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DYNAMICS OF AN UMBILICAL CABLE FOR UNDERGROUND BORE-WELL APPLICATIONS

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Abstract— A general model for an umbilical cable for underground bore-well applications is considered. The response of one-degree-of-freedom, nonlinear system under external excitation forces and the effect of the parameters ω^2, β and f on the excited system are investigated. Variation of the parameter ω^2 leads to multi-valued amplitudes and hence to jump phenomena. The simulation results are achieved using MATLAB 7.12.0 (R2011a) Simulink.

Keywords-*Umbilical cable; One-degree-of freedom; Phase plot; Excitation force.*

I. INTRODUCTION

Cable structures play an important role in many engineering fields, such as civil, ocean and electrical engineering. Umbilical cables are deployed underground for bore well related remote control applications.

Arafat and Nayfeh studied the motion of suspended cable with primary resonance excitation [1]. The principal parametric resonance for one-degree-of-freedom system with cubic nonlinearities under parametric excitation is investigated by El-Nagger and Alhanadwah [2]. Mahmoud et.al studied the periodic solutions of excited dynamical nonlinear systems using generalized averaging method [3]. Nayfeh et al. investigated the nonlinear nonplanar responses of suspended cables to external excitations [4].

The global bifurcations and the chaotic dynamics, as investigated by Zhang and Tang, of the suspended inclined cable under combined parametric and external excitations can be found in [5]. Srinil et.al studied the non-Linear dynamics of suspended cable structures resonance [6, 7]. Though, experimental studies have been conducted by Alaggio and Rega [8] [9], the stability regions have not been analyzed. Abd Elkader used a modal model to compute the instability boundary range of excitation frequencies for 2:1 internal resonance [10]. Sayed, Amer and Hameed [11], investigated the non-linear dynamics of a two-degree-of freedom vibrating system.

The response of one-degree-of freedom, non-linear system under multi-parametric and external excitation forces simulating the vibration of the cantilever beam is studied by Amer and Sayed. [12]. A three-degree-of-freedom model to simulate non-linear response of suspended, inclined cables driven by planar excitation is used by Lee and Perkins [13]. Eissa investigated the non-linear mechanical oscillators subjected to parametric and excitation forces [14]. Al-Qaisia and Hamdan studied the steady state periodic response of single-mode and two-modes [15]. The stability of the periodic solution of the vibration of nonlinear coupled Van Der Pol oscillations under external and parametric excitation is investigated by Kamel [16].

Queini and Nayfeh studied the problem of suppressing the vibration of a structure of a cantilever beam subjected to a principal parametric excitation [17].

From the above literature survey and to the best of the knowledge of the authors, no such work in line with the proposed concept was undertaken.

In the current work, the cable is modeled as a simple cylinder: as a one-degree-of freedom nonlinear system subjected to unidirectional flow induced excitation. As is the case of one end fixed cylinder, the oscillation amplitude is assumed to be negligible.

II. MATHEMATICAL EQUATION

A general equation describing parametrically and excited mechanical system [18] is given by

$$\ddot{x} - \mu\dot{x} - \beta x^3 + \gamma x^4 \dot{x} + \omega^2 x = f[\delta(t)] \quad (1)$$

Where x denotes the in-plane displacement of the cable and dots denote derivate with respect to time *t*. The parameter μ is the damping coefficient, ω^2 is the frequency associated with the in-plane displacement, β, γ are the coefficients of nonlinear parameters, $\delta(t)$ may represent the external excitation force acting on the cable due to the underground fluids and *f* is the external force amplitude.

Equation (1) may represent the motion of a beam or plates under combined axial and transverse excitation.

(1) is implemented using MATLAB Simulink. The solver type used is ode4 (Runge-Kutta) and the step size is fixed to 0.1.

As the cable traverses through the bore well, it is subjected to excitation, due to self-drag and also due to underground fluids. Fig.1 shows the schematic of a single-degree-of- freedom inclined cable under parametric and external excitation.

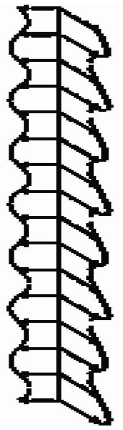

Figure 1: A schematic of an inclined cable under excitation

III. SYSTEM IMPLEMENTATION

The response of single-degree-of-freedom nonlinear system under external and parametric system is studied. II (1) is implemented using MATLAB Simulink. The model is shown in fig 2.

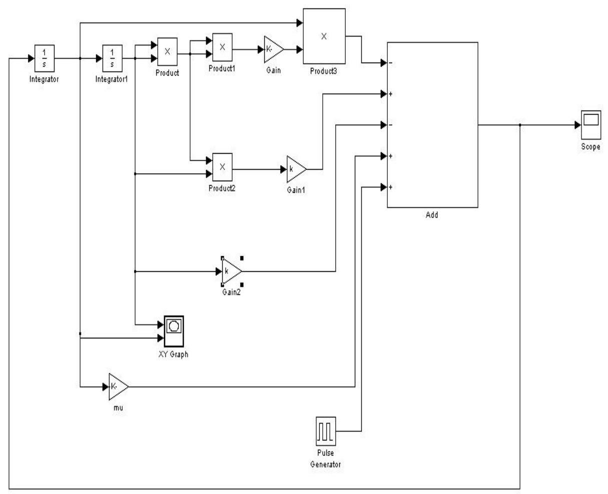

Figure 2: SIMULINK implementation of II(1)

The term $\ddot{x}$ is obtained by successive integration. The gain blocks represent the different parameters (γ, β, ω^2, μ) of the cable. The variation of the corresponding initial conditions is implemented by entering the values in the gain blocks. The rollers are assumed to send the cable at a speed of 30m/sec. The simulation time is set for 300 seconds. Hence the performance of the system for a distance of 9 km could be studied.

IV. RESULTS AND DISCUSSION

The stability zone and the effect of different parameters are analyzed. The representative numerical solutions are studied and included. The effect of different parameters on the vibrating system behavior are investigated and discussed.

A. Numerical solution

Fig.3 shows the response of the inclined cable for the non-resonant values of μ = 0.05, β = 0.4, γ= 0.5, *f*=4 and ω^2 =5. The above selected values are the basic case for computing the solution. From this figure it may be observed that the maximum steady state amplitude is about twice the excitation amplitude *f* and it can be noticed that the XY plot shows a limit cycle.

The amplitude with increasing time tends to steady state motion and has a stable solution.

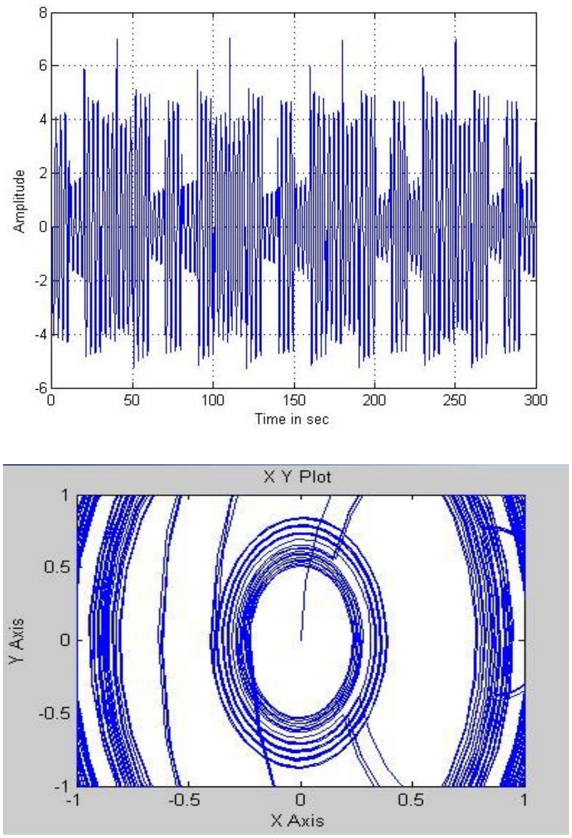

Figure 3: Numerical solution of the time response at selected values (basic case): μ = 0.05, β = 0.4, γ= 0.5, *f*=4 and ω^2 =5.

B. Study of effect of different parameters

Nonlinear parameter β: The value of β is varied from 0.5 to 1 and the response is observed. From fig.4 (a)-(d), it may be understood that for increasing value in nonlinear parameter β, the branches of the steady state amplitude curve are contracted, indicating stability. This may be also inferred from XY plot. Also an increase in the excitation force *f*, increases the amplitude, but no significant effect on the stability was observed. The response amplitude of the in-plane mode is increased. This increase may be attributed to the soft spring effects of the stainless steel umbilical cable.

Frequency of the in-plane displacement, ω^2: For increasing value of ω^2, it is observed that the modes of vibration have increasing magnitudes and there exists a chaotic dynamic motion as shown in Fig.5 (a)-(d).

For increasing amplitude of the excitation force *f*, an effective nonlinearity of hardening type is observed.

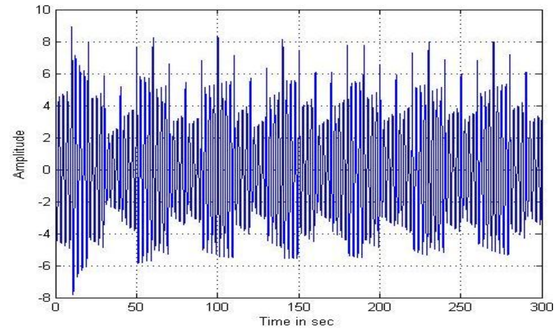

Figure 4(a): Amplitude plot for β=0.5

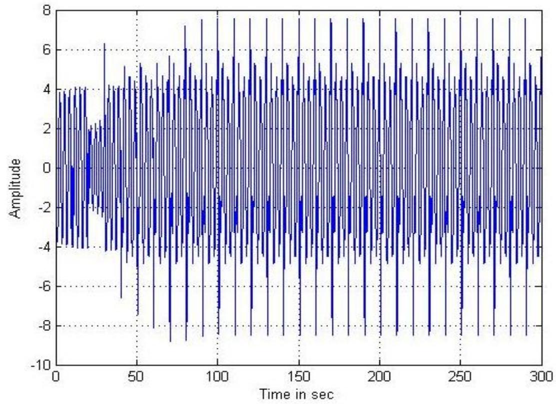

Figure 4 (b): Amplitude plot for β=1

From Fig.5 (a)-(d), it may be observed that if the initial conditions is varied (i.e., ω^2 =102), chaotic motion is exhibited by the cable. The phase plots (i.e. Fig 5(b) and Fig. 5(d)) confirms the chaotic behavior of the cable

From fig.5(a) and 5(d) it may be inferred that the external excitation force by the sourounding fluid on the cable affects the amplitude of chaotic signal.

By varying the initial conditions slightly (i.e. ω^2 =103) the chaotic behavior ends, as shown in fig.6 (a) - (b).

By analyzing fig. 4 (a)-(d), it can be observed that for basic value of ω^2 =5, limit cycle exists. Upon changing the

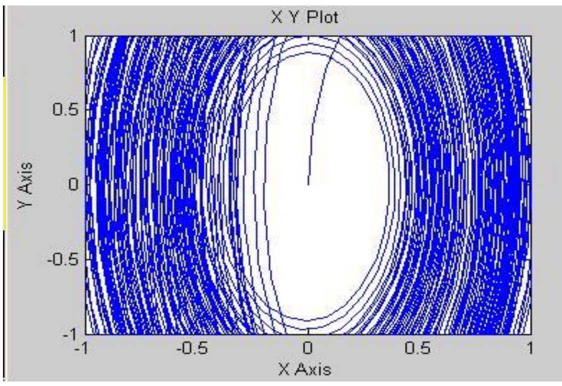

Figure 4(c): Phase plot for β=0.5

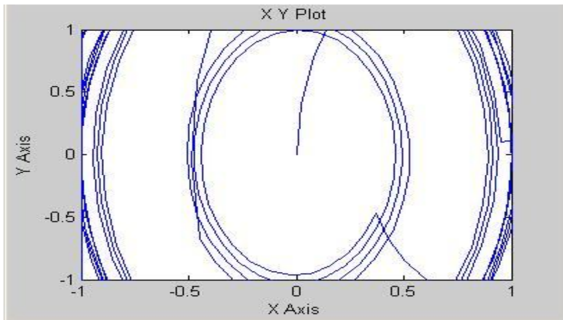

Figure 4(d) : Phase plane plot for β=1

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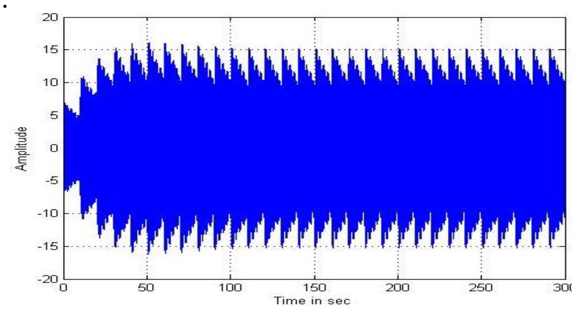

Figure 5(a): Response for ω^2 =102 *f*=4and β=1

initial value of ω^2 to 102, chaotic behavior is observed as in fig. 5 (a)-(d). Further changing the value of ω^2 to 103, as shown in fig. 6(a)-(b), chaos ends. Thus the Lyapunov exponent is inferred to be positive and that the system is sensitive to initial conditions. Hence it may be confirmed that a chaotic dynamic motion exists.

Also it is observed that for higher values of ω^2 has very less significance on the behavior of the system

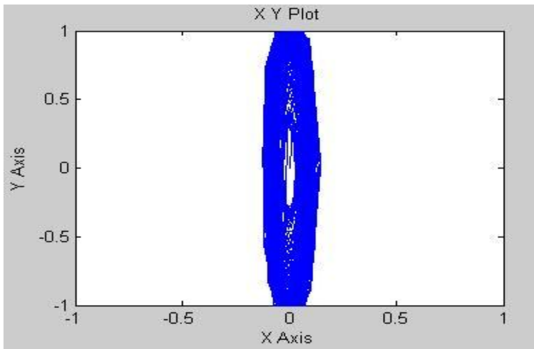

Figure 5(b): Phase plot for ω^2 =102 *f*=4and β=1

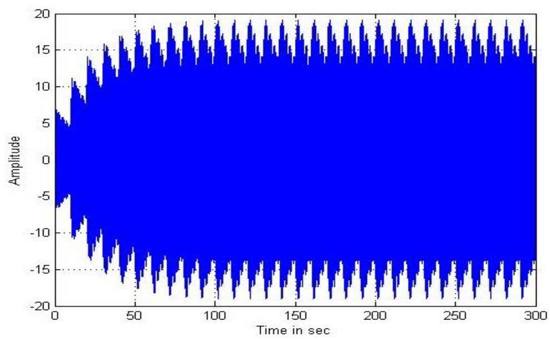

Figure 5(c): Response for ω^2 =102 *f*=5 and β=1

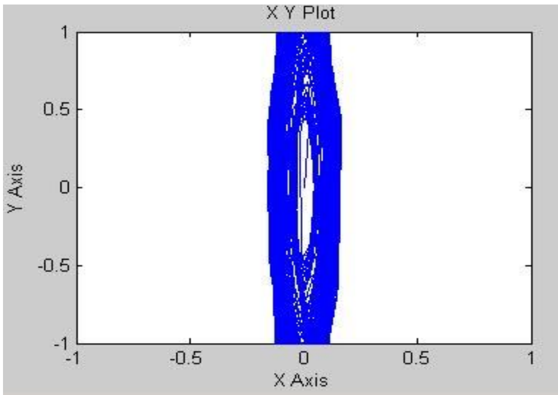

Figure 5(d): Phase plot for ω^2 =102 *f*=5 and β=1

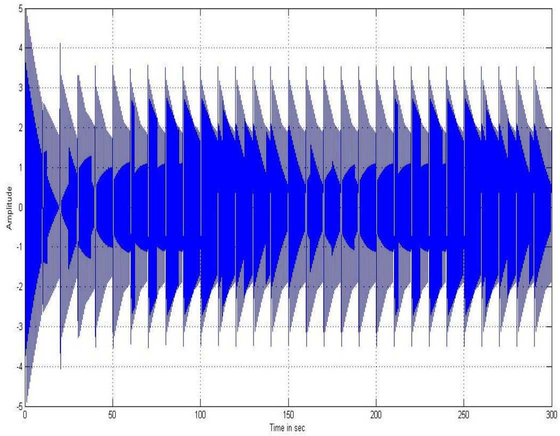

Figure 6(a): Effect of increasing value of in plane dispacement, ω^2 =103

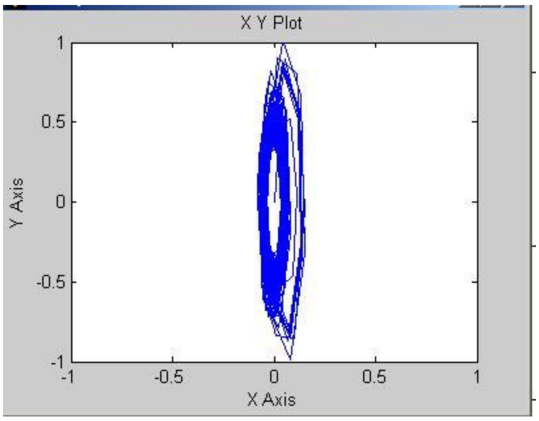

Figure 6(b): Phase plot for increasing value of in plane dispacement, ω^2 =103

V. CONCLUSION

Umbilical cables are very efficient structural members and are being widely used in many underground applications. The nonlinear dynamic response of the single degree of freedom nonlinear system subjected to parametric and external excitation is investigated. MATLAB Simulink model is constructed to obtain the solution of the considered system up to second order approximation. The chaotic response of this system is also investigated. The effects of some nonlinear parameters on the vibrating umbilical cable are analyzed. From the analysis, the following may be concluded.

- The amplitude of the modes is increasing for increasing external excitation force. This may be helpful in deciding the diameter of the bore well, as any interaction of the umbilical cable with the ground may result in the degradation of the cable performance.

- For increasing nonlinear parameter β, there is an increase in the stability as the branches of the steady state curve are contracted. The parameter indicates the choice of the quality of the cable, as β represents the soft spring effects.

- Variations of initial conditions for the frequency of in-plane displacement lead to multi-valued amplitudes and hence jump phenomena. Chaotic behavior was observed for increased value of ω^2. The positive Lyapunov exponent, as observed, confirmed the presence of chaotic behavior.

- The speed with which the umbilical cable is being sent underground may be related to the frequency of the in-plane displacement. Hence proper rate must be ensured for safe operation of the cable.

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