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Experimental and numerical investigation of parametric resonance of flexible hose conveying non-harmonic fluid flow

Jan Łuczko [a], Andrzej Czerwiński [b,*]

[a] Institute of Applied Mechanics, Faculty of Mechanical Engineering, Cracow University of Technology, Jana Pawła II 37, 31-864 Krakow, Poland
[b] Institute of Machine Design, Faculty of Mechanical Engineering, Cracow University of Technology, Jana Pawła II 37, 31-864 Krakow, Poland

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ABSTRACT

The article presents an analysis of a model describing transverse vibrations of an elastic hose induced by non-harmonic fluid flow pulsation. The equation of motion is given as a nonlinear partial differential equation with periodically variable coefficients. The Galerkin method is employed, utilising orthogonal polynomials as shape functions. The effect of selected parameters on increased vibration intensity range and the character and form of vibrations is investigated. It is demonstrated that sub-harmonic and quasi-periodic vibrations can be induced in the simple and combination parametric resonance range. The occurrence of the parametric resonance phenomenon is evidenced by experimental data.

1. Introduction

The main function of pipes in hydraulic drive systems in machines and installations is to transfer energy between the machine sub-assemblies. The use of steel rigid pipes guarantees a secure and durable connection, however this method is in some cases impracticable. Steel rigid pipes cannot be used at all when the elements to be connected move with respect to one another whilst in service, or when they are unfavourably arranged or when the system requires frequent reconfigurations. In such cases, the use of an elastic pipes is a recommended option.

Pipes used to handle high oil pressures are typically made of synthetic rubber reinforced with steel braids [1–4]. Composite structure of the pipe guarantees its high elasticity and resistance to the internal thrust forces. However, they feature a relatively low lateral stiffness which, under certain conditions, favours the induction of large-amplitude vibrations in the hydraulic system.

One of the main causes of vibrations is time variable flow rate of fluid [5,6]. Periodic flow pulsations are associated with the operating characteristic of the supply pump [7] or with a designed flow rate control action. Flow pulsations due to the pump operation occur as a polyharmonic signal with one dominating component whilst pulsations due to control action are typically of the impulse type. The phenomenon of parametric resonance can occur under the specified flow conditions:

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[*] Corresponding author.
E-mail address: ac@mech.pk.edu.pl (A. Czerwiński).

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mean flow velocity, amplitude and frequency of pulsation. In order to find the amplitude of parametric vibration it is required that nonlinear models of the systems should be investigated.

The problems involved in modelling and dynamic analysis of pipes with pulsating fluid flows were addressed by numerous authors already in the 1970s. The first researchers who performed the correct analyses of pipe vibration induced by fluctuating flow velocity were: Ginsberg in 1973 [8] for a pipe simply supported at both ends; Païdoussis and Issid in 1974 [9] for a cantilevered pipe and Païdoussis and Sundararajan in 1975 [10] for a clamped–clamped pipe. These authors found the parametric vibration ranges (instability ranges) by the Galerkin [8], Bolotin [9] or Floquet [10] methods. Calculation results were then verified experimentally [11].

Holmes [12] investigated a case of a pipe fixed at both ends and incorporated a nonlinear term associated with the axial extension force to the linear equation derived by Païdoussis and Issid [9]. Assuming the Voigt–Kelvin type visco-elastic model of the material, the motion of the pipe was described by one partial differential equation. Semler and Païdoussis [13] introduced a nonlinear equation of motion for cantilevered pipes, assuming the centreline to be non-deformable. Gorman et al. [14] gave a nonlinear description of the pipe motion for unsteady flows, employing the finite difference method and the method of characteristics. A comprehensive review of the modelling and analysing methods was given by Païdoussis in his two-part monograph [5,6].

The nonlinear analysis of parametric resonance was first performed by Yoshizawa et al. [15] in 1986, Namachchivaya [16] in 1989 and Namachchivaya and Tien [17] in 1989, who investigated the influence of the system parameters on the simple and combination resonance range. Jayaraman and Narayanan [18] used the Galerkin method to investigate the simple principal parametric resonance, indicating the possibility of generating chaotic vibration. Using the multiple scales method, Oz and Boyaci [19] determined the principal parametric resonance range in space defined by frequency- pulsation amplitude and mean flow velocity for variable fluid mass to pipe mass ratios. Nikolić and Rajković [20] conducted a bifurcation analysis for the model pipe supported at both ends, taking into account the gravity forces. Panda and Kar [21] used the perturbation technique in their investigations of simple and combination parametric resonances, demonstrating the possibility of periodic, quasi-periodic and chaotic vibration. Using the two-mode Galerkin method, Wang [22] investigated the model of a simply supported pipe with constraints imposed upon its motion, demonstrating the possibility of chaotic vibration. Dai et al. [23] examined the influence of flow velocity in the sub-critical and supercritical regime by the four-mode Galerkin method. Zhang and Chen [24] applied the multiple scales method to investigate the effects of external excitation in the supercritical range for a simply supported pipe.

In most studies investigating the flow-induced parametric resonance, the authors assume the harmonic variations of flow velocity [14–23,25,26]. It often turns out, however, that the value of flow velocity needed to trigger the resonance in hydraulic system is too high and hence most unlikely to occur in real systems. Furthermore, resonance occurs mainly in the upper range of the excitation frequencies. Hydraulic systems are also investigated to study the water hammer effect due to rapid closing or opening of the valve (Zhao et al. [27]). This is a separate issue, beyond the scope of this paper. When the control action requires that particular valves should be periodically opened and closed, we get a periodically varying excitation, which cannot be described by a harmonic function. Of particular importance is opening time to closing time ratio (the duty factor), affecting the waveform of the pulse excitation. Frequent changes of flow velocity can be described by a non-symmetric rectangular waveform. In this study will be demonstrated theoretically and verify it experimentally that this nature of excitation can give rise to parametric vibrations even for smaller values of flow velocity at in several resonance ranges within the range of low flow pulsation frequency.

In most works [14,15,18] the authors investigate nonlinear models of pipes for fixed values of the system parameters. In some cases bifurcation diagrams are determined, showing the effect of single parameter on the character of vibration [21–23,25]. In few papers only the simultaneous influence of two parameters is analysed, most frequently on the stability range on the plane: pulsation frequency-mean flow velocity [28] and on the plane: frequency-pulsation amplitude [29], and hardly ever, the influence on the level of vibrations.

When investigating the resonance effect in the range of first two natural frequencies, for example by the two-modal Galerkin method, approximate methods (eg. perturbation or multiple-scales methods) can be used to determine how a larger number of system parameters influence on the pipe vibration [30]. Such conducted analysis is, however, difficult to implement if a larger number of modes are involved in the Galerkin method.

The need for taking into account a great number of modes of vibration is suggested by results of experiments obtained for flexible pipes. The significant problem is to find an effective research methodology which would allow to analyse relatively fast the influence of numerous factors on dynamic behaviours of such hoses. This study is an attempt to address this issue, focusing on the influence of the character of excitation on parametric vibrations of the pipe. In the analysis the model proposed by Holmes [12] is applied. Numerical simulations are performed to determine those range of parameters in which the parametric resonance may occur, posing a major threat to the entire structure. These results are verified by experiments carried out on a pipe fixed at both ends.

2. Differential equation of motion and discretization

Let us consider a horizontal, straight pipe of length L, clamped at both ends. The pipe conveys fluid flowing with variable velocity $U_f(t)$. It is assumed that the fluid velocity is constant in the pipe's cross-section and does not change along its length. The fluid is assumed to be incompressible, the pipe diameter is small in relation to its length and the cross-profile shape and