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Nonlinear longitudinal oscillations of fuel in rockets feed lines with gas–liquid damper

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ABSTRACT

The mathematical model of the fuel oscillations in the rockets feed lines with gas–liquid dampers is derived. The nonlinear model of the gas–liquid damper is suggested. The vibrations of fuel in the feed lines with the gas–liquid dampers are considered nonlinear. The weighted residual method is applied to obtain the finite degrees of freedom nonlinear model of the fuel oscillations. Shaw–Pierre nonlinear normal modes are applied to analyze free vibrations. The forced oscillations of the fuel at the principle resonances are analyzed. The stability of the forced oscillations is investigated. The results of the forced vibrations analysis are shown on the frequency responses.

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1. Introduction

Pogo is nickname for structural vibrations instabilities in rockets and spacecraft structures caused by liquid propellant rocket engine thrust oscillations induced by structural motion [1–3]. This phenomenon was first identified and analyzed in the early 1960's when observed the longitudinal vibrations of the Titan II rocket. The Space Shuttle was the first launch vehicle developed with requirement to be free of pogo instability. The most common design solution to eliminate the pogo instability is the installation of gas filled accumulator on liquid propellant feed lines to decouple the structural and propulsion system dynamics and reduce thrust oscillation feedback [3]. Such accumulators are called gas–liquid dampers in Russian-language publications [4].

Stability analysis for lateral and longitudinal vibrations of launch vehicles is presented with special emphasis on pogo by Mori [5]. The differential equations of the pogo are obtained by coupling the structure vibration equations and the propulsion system equation in [6]. A detailed mechanics based model is developed to analyze the problem of structural instability by Trikha, Mahapatra, et al. [7]. The coupling among the longitudinal vibrational modes and the transverse vibrational modes are considered. The model also incorporated the effects of the aerodynamic pressure and the propulsive thrust of the vehicle. A single mass-spring model of pogo oscillations is considered by Glaser [8]. The Nyquist stability criterion is used.

In the present paper the fuel vibrations in the rockets feed lines are investigated. The gas–liquid damper is attached to prevent the pogo phenomenon in the rockets. The eigenfrequencies of the fuel in the feed line with the damper differ essentially from the longitudinal vibrations of the rockets airframe. Therefore, the vibrations of these two subsystems are uncoupled and these two systems are considered independent. The nonlinear model of the gas–liquid damper is suggested. Therefore, the fuel vibrations in feed lines with the dampers are considered nonlinear. Finite degrees of freedom model of the fuel vibrations is

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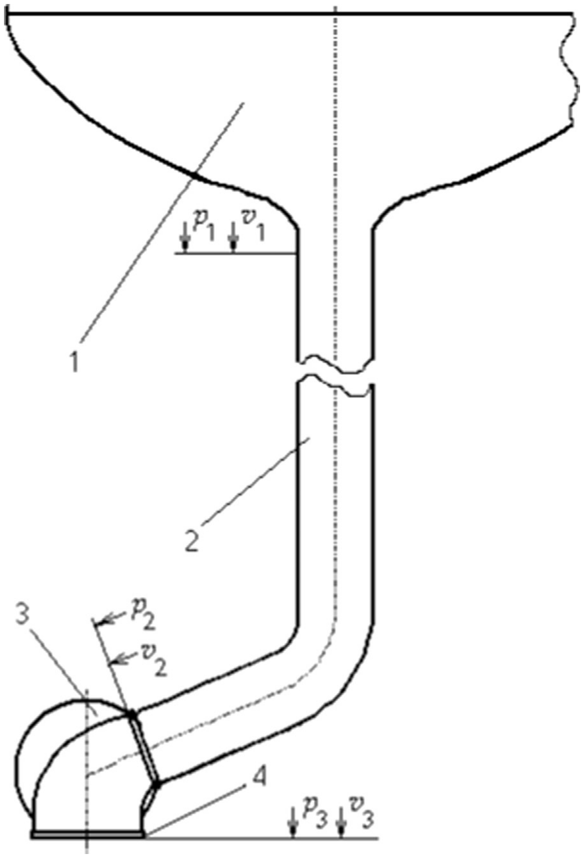

Fig. 1. Diagram of feed line; 1 is tank for fuel; 2 is feed lines; 3 is gas–liquid damper; 4 is volumetric pump.

derived on the basis of the weighted residual method. The Shaw–Pierre nonlinear normal modes (NNMs) are applied to analyze the finite degrees of freedom system. It is considered the rocket feed line, which is designed on the Yangel Yuzhnoye State Design Office [9]. The analysis of the effect of gas–liquid damper nonlinear properties on the fuel vibrations is the main aim of this paper.

Shaw–Pierre NNMs are suggested in [10]. The detailed review of NNMs development is published by Mikhlin, Avramov [11]. The review of this theory application is presented in [12]. NNMs are very effective for analysis of the mechanical vibrations absorption by nonlinear dampers [11–17].

2. Problem formulation and equations of the system motions

The sketch of the feed line with the gas–liquid damper is shown on Fig. 1. The principal units of this structure are denoted by numbers on Fig. 1. The fuel is moved in the feed lines 2 from the tank 1 into the turbine pump 4. The gas–liquid damper 3 is installed at the end of the feed line.

The vibrations of the fuel, which is moved on the feed line, are analyzed. It is assumed, that the fuel is inviscid and compressible. The pipe is considered long, elastic. It has circular cross section, constant thickness and constant diameter. As the pipe is long, the first several eigenfrequencies of the fuel vibrations in the feed line are small. The eigenfrequencies of the pipe mechanical vibrations are significantly higher the fuel eigenfrequencies. Therefore, if the fuel oscillations are analyzed, the pipe mechanical vibrations are not taken into account. The problem of the motions of the compressible fluid in elastic pipe with circular cross section is reduced to the problem of the motions of the compressible fluid with smaller elastic modulus in the inflexible pipe by Zhukovsky [18]. He suggested the effective modulus of elasticity. The effective sound speed c is determined by the Zhukovsky formula:

$$c=\left(\frac{1}{c_0^2}+\frac{\rho D}{E\delta}\right)^{-1/2},$$

where c_0 is sound speed; E is pipe wall modulus of elasticity; D and δ are diameter and thickness of the pipe; ρ is fuel density. The rockets feed lines have major diameter and small thickness of wall. Therefore, the effective sound speed of the fuel in the feed line is notably less than c_0.

The velocity of the fuel is small in comparison with the sound speed in the feed line. The fuel motions in the feed line are described by the Euler equation and the continuity equations. These equations take the following form [4]:

$$-\frac{\partial p}{\partial x}=\rho\frac{\partial v}{\partial t};\ -\frac{\partial p}{\partial t}=c^2\rho\frac{\partial v}{\partial x}, \tag{1}$$

where x is lengthwise coordinate of the feed line; p is oscillations of the pressure; v is oscillations of the velocity; v_0 is constant fluid velocity. The fluid velocity is the sum of the constant velocity v_0 and the oscillations of the velocity $v(x,t)$. Note, that Eq. (1) contain only the oscillations of velocity $v(x,t)$. The pressure of the fluid in the feed line $p_T(x,t)$ consists of the constant value of the pressure p_0 and the oscillations of pressure $p(x,t)$: $p_T(x,t)=p_0+p(x,t)$.

It is considered the rocket, which was designed by Yangel Yuzhnoe State Design Office [9]. As follows from the experimental studies of this system, the first eigenfrequency of the fuel longitudinal vibrations in the feed line is close to the first eigenfrequency of the rockets airframe. Therefore, the pogo instability can be observed. In order to prevent this phenomenon, the first eigenfrequncy of the fuel vibrations is decreased by installing the gas–liquid damper. Then two vibratory subsystems (the rocket airframe and the feed lines with the fuel) are uncoupled and they can be analyzed independently. The schematic diagram of the gas–liquid damper is shown on Fig. 2. This damper has the cage 1, the upper part of which is filled by inert gas 2. If the oscillations of the pressure take place in the feed line 3, the fuel 4 leaks through the holes 5. Then, the gas acts as elastic unit with small stiffness. The amount of gas in the cage 1 is governed by the supply through the valve 6.

The effect of the nonlinear properties of the gas–liquid damper on the longitudinal vibrations of the fuel is investigated in this paper. The nonlinear model of the gas–liquid damper is developed. This mathematical model is based on the assumption, that the compressibility of the fluid is neglected in comparison with the gas compressibility [4]. The variation of the gas volume in the damper is

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