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THE OCCURRENCE OF LOCK-IN UNDER HIGHLY SHEARED CONDITIONS

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Experimental results are presented which show that two dimensionless parameters may be used to predict the likelihood of lock-in under sheared flow conditions. One parameter is N_s, the number of potentially responding modes within the vortex-shedding frequency bandwidth generated by the sheared flow. The second, $\Delta V/V_{\mathrm{avr}}$, called the shear parameter in this paper, is the ratio of the change in velocity of the flow over the length of the cylinder to the spatially averaged flow velocity over the length of the cylinder. Unexpected results are shown which reveal that lock-in may occur under highly sheared conditions. The probable cause of the lock-in is that, under highly sheared conditions, the power available to one particular mode may dominate all other modes. This condition is less likely to develop in flows with lower velocity gradients.

1. INTRODUCTION

LOCK-IN BEHAVIOR FOR FLEXIBLE cylinders under uniform flow conditions is a well-documented phenomenon (Griffin & Ramberg 1982). Lock-in has also been observed at the 50th mode for an ocean cable in a weakly sheared flow (Vandiver 1993). There are also many documented cases in which lock-in never occurred (Kennedy & Vandiver 1979; Kim *et al.* 1985). In these cases the number of modes excited by the shear usually exceeded 100. It has been shown that sufficiently large mode numbers and damping lead to infinite cable behavior in which standing waves are not achieved and lock-in is never observed (Vandiver 1993). The nondimensional parameter introduced to predict infinite cable behavior was $n\zeta$, the product of the mode number and the damping ratio for the mode. When this parameter exceeds approximately 1, then infinite cable vibration properties are observed and standing waves and lock-in, are not observed. The accumulated experience has led to a generally held belief that long, flexible cylinders exposed to strongly sheared flow exhibit multiple mode, non-lock-in response behavior.

It was with some surprise that the authors encountered numerous cases with highly sheared flow in which lock-in was observed, and many more cases in which moderately sheared flow did not lead to lock-in behavior. In this paper these experimental results

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are described and two dimensionless parameters are discussed which may be used to predict lock-in behavior. The first dimensionless parameter is N_s, the number of potentially responding modes within the vortex-shedding frequency bandwidth resulting from the sheared flow. The second, $\Delta V/V_{avr}$, is called the shear parameter in this paper. It is the ratio of the change in velocity of the flow over the length of the cylinder to the spatially averaged flow velocity over the length of the cylinder.

2. DESCRIPTION OF EXPERIMENTS

Allen *et al.* (1994) conducted a series of 787 vortex-induced vibration tests of flexible cylinders in water in a circulating channel with a test-section 3·66 meters deep. The flow was shaped by several screens to provide uniform flow or a variety of sheared flows. Beneath the floor of the channel there was a deep pit filled with water, as shown in Figure 1. Cylinders with total lengths of up to 17·7 m were deployed in the channel and pit. The excitation came from the upper 3·66 m of the cylinder exposed to the flow. The water surrounding the cable in the pit provided only hydrodynamic damping. A variety of tensioned cylinders were tested, including steel, aluminum and plastic tubes, and steel wire. The cylinders varied from 0·00635 to 0·02667 m in diameter, and Reynolds numbers varied from 500 to 54 000. Cylinder mass ratios varied from 1·1 to 7·2. Table 1 shows the cylinder properties.

Cylinder motion was measured by bi-axial accelerometers mounted at locations which varied, depending on the cylinder length and expected responding vibration modes. Usually one accelerometer was mounted in the still water region near the bottom of the cylinder and another in the moving water region near the top. Current profiles were measured and mean flow speed was regulated by adjusting the r.p.m. of the ship propeller which drove the circulation in the closed circuit channel. Tension was measured by a cell at the top end of the cylinder. Tension was adjustable to make it possible to control the natural frequencies and modal spacing.

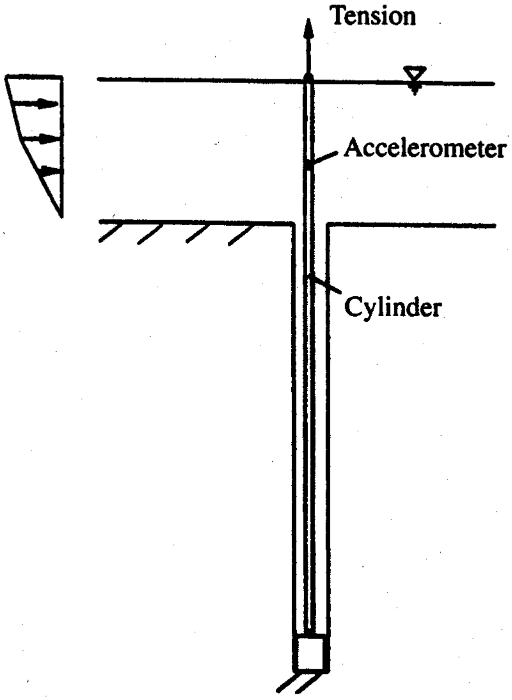


Figure 1. Model test configuration.

TABLE 1
Test cylinder properties

Material	Outside diameter, inches (mm)	Inside diameter, inches (mm)	Mass ratio ($m/\rho D^2$)
ABS tube*	0·625 (15·9)	0·5 (12·7)	1·086
ABS tube*	1·125 (28·6)	1·0 (25·4)	0·832
ABS tube**	0·625 (15·9)	0·5 (12·7)	0·799
Steel wire (solid)	0·231 (5.87)	0·0	6·167
Aluminum tube I*	0·25 (6·35)	0·152 (3·86)	1·718
Aluminum tube II*	0·375 (9·53)	0·305 (7·75)	1·286
Aluminum tube III*	0·625 (15·9)	0·555 (14·1)	1·098
Steel tube*	1·05 (26.7)	0·742 (18·8)	3·51
Steel tube*	1·375 (34·9)	1·00 (25·4)	3·35

* Flooded with fresh water
** Flooded with high concentration salt water

3. EXPERIMENTAL RESULTS

3.1. UNIFORM FLOW TESTS

Many tests were conducted with uniform flow over the upper portion of the cylinder. A movable shroud allowed the excitation length to be varied from 0 to 3·67 m. The remaining length of the cylinder inside the shroud and in the pit was exposed to still-water hydrodynamic damping. The still water region was not included in the computation of the shear parameter, $\Delta V/V_{avr}$. The 489 uniform flow tests were dominated, not surprisingly, by single-mode lock-in response. The criterion used to identify single-mode dominance was that the acceleration response spectrum of the cylinder had to be dominated by a single resonant mode peak. No secondary modal peak could exceed 5% of the magnitude of the dominant one.

3.2. SHEARED FLOW TESTS

In all, 298 sheared flow cases were evaluated. Shear flow profiles were generated which had shear parameters of approximately 0·6 to 1·6. The sheared flow profiles were approximately linear. Depending on the material and the tension for the cylinder being tested, the number of modes which could potentially be excited by vortex shedding varied from 1 to 20. The results revealed that for some cases lock-in occurred when the shear was quite high.

The results are most easily shown in a two-dimensional map of N_s versus $\Delta V/V_{avr}$, as shown in Figure 2. On this figure there is a solid line, forming a crude "U" shape. Outside and below the "U" is a region in which the dominant behavior is single-mode lock-in. Inside of the "U" is a region of multiple-mode, non-lock-in, response behavior. This "U"-shaped curve is a probabilistic boundary, not a sharp divide in the expected behavior. The observations from the 787 experimental runs and prior knowledge from experiments described in the literature were used to establish the location of the "U" such that, inside of the "U", multi-mode, non-lock-in response is highly probable, and outside of the "U", single-mode-dominated lock-in is highly probable. As more data is gathered, confidence in the exact location of the "U" will grow.

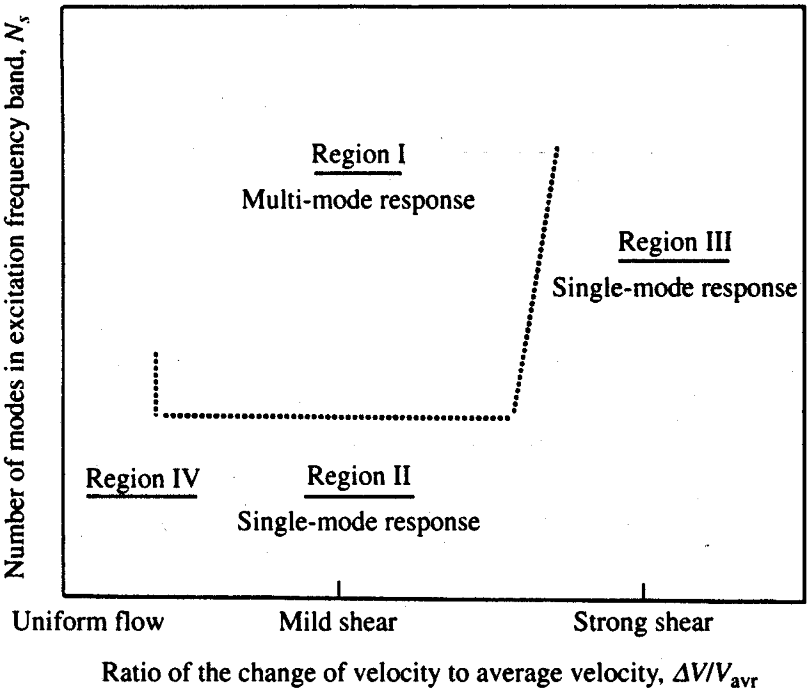


Figure 2. Identification of multi-mode and single mode response regions.

The base of the "U" corresponds to $N_s = 3$ modes. Below this line lock-in, dominated by a single mode, was common in Allen's tests, even when the shear parameter was as great as 0·7, indicating that the change in flow speed was 70% of the average. Data from such cases are presented in Figure 3. Each data point is an individual experimental run. Of the open circle data, 90% points in region II beneath the "U" exhibited single mode lock-in. In contrast the data points marked with an asterisk, "*", in region I inside of the "U" were dominated (88%) by multi-mode non-lock-in behavior.

Also shown in Figure 3, marked with "+" symbols, are a group of data points in

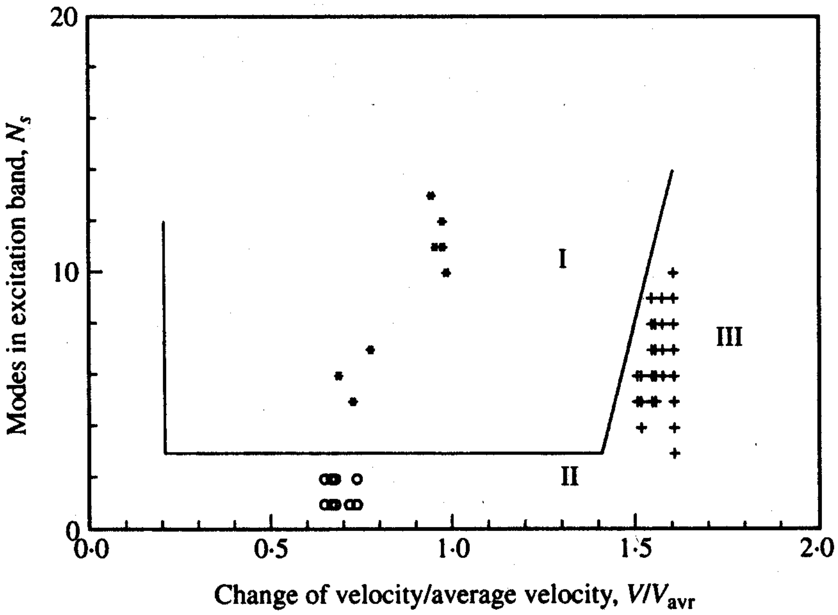


Figure 3. Response behavior as a function of N_s and $\Delta V/V_{avr}$ for Aluminum and ABS tubes: *, 88% multi-mode response; +, 67% single-mode response; O, 90% single-mode response.

region III to the right of the "U". In these cases 67% were dominated by single-mode lock-in. These cases are in a region of high shear, where $\Delta V/V_{\text{avr}} = 1{\cdot}6$. The number of potentially responding modes was as great as 10. These results are the most surprising. Conventional wisdom would have suggested that lock-in response was not likely to happen in such highly sheared flow. Thus, it appears that when the shear parameter exceeds 1·4 approximately, single-mode dominance is likely to occur.

Region IV corresponds to cases in which the shear parameter is 20% or less. For most cylinders in water, the range of reduced velocity, V_r, which permits lock-in is at least ±10% of from the optimum value (which is 5 to 6 depending on Reynolds number). Since reduced velocity is defined as $V_r = V/(f_n D)$, it is proportional to flow speed. Therefore, a variation in V_r of ±10% is equivalent to the same per cent variation of flow speed. Hence, when the shear parameter is 20% or less, lock-in of a single mode is possible over the entire length of the cylinder at whatever mode number, n, is best matched to the flow. Lock-in is commonly observed when the variation in flow velocity is less than 20% of the mean velocity. This explains the left-hand boundary of the "U".

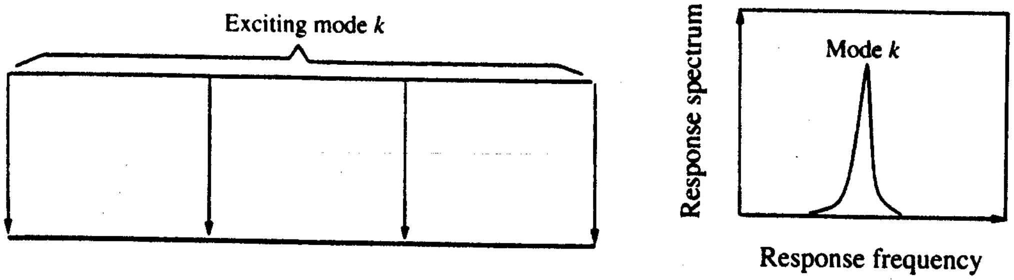
4. A PROPOSED EXPLANATION FOR LOCK-IN IN HIGHLY SHEARED FLOW

Many factors may disrupt the lock-in or wake synchronization process. An important one is the presence of vibration frequency components which are not at the lock-in frequency. Because of the shear, the shedding frequency may vary along the length. In different regions, different modes may be resonantly excited. Although the excitation for each mode may be confined to a small region, each mode responds as a standing wave, which affects the entire cable. Thus, at any location, the response spectrum will reveal a superposition of modal responses with each one being prominent at its own natural frequency. It has been experimentally demonstrated that multiple frequency components may disrupt the local, lock-in process (Shargel 1980; Venugopal 1996). Thus, if one mode has sufficient vibration energy it may prevent competing modes with lower response levels from developing wake-synchronized power-in regions.

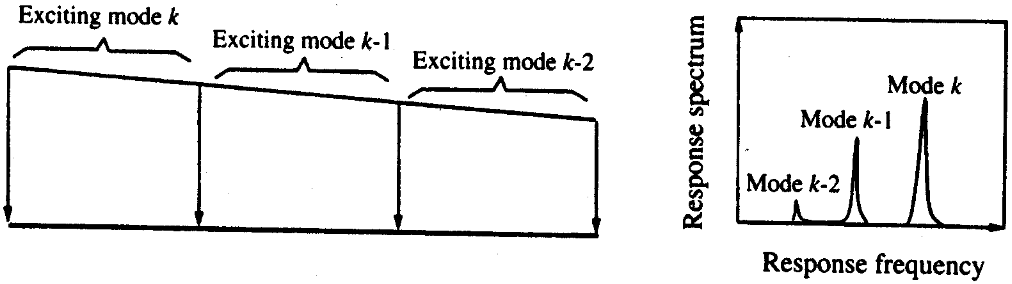
It is also known that lock-in is a very nonlinear phenomenon. If one mode is able to achieve sufficient response amplitude, then wake synchronization for other modes may be suppressed, even in regions of the cable which would appear to favor lock-in with those modes. This is what the authors believe is happening in region III to the right of the "U".

The relative amount of hydrodynamic power available to each mode in various flow conditions is conceptually illustrated in Figure 4. The left side of this figure shows potential lock-in regions along the length of a cable for three flow cases: (a) uniform, (b) mildly sheared, and (c) strongly sheared. The amount of hydrodynamic power available to drive each mode is shown as a qualitative vertical coordinate. The amount of power per unit length locally available to a mode is approximately proportional to the cube of the flow velocity. In the case of a uniform flow, only one mode extracts power from a long length of the cable and a spectrum with a single peak results, as shown on the right-hand side of the Figure 4(a). There are many examples in the literature to support this case (Griffin & Ramberg 1982).

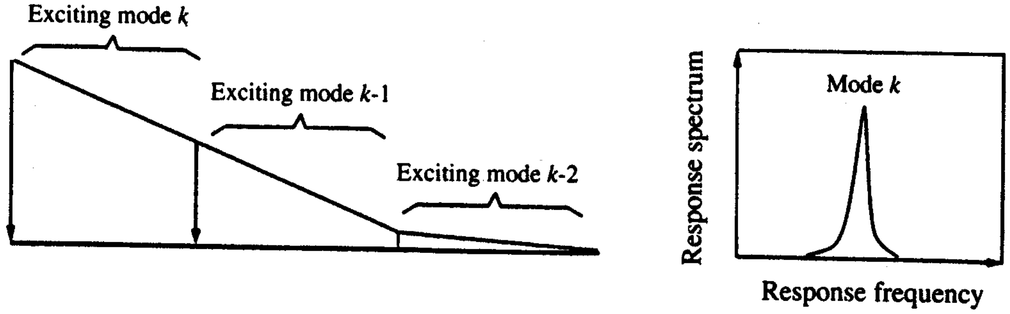
In the case of mild shear, several modes have significant available input power. No single mode is able to create sufficient vibration response to prevent the other modes from locally interacting with the wake. Several peaks appear in the response spectrum, as shown in Figure 4(b). Wake synchronization is dramatically reduced, resulting in



(a) Uniform flow: only one mode is excited, single mode response



(b) Mild shear: several modes have comparable input energy, multi-mode response



(c) Strong shear: one mode may have dominant input energy, single mode response

Figure 4. The relationship between shear gradient and dynamic response behavior.

lower total r.m.s. response. Many examples of such response were observed in the tests conducted by Allen. An analysis of the individual modal contributions to multi-modal response may be found in Vandiver & Jong (1987).

In the strongly sheared flow case, mode *k*, as depicted in Figure 4(c), has much greater input power than the others. Its response, which is felt everywhere on the cable, prevents the lesser excited modes from locally extracting significant power from the wake. A single response frequency dominates. This appears to be what is happening in region III to the right of the "U". Such behavior was observed for the Region III data points in Figure 3. This type of behavior has also been observed for full-scale risers in Gulf of Mexico eddy currents.

It is important to note that, in sheared flow cases, stationary response is rarely observed. When single mode dominance occurs, lock-in may shift from one mode to another due to temporary variation in flow, fluctuations in tension or turbulence. Lock-in events are sometimes separated by a period of multiple-mode response. In cases such as those depicted in region II, where single mode dominance is rare, there is considerable time-domain fluctuation of modal response energy between various modes.

When single-mode dominance occurs in a sheared flow, it usually does so with response amplitudes typical of lock-in. The r.m.s. response in the single-mode dominated cases is usually considerably greater than the total r.m.s. response in the multiple-mode cases. Hence it is important to be able to predict the possibility of occurrence of single-mode dominated behavior in strongly sheared flow.

5. CONCLUSION

Although hundreds of cases were observed, there are vast regions of the $\{N_s, \Delta V/V_{\text{avr}}\}$ space which have not been explored. What will happen at values of $\Delta V/V_{\text{avr}}$ higher than 1·6 is not known. In uniform flows the possibility of lock-in exists at very high mode numbers, when N_s, the number of possibly responding modes, is by definition close to 1. However, in sheared flows, lock-in ceases to be a possibility when the product of the mode number, n, and the modal damping, ζ, approaches 1, because standing wave behavior ceases to exist away from the ends of the cable. For the wire rope case described in Vandiver (1993), the shear was quite mild ($\Delta V/V_{\text{avr}} = 0{\cdot}2$) and $N_s = 10$. In this case, lock-in was observed at around the 50th mode, and moved from one mode to the next as the tidal flow varied.

The shear parameter used here, $\Delta V/V_{\text{avr}}$, is quite crude. A better indicator of whether or not single-mode dominance may occur is probably a direct comparison of the power available to each mode. Further work needs to be done to quantify when the ratio of available power between two modes favors the dominance of one of them. Experiments are needed to understand better the effect of secondary frequency components on the lock-in process.

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