International Journal of Offshore and Polar Engineering
Vol. 4, No. 3, September 1994 (ISSN 1053-5381)
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An Engineering Approach To Characterize the Lock-in Phenomenon Generated by a Current on a Flexible Column

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ABSTRACT

Experience with free-standing conductor pipes in the Gulf of Guinea (Africa) has shown that they may fail quite unexpectedly. Lock-in from vortex-induced vibrations was considered as a possible source of increased fatigue and damage. The objective of this study was to provide engineers with a simple, yet realistic tool to estimate stresses that may arise from lock-in phenomenon. Based on published work, an original straightforward algorithm is presented in this paper. A case study is presented for a real structure installed in Africa.

POSITION OF PROBLEM

To tackle the problem of vortex-induced vibrations numerically, various options (Blevins, 1990; Every et al., 1982; Griffin and Ramberg, 1982; King, 1977; Sarpkaya, 1979) are available. Our choice was to take advantage of the well-known feedback characteristics of the lock-in phenomenon and to include this effect in a novel algorithm. The Vortex-Induced Resonance Feedback Algorithm (VIRFA) is presented in the next paragraphs.

Our approach is based on the following assumptions:

- One mode shape is predominant and induces lock-in in the transverse direction.
- Only current is considered at this time as the major source of lock-in.

The flow is characterized in a classical manner by the Reynolds number $Re = UD/\upsilon$ and the Strouhal number $S_t = f_s D/U$. To describe VIV in waves, the Keulegan Carpenter number $KC = UT/D$ would be introduced as well.

To characterize the lock-in phenomenon, it is usual to define a stability parameter $K_s = 4\pi m_e \xi_s / \rho D^2$ and a reduced velocity parameter $V_r = U/f_N D$. Following Iwan (1981), Patel and Lyons (1986) and Patel and Jesudasen (1987), the stability parameter depends on a modified damping ratio ξ_s. ξ_s accounts for structural damping and damping generated in a region outside the lock-in area from hydrodynamic drag forces. Other parameters with an influence on the calculation are the mode shapes and the natural frequencies.

VORTEX-INDUCED RESONANCE FEEDBACK ALGORITHM

Model for Hydrodynamic Forces

The hydrodynamic forces are expressed in terms of a modified Morison equation on slender structures. For the in-line motion, the hydrodynamic force component is:

$$F_x = 1/2 \rho D C_D \left|[\mathbf{U}-\mathbf{v}]_n\right| [\mathbf{U}-\mathbf{v}]_n \cdot \mathbf{i}$$

$$+\rho \frac{\pi D^2}{4} \left(C_M \frac{d(U_{nx})}{dt} + (1-C_M)\left(\frac{d\mathbf{v}}{dt}\cdot \mathbf{i}\right) + C_M [\mathbf{U}-\mathbf{v}]_n \cdot \mathrm{grad}(U_{nx}) \right) \quad (1)$$

This expression includes convective inertia terms detailed in Foulhoux and Bernitsas (1992). A lift term is introduced in the transverse direction to describe lock-in, as follows:

$$F_y = 1/2\, \rho D(\mathbf{U}\text{-}\mathbf{v})_{nx} |\mathbf{U}\text{-}\mathbf{v}| \,(C_{ml}\sin(\Omega\tau) + C_{dl}\cos(\Omega\tau)) \text{ when lock-in occurs} \quad (2a)$$

$$F_y = 1/2\, \rho D(\mathbf{U}\text{-}\mathbf{v})_{ny} |(\mathbf{U}\text{-}\mathbf{v})_n| \text{ when lock-in does not occur} \quad (2b)$$

$$\Omega = 2\pi f/f_N \quad (3)$$

$$\tau = f_N t \quad (4)$$

C_{ml} and C_{dl} are adjusted from the equation of motion of a single degree of freedom system (Sarpkaya, 1978). The coefficients are computed for every discretized element and depend on the mode shape. Ω is computed at every time-step.

The forces defined by Eqs. 1~4 enable the engineer to calculate the motion of the structure with vortex-induced exciting forces. Full coupling between in-line and transverse motions is achieved. The various motions resulting from this model are :

- In-line displacement due to drag and inertia forces.
- Transverse motion due to a lift force oscillating at frequency $f \cong f_N$.
- In-line displacements caused by a drag term oscillating at $f' \cong 2f_N$. This last term simply appears when the body vibrates in the transverse direction. It is consistent with experimental observations (Griffin, 1984).

Calculation Method:

Experiments have shown that the frequency ration Ω varies with time and is very dependent on the reduced velocity (Griffin and Ramberg, 1982). Similarly, we observed that, numerically, the response of the structure was very sensitive to small variations of Ω. It was therefore interesting to manage the self-limiting process observed on test structures by controlling this parameter. These are the basics of the VIRFA method.

Calculations are performed in two steps. First, the dominat mode of vibration is identified, and the effective structural damping and maximum expected amplitude of vibration are derived for that mode. The procedure follows Iwan (1981) and Patel and Lyons (1986) closely. Then, the VIRFA principle is included in the time-domain simulation scheme: At each time step, the lift

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Received March 31, 1993: revised manuscript received by the editors December 30, 1993. The original version (prior to the final revised manuscript) was presented at the Third International Offshore and Polar Engineering Conference (ISOPE-93), Singapore, June 6-11, 1993.

KEY WORDS: Hydrodynamic forces, vortex-induced vibrations, lock-in, conductor pipes.