can also affect the riser structural behavior and integrity by the presence of vortex-induced vibration (VIV). This study aims to investigate and understand the behavior of slug-conveying catenary riser under uniform and random slug excitations, in combination with VIV. The steady-state slugs are considered and modelled by a series of liquid and gas phases flowing at certain rates inside the riser pipe. Each slug unit consists of a slug liquid (oil, water or their mixture) and gas pocket. In the uniform slug flow cases, all slug units have their equal slug liquid lengths. Time-domain simulations are conducted for different slug units of 20*D*, 30*D*, 40*D* and 50*D*, where *D* is the pipe internal diameter, and for different internal flow rates. The non-uniform slug flow case is considered by randomly generating the time-varying slug liquid and unit lengths. Multi-frequency oscillations of the catenary riser are observed, triggered by the transient slug excitations rendering the fundamental vibration mode which is sustained over the ensuing steady-state slugging period. The random slug-induced vibration (SIV) entails larger response amplitudes which are critical from the fatigue life viewpoint, especially when VIV is also accounted for. For riser SIV analysis, only in-plane response is observed; nevertheless, the interaction of riser SIV and VIV generates both in-plane and out-of-plane responses with larger 3-D dynamic responses, deformations and stresses. Such combined SIV and VIV should be specially considered during the riser analysis and design by also taking into consideration the travelling random-like or intermittent slug flows.

INTRODUCTION

Multiphase flows are likely to encounter from a deep-water well where flowlines and risers may experience different flow patterns of multi fluids. A two-phase flow pattern depends on many factors, and largely due to the gas and liquid superficial velocities, as well as the seabed terrain condition.

Slug flow is one of the flow patterns which is not favoring the integrity of the subsea assets. This is mainly because of the fluctuation of forces that may harm the structure from a fatigue life viewpoint. An increased flow velocity to a specific value, can lead to unstable, highly-oscillating systems (Gregor and Paidoussis, 1966). Some studies showed that the combined irregular wave and slug flow excitations could reduce by almost a half of the fatigue life of a flexible riser (Gundersen et al., 2012). Further, the VIV excitation increases the corresponding stresses (Srinil 2011) as well as the amplified mean drag forces (Srinil, 2010; Zanganeh and Srinil, 2016).

In this study, a numerical model is presented to investigate the dynamic response of a slug-conveying steel catenary riser subjected to slug excitations by also considering the VIV effect.

CATENARY RISER AND SLUG FLOW MODELS

A flexible catenary riser with the spring-mass-damper beam elements is considered, based on the riser properties shown in **Table 1**. To exclude the seabed interaction effect, the riser is modelled from its touchdown point until the top end on the sea level as in **Figure 1**. The global origin is located at the top end while the local axis system is positioned at the nodes. OrcaFlex is used for the riser dynamic response analysis whereas Matlab is applied for post-processing and generating random inputs.

Table 1. Riser properties (Chatjigeorgiou, 2017)

Riser Parameters	Values
Pipe Outside Diameter, D_O [mm]	429
Pipe Inner Diameter, D [mm]	385
Young's Modulus [GPa]	207
Steel density [kg/m^3]	7800
Water Depth, *Wd* [m]	1000
Riser Length, *L* [m]	2025
Bottom end offset, x_b [m]	1688

A slug unit concept is considered, consisting of the liquid slug and gas pocket, with liquid film and bubbles within the slug (Chatjigeorgiou, 2017). These components travel in different velocities when the slugging phenomenon occurs, as indicated in **Figure 2a** where u_b, u_l, and u_g are the bubble, liquid and gas velocities, respectively. For the sake of simplicity, the flow may be modelled as an idealized slug flow which consists of liquid slugs and gas pockets traveling at the same velocity (Bordalo *et al.*, 2015) as shown in **Figure 2b**.

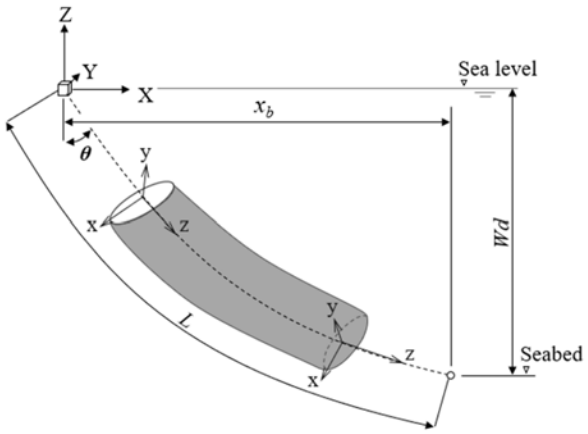

Figure 1. Element model of steel catenary riser

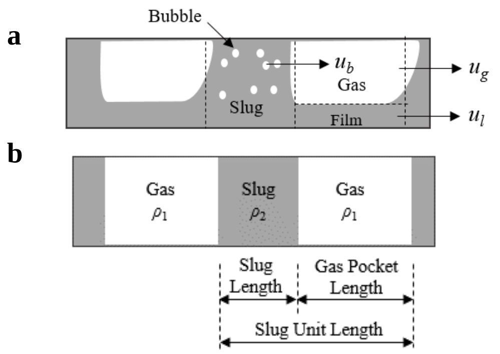

Figure 2. a) Slug unit model, b) Idealized slug unit model

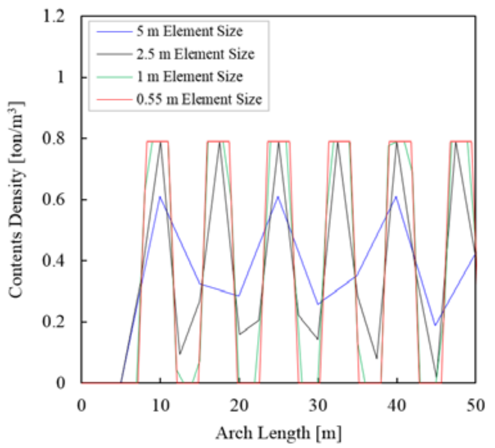

Figure 3. Element length sensitivity check; taken for 20*D* slug unit length with equal liquid slug and gas lengths

The slug length is one of the most important and challenging parameters in investigating the resulting structural responses, as it influences the energy produced by the travelling mass. Hout *et al.* (2003) observed that the slug and Taylor bubble's lengths are laying within 10*D* to 20*D*, through the conducted experiment. Abdulkadir *et al.* (2014) suggested 12*D*, 4*D*, and 8*D* for the slug unit, liquid slug and gas pocket lengths, respectively. In this work, the slug unit length is assumed to be 20*D*-50*D* with equal lengths of liquid slug and gas film regions. Note also that the superficial velocities of the gas and the liquid are assumed to be equal and uniform along the riser length. Internal pressure changes are only due to the hydrostatic losses. The effect of interfacial shear friction forces are disregarded. The liquid and gas densities are taken as 790 and 0.675 kg/m^3, respectively.

The chosen riser finite element size is also important for the numerical convergence purpose: it must also be small enough to accommodate the slug unit length. Sensitivity of the spatial discretization is shown in **Figure 3** which presents the liquid density variation for the first 50 m riser length from the top. To justify the optimal element length, it can be seen that the element size greater than 0.55m fails to capture the spatial variation of the specified density value across the slug unit length. As for the numerical integration, a time step of 0.1 s was found to give a numerical result convergence. To capture the effect of travelling multiphase flows in combination with the riser curvatures, both the centrifugal and Coriolis forces are accounted for.

As for the VIV modelling, the Iwan-Blevins wake oscillator model and associated empirical coefficients in OrcaFlex are considered for simulating the hydrodynamic lift force fluctuation resulting in cross-flow-only VIV. The effect of in-line static drag is also considered, enabling an initial 3-D catenary equilibrium profile. However, the drag magnification is disregarded although its impact can be important depending on system parameters as highlighted in Zanganeh and Srinil (2016). In this study, we consider the SIV-VIV interaction by either varying the current flow velocity for a fixed internal flow rate, and vice versa.

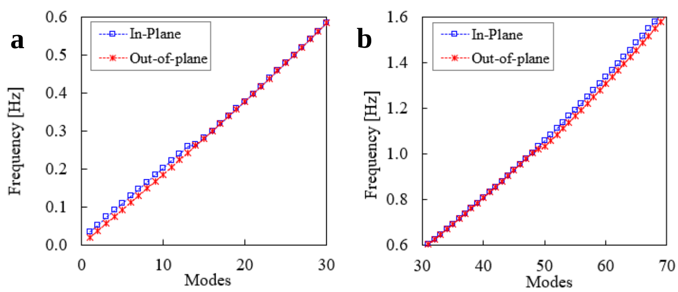

Figure 4. Modal analysis of in-plane and out-of-plane natural frequencies: a) Mode 1 to 30 b) Mode 31-70

UNIFORM SLUG EXCITATION

In investigating SIV, it is necessary to observe the modal frequencies of the riser where resonance is likely to occur. A modal analysis is performed for a partially-filled pipe (Srinil *et al*. 2009), by assuming the fluid with the average density of the gas-liquid occupying the internal space. **Figure 4** compares in-plane/out-of-plane natural frequencies for the first 70 modes.

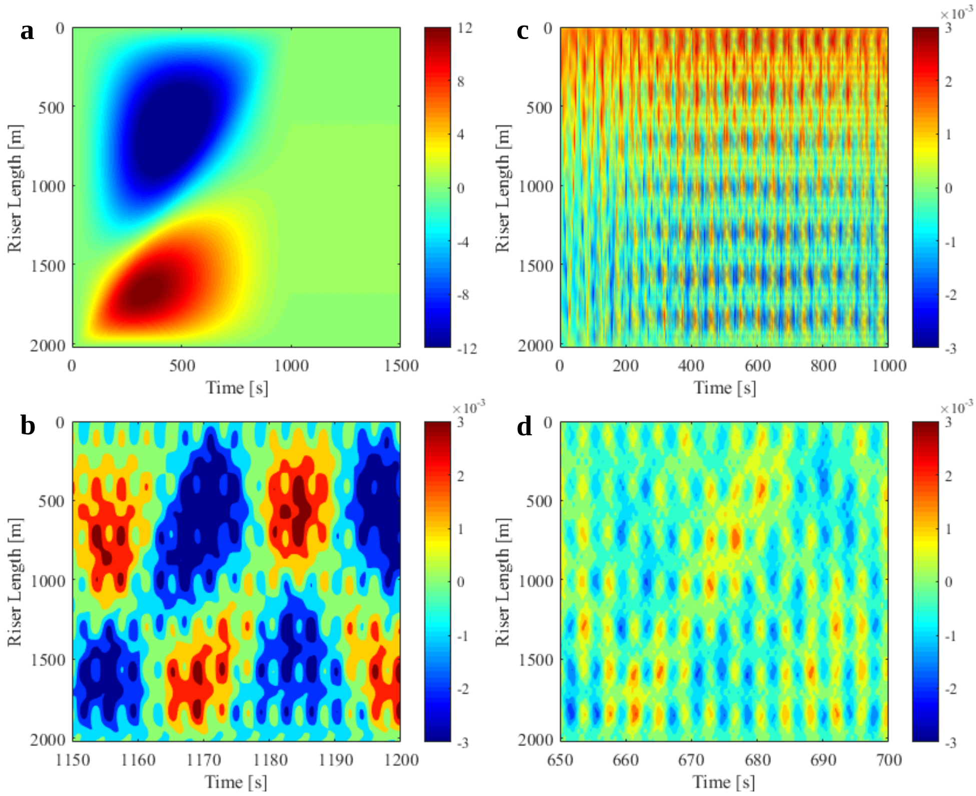

Figure 5. Time-space varying normal response with 20*D* slug unit and equal gas and liquid lengths: a) transient displacements, b) magnified steady-state response, c) riser response after the transient by pre-locating the slugs, d) steady-state focus

The internal flow velocity of 2 m/s is selected for the initial investigation, as well as the slug unit length of 20*D*, with equal liquid slug and gas pocket lengths. The input slug frequency is about 0.26 Hz as shown subsequently in **Figure 7c** obtained through the Fast Fourier Transformation (FFT) analysis of the contents density time-varying value.

Figure 5a and **5b** depict riser normal responses from the initially-emptied pipe, and then contains the travelling slugs and gas pockets. On the other hand, **Figure 5c** and **5d** reveal the response excited by the slug flow which is pre-located prior to the simulation. There is a significant difference between the results of the two numerical settings which seem to be caused by the transient flow effect. Note that the empty pipe scenario is considered from a numerical, rather than practical, perspective as real-life risers are typically installed in a flooded condition. The initial slugs in an empty pipe force the riser to bend outwards the curve in the lower part, that results in two peaks shape as illustrated in **Figure 6a**. The situation does not occur at the pre-located setting, in which it mimics a condition where the system is already in a steady state condition.

An excursion of around 12m (about 30*D*) is found because of the flow initiation process. As seen from **Figure 5b**, there are at least 2 frequencies progressing in the oscillation. **Figure 7a** indicates the oscillation frequencies which are dominated by the lower frequency of 0.035 Hz: this is interestingly the riser first natural frequency nearly resonating with the slug frequency of 0.26 Hz. The associated two-peak modal shape sustains over the simulation time. Such phenomenon agrees with Bordalo *et al.* (2008) who stated that the transient internal flow momentum could excite the riser to oscillate. **Figure 6b** depicts the first in-plane modes of the steel catenary riser, taken from the modal analysis (Srinil et al. 2009), in comparison with **Figure 6a**.

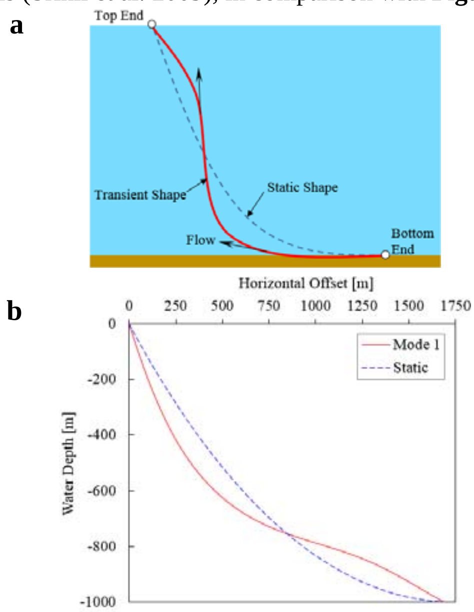

Figure 6. a) Illustration of the slug initiated displacement, b) Fundamental mode (50 times enlarged for clarity)

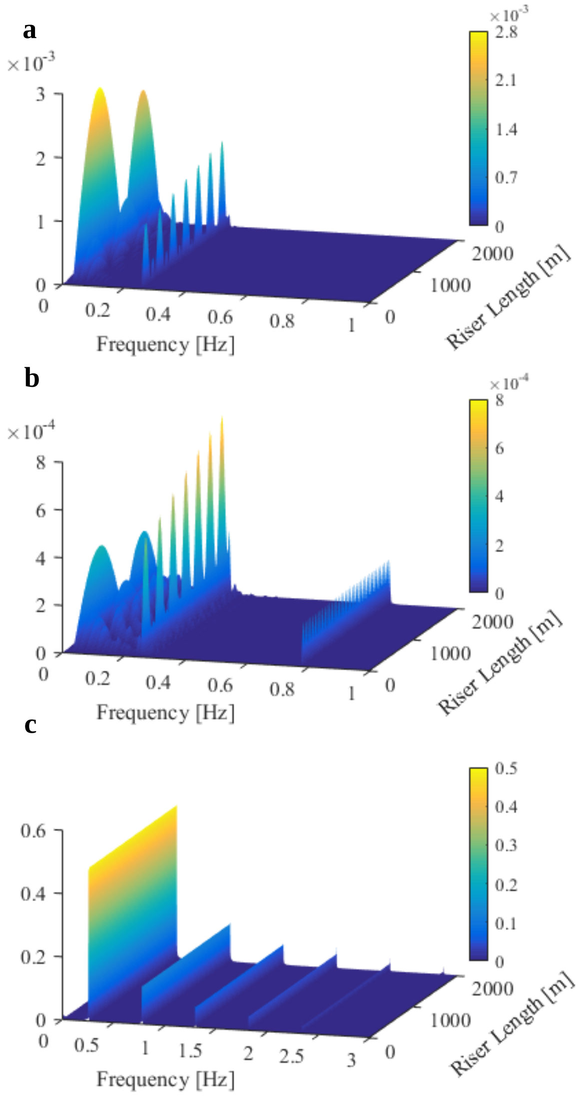

Figure 7. Frequency domain plot of riser response with 20*D* slug unit with equal liquid and gas lengths: a) considering flow initiation, b) pre-located slug setup, c) slug flow excitation frequency

The pre-located slug is presented to prove that the slug initiation may result in the first mode lock-in. **Figure 7b** demonstrates the frequency domain plot of the second setup, and it is notable that the first mode vibration is diminished. The slug direct excitation at 0.26 Hz now becomes the main frequency of the oscillation. Despite its low amplitude, this frequency is close to the 13th modal frequency and causes a resonance on the riser.

RANDOM SLUG EXCITATION

In practice, the slug unit might not be in a uniform size. A time-varying randomness in the slug unit length and liquid slug length is introduced to accommodate the unknown parameters and understand the resulting behaviors of such conditions. This non-uniformity is applied throughout the riser length.

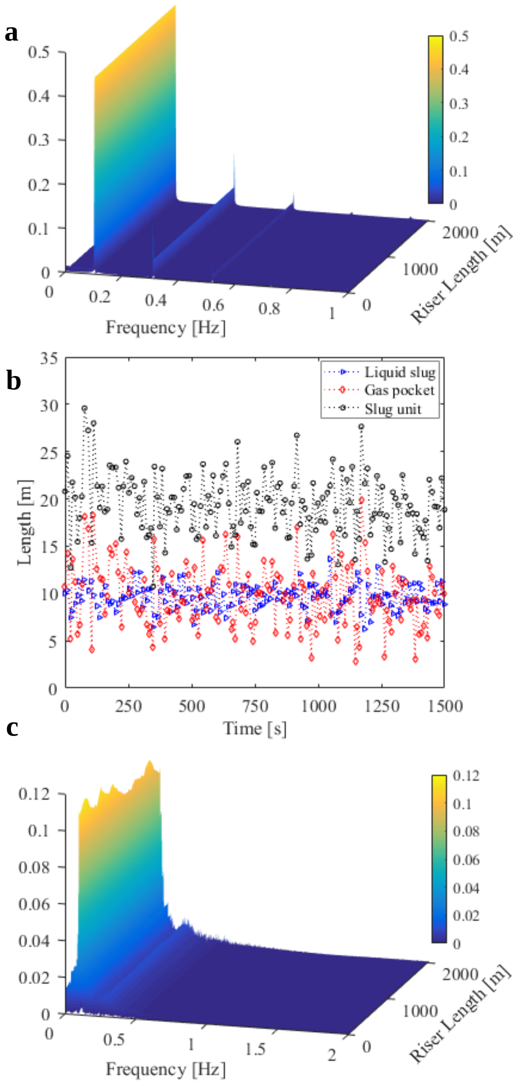

Figure 8. Frequency domain plot of riser response with a) 50*D* slug unit with equal liquid and gas lengths, b) pseudo-random slug unit length and slug lengths, c) the corresponding frequency domain plot for random slug unit and liquid lengths

With a pseudo-random sampling method, mean values of 50*D* and 25*D* of the slug unit length and liquid slug length, respectively, are taken for the investigation which includes the 15% standard deviation for the variation across the time series. Riser response comparison between uniform and non-uniform slug length effects is presented.

Figure 8a shows the slug flow main frequency at 0.1 Hz representing the uniform 50*D* slug unit length and 25*D* liquid slug length flowing at 2 m/s velocity. Meanwhile, the spreading of the slug length over the simulation time from the random number generation is shown in **Figure 8b**. Accordingly, **Figure 8c** exhibits the broadband slug frequencies, as a result of the slug length randomness.

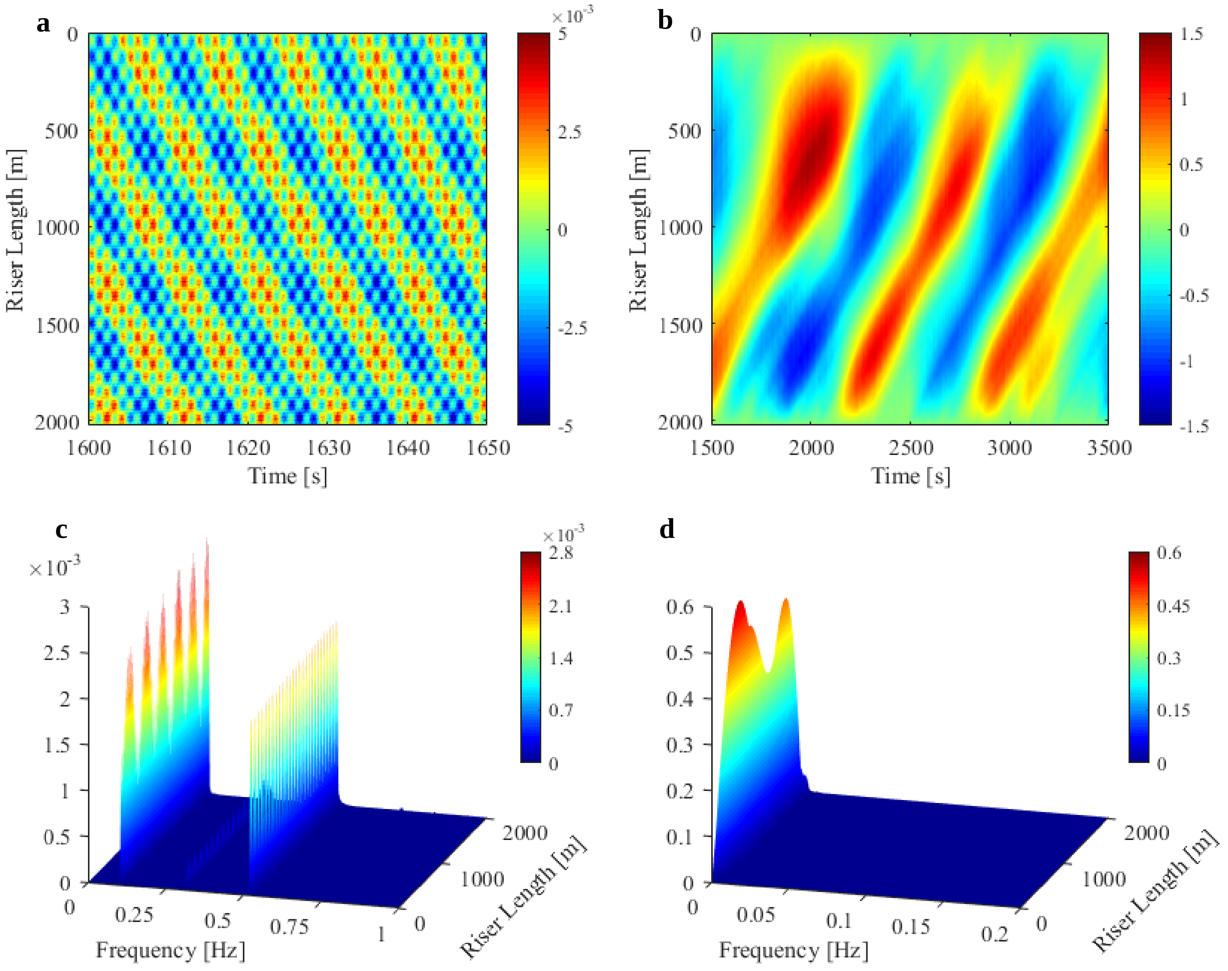

Figure 9. Time-space varying response of catenary riser with a) uniform 50*D* slug unit with equal liquid and gas lengths, b) random slug unit and liquid lengths; the response frequency domain of c) uniform and d) non-uniform slug length cases

Figure 9a and **b** shows the difference on the response from the uniform and non-uniform slug's length. A steady oscillation is found in the uniform slug length case, while much larger amplitude of around 4*D* with slow progression is observed from the non-uniform case.

On these conditions, the slugs are pre-located, that the transient effect does not appear in the time-space domain response plot. **Figure 9c** clearly shows that the main frequency come from the slug flow excitation, in regards to **Figure 8a.**

Meanwhile, the frequency analysis for the non-uniform case depicts that a very low frequency, almost zero, controls the vibration, as shown in **Figure 9d**. This low frequency indicates that randomly deployed slug length leads to temporal displacements on the riser rather than a steady vibration.

COMBINED SIV AND VIV EFFECTS

Apart from the internal flow, the external environmental flow condition will also influence the dynamics of the riser. In this work, the steady drag and vertically uniform current flow is considered. The current is set to flow perpendicular to the riser curvature plane as this could produce the largest-amplitude VIV (Srinil et al. 2018). The mean static drag with a drag coefficient of 1.2 also makes the catenary static profile three-dimensional prior to the oscillation. Attention here is placed on the cross-flow, in-plane, VIV response in conjunction with the in-plane SIV, despite out-of-plane motion (not herein reported) is also observed due to the non-planar static profile and SIV-VIV interaction. Two cases are presented: the catenary riser subject to external flow VIV only and VIV-SIV with ramdon slug flows.

Based on the Strouhal law, the vortex-shedding frequency f_s = St V/D_o is a function of Strouhal number (St), flow velocity (V), and pipe external diameter (D_o). This frequency may excite the structure to vibrate dominantly if it resembles, or being commensurable to, the structural natural frequency, i.e. the lock-in. Accordingly, by assuming St=0.2, the resulting vortex-shedding frequency from the 2 m/s current flow is 1.04 Hz.

The time-space varying response plots in **Figure 10a** and **10b** indicate that the combined current VIV and slug flow excitation generally experiences higher amplitudes than the current-only case. It is also notable that these two cases produce different travelling wave patterns.

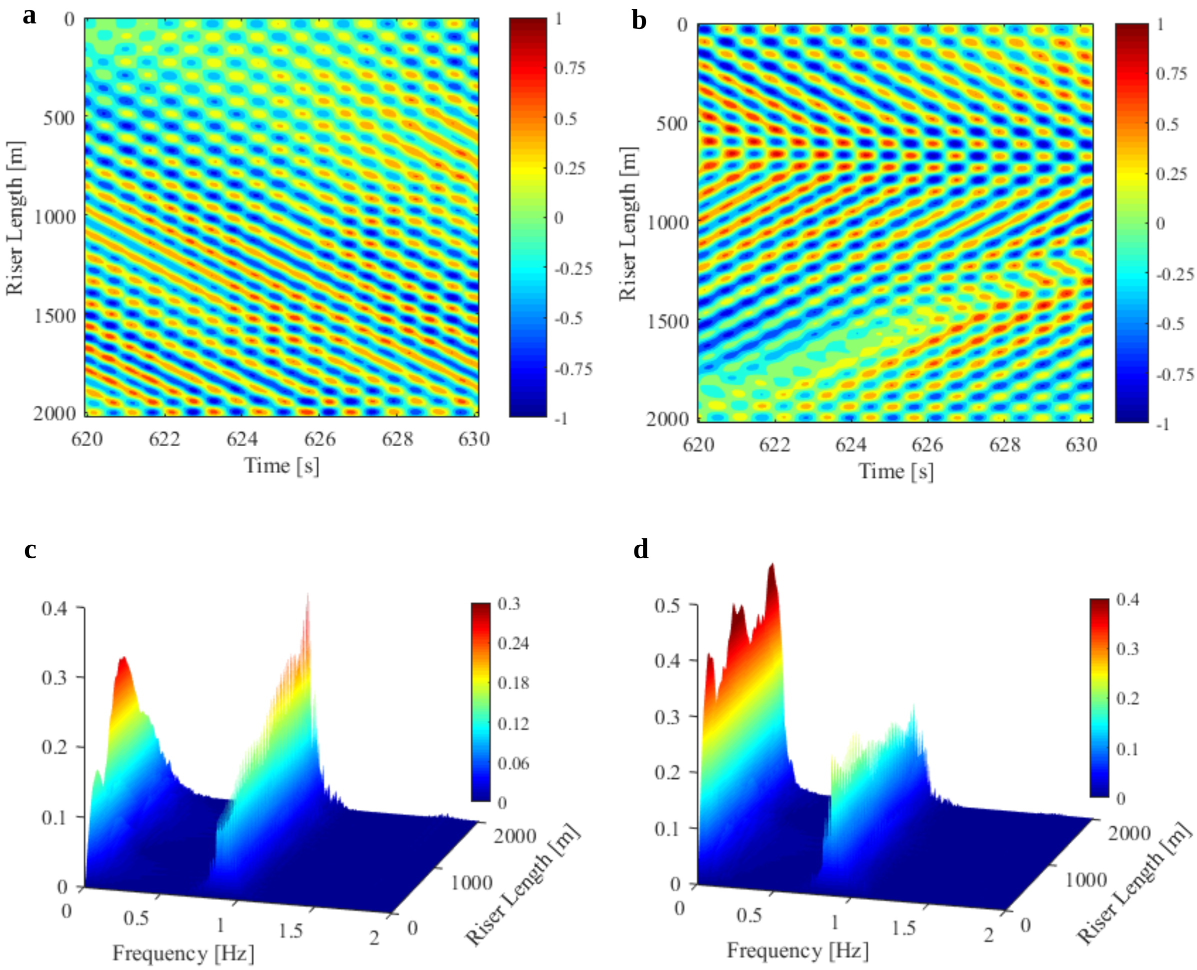

Figure 10. a) Cross-flow time-space varying riser response with 2 m/s current flow involving b) random-length slug unit and liquid; frequency domain of c) VIV-only case and d) combined VIV-SIV with the non-uniform slug length

Figure 10c presents the frequency domain plots in the VIV case. The vortex-shedding frequency seems to excite the fundamental frequency at 0.88 Hz. For the combined VIV-SIV case, the oscillation at 0.88 Hz frequency becomes less powerful than the low frequency oscillation, due to the presence of random slug length excitation, as shown in **Figure 10d.**

EFFECT OF SLUG UNIT LENGTH

Figure 11a depicts the slug-induced and 1st mode vibration amplitude changes with slug unit length increases, adopting the uniform length condition and 2 m/s internal flow velocity. The figure presents the slug unit length in regard to the pipe internal diameter versus describing the amplitude about the pipe outer diameter. The 1st mode vibration seems to attenuate as the slug unit elongates. On the other hand, the increasing slug length leads to a larger amplitude with a relatively gradual increment.

The random slug unit and component length cases suggest distinctive results as summarised in **Figure 11b**. The fundamental modal vibration appears to prevail riser dynamics, being stronger than that observed in the direct slug excitation case. However, the major oscillation is dictated with the low-frequency vibration due to the slug length non-uniformity, as discussed earlier. This response persists more than 10 times of the slugging, with the 1st modal amplitude, although temporally the spatial displacement does not have an obvious pattern of repetition and depends on the slug length randomness.

Considering both analyses for uniform and non-uniform length cases, the amplitudes of the vibrations generally increase with the slug unit length, potentially due to the increasing effects of momentum and Coriolis dynamic forces.

EFFECT OF SLUG FLOW VELOCITY

Slug flows with a uniform 50*D* slug unit length but different velocities are now studied, to understand the qualitative trends with regard to the vibration amplitudes.

Figure 11c indicates the variation in the riser response amplitudes due to SIV according to the variation in the slug flow velocity.

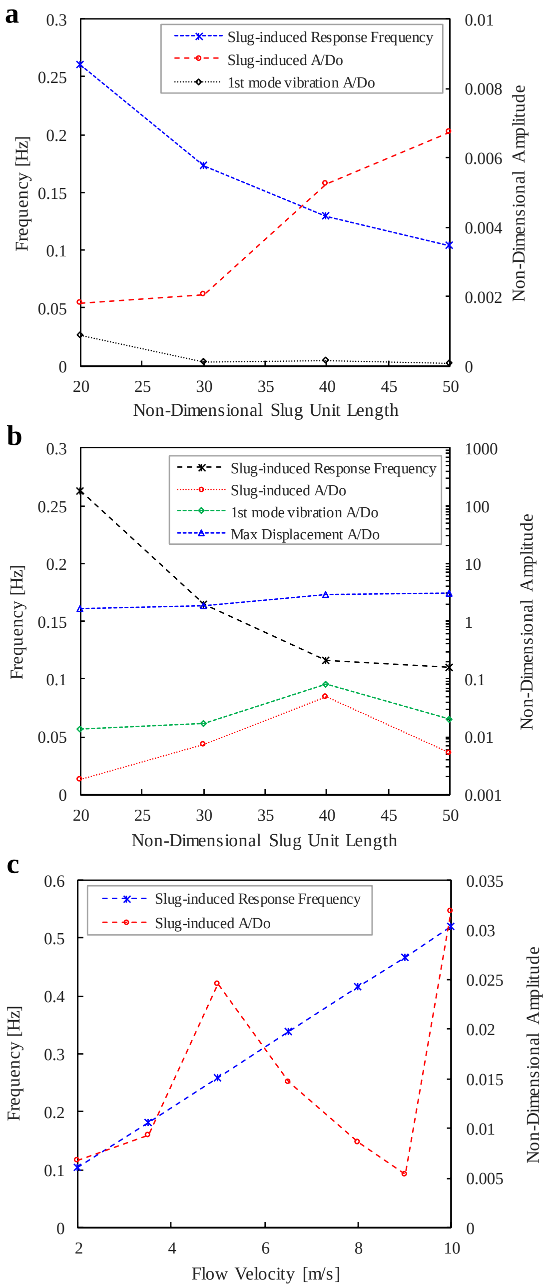

Figure 11. Response amplitude variation with a) uniform slug unit length, b) mean length of the non-uniform slugs, c) internal flow velocity

There is no clear trend to conclude the relationship between the flow velocity and response amplitudes. This is mainly due to the lock-in condition occurring at a particular current velocity or slug frequency: the excitation becomes resonant to the natural frequency and produces a high amplitude.

EFFECT OF CURRENT FLOW VELOCITY

The random slug unit of 50D mean length and 25D mean liquid slug length, flowing at 2 m/s velocity, is used to observe the amplitude variation with the current flow speed.

Figure 12a demonstrates that the mean response values increase with current speed, and there are only slight differences

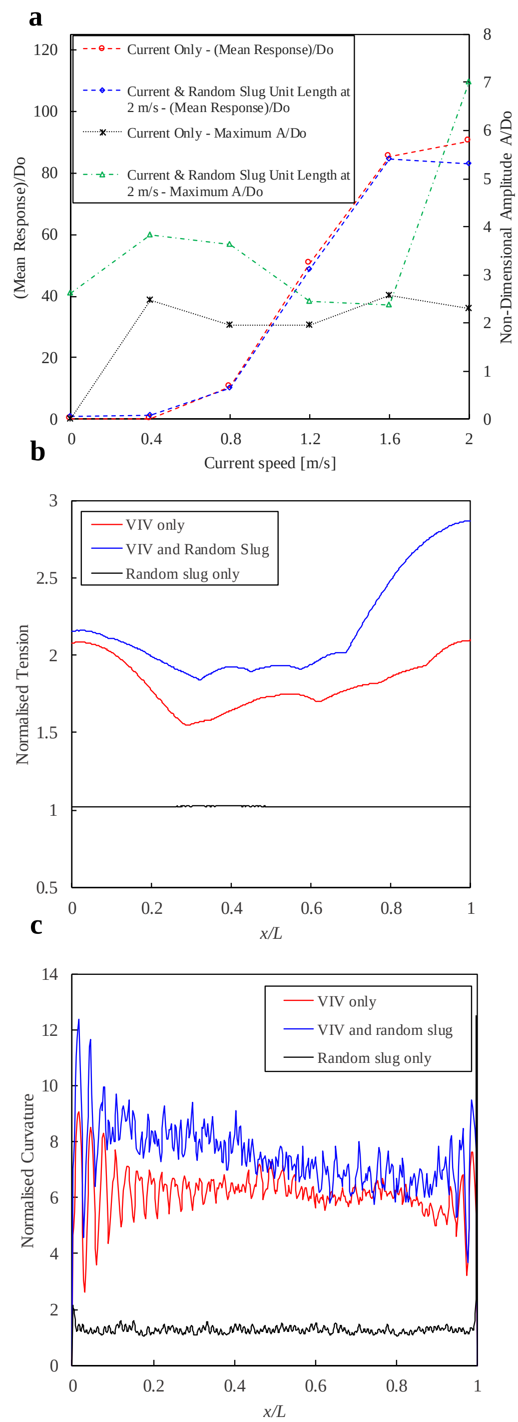

Figure 12. a) Mean and maximum response for VIV only and VIV-SIV cases, with varying current flow speed, b) normalized maximum tension and c) curvature over the length of the riser in VIV and VIV-SIV cases

on the mean values resulting from the combination of slug and VIV excitation. Meanwhile, the VIV-SIV oscillation amplitudes are predominantly higher than the current VIV-only case. Both cases generally reveal their increasing amplitudes with increasing current flow velocity.

The resulting tension force of the riser in different cases are important to describe the potential increasing stresses, and eventually fatigue damage effect. Three cases are presented in **Figure 12b**, in observing the increasing value of the tension force. In this plot, the normalized tension force is the maximum nodal tension force over the simulation time, divided by the static tension at t = 0. There is a small dynamic tension force gained upon the random slug flow excitation, whilst the VIV case creates at least double the force at the static condition on the riser end zones. The combination of VIV and random slug excitation further increases the dynamic tension, almost reaching 3 times the static condition at around the riser bottom end.

Similarly, the curvature which describes the bending stress becomes higher with the combination of VIV and non-uniform slug flow, as shown in **Figure 12b**. The amplitude diagram of the curvature shows oscillation throughout the riser length, because of the worst-scenario, coupled VIV-SIV.

CONCLUSIONS

Dynamic responses of a steel catenary riser subject to slug liquid-gas flow excitations have been numerically investigated. Steady-state and random slug excitations have been considered, in combination with external cross-flow VIV caused by uniform current flows perpendicular to the catenary riser's curvature plane. The steady-state slugs are modelled through a series of liquid-gas phases flowing at certain rates inside the riser pipe. Each slug unit consists of a slug liquid and gas pocket of equal lengths. The random slug flow excitation is considered by randomly generating the time-varying slug liquid and slug unit lengths.

Multi-mode and -frequency oscillations of the catenary riser are observed, depending on the initial transient conditions and slug flow properties. The random SIV with non-uniform slug lengths entails greater response amplitudes which are critical from a riser dynamic fatigue design perspective, especially when VIV is also taken into account. Although SIV entails in-plane response, riser out-of-plane and in-plane vibrations are further generated by the drag-induced three-dimensional profile and combined SIV-VIV interactions amplifying the overall dynamic displacements and (axial/bending) stresses.

The resonant SIV effect increases with the slug unit length, depending on the locked-in vibration mode and the effect from VIV in the case of varying current velocity. Experimental and computational fluid dynamics studies should be further carried out for a curved riser with different catenary, lazy-wave and S-shaped configurations, by investigating the effects of internal multiphase slugging physics in transient, random and steady-state scenarios, and in combination with external current flows leading to the combined VIV-SIV effects on the riser fatigue. These are within the scope of our ongoing studies.

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