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ORIGINAL ARTICLE

Experimental studies of water hammer in propellant feed system of reaction control system

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Abstract Water hammer pressure transient produces large dynamic forces which can damage the pipes and other assemblies in the feed line of a reaction control system (RCS). It has led to the failure of pressure transducers monitoring the manifold pressure in the feed line of RCS. Therefore, water hammer studies have been carried out to understand its effect in feed line. Feedline system has been simplified to develop a mathematical model and experiments have been carried out at extensive levels. The mathematical model was developed considering pipe of uniform c/s and moving liquid-gas interface. The experimental studies have been done using water as working medium instead of actual propellant. The studies showed that rate of pressurization have a very critical role on the water hammer amplitude. Sensitivity studies have been also carried out to study the effect of density, friction and initial liquid column length on water hammer amplitude.

1. Introduction

Water hammer is a phenomenon leading to sudden increase in fluid pressure, which results in pressure waves that travel along the pipe at sonic velocities. In the presence of pressure waves, dynamic stresses are created in the pipe wall, which may lead to pipe or some other components to failure. The phenomena of water hammer and its working has been understood using references [1–8]. Therefore, it has to be considered while designing and analyzing a reaction control system. The mechanism by which it can occur is explained through Fig. 1, which is a layout of one type of liquid Bi-Propellant reaction control system (RCS) used in missile. During the missile launch, propellant feed lines are initially empty and after gas pyro valve initiation,

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Nomenclature

RCS	reaction control system
GPV	gas pyro valve
PR	pressure regulator
PT	pressure transducer
HFV	high flow valve
VTP	velocity trimming package
BV	ball valve
BDV	burst diaphragm valve
SV	solenoid valve
OUP	orifice upstream
D	diameter of the pipe
t	time
p	pressure (unit: bar)
u	velocity (unit: m/s)
ρ	density (unit: kg/m^3)
c	velocity of pressure wave (unit: m/s)
f	friction factor
x	length along the pipe (unit: m)
λ	fraction of initial feed line length filled with liquid
l	liquid

feed lines are filled with propellant & pressure builds up to nominal value. At this time water hammer pressure transients are possible. Therefore, experimental studies have been carried out to ascertain its magnitude and its effect on integrity of joints and associated sub-systems (ex: - solenoid valves, propellant valves, etc).

Hence, a one-dimensional mathematical model has been developed to predict water hammer pressure in propellant feed system and series of tests conducted using water as medium. This article contains both descriptions of mathematical model and experimental results.

2. Mathematical model

A one-dimensional mathematical model for water hammer in propellant feed line with entrapped air developed with time varying liquid column and uniform gas compression [1]. The physical model consists of a partially filled pipe of uniform c/s. as shown in Fig. 2. The model assumptions are as follows:

1. Complete separation of air from the liquid.
2. Effect of bends, constrictions and local stiffening neglected.
3. At $t=0$, sudden increase in pressure is imposed at the pipe inlet.
4. Ideal gas and isentropic compression and expansion.
5. The index of expansion of air is taken as 1.4.
6. The friction factor in liquid region is computed based on Darcy-Weisbach pipe friction factors.
7. Effect of surface tension neglected.

In the liquid region, the pressure and velocity are governed by water hammer equations as described below:

$$\frac{\partial p_l}{\partial t}+\rho_l \cdot c_l^2 \cdot \frac{\partial u_l}{\partial x}=0 \tag{1}$$

$$\frac{\partial u_l}{\partial t}+\frac{1}{\rho_l}\frac{\partial p_l}{\partial x}=\frac{f}{2D}u_l|u_l| \tag{2}$$

The governing equations are non-dimensionalized and solved using method of characteristics. The method of characteristics is used to solve partial differential equations which are of hyperbolic type. This method is applied to transform the Eqs. (1) and (2) in a system of ordinary differential equations which can be easily integrated numerically to obtain the water hammer pressure peaks [9,10]. In the present solution, time step size is variable, and is determined at each time level such that a 'liquid-gas interface' does not travel farther than single grid size in a given time step. The computational grid used in solving is shown in Fig. 3. In the interior of liquid region, the solution is advanced in time by forcing the right-moving and left-moving characteristics to intersect on an interior grid point at the next time level. Over a single time step, characteristics are approximated by straight line segments. Characteristics will intersect at the target grid point, on the next time level, only if they originate from specific locations on the current time level. Origination points are denoted in Fig. 3 by A through B for the interior mesh points, by E, for the interfacial grid points, and by G for the boundaries. Points of origination for the characteristics are computed as part of the solution. At interior mesh points where the right-

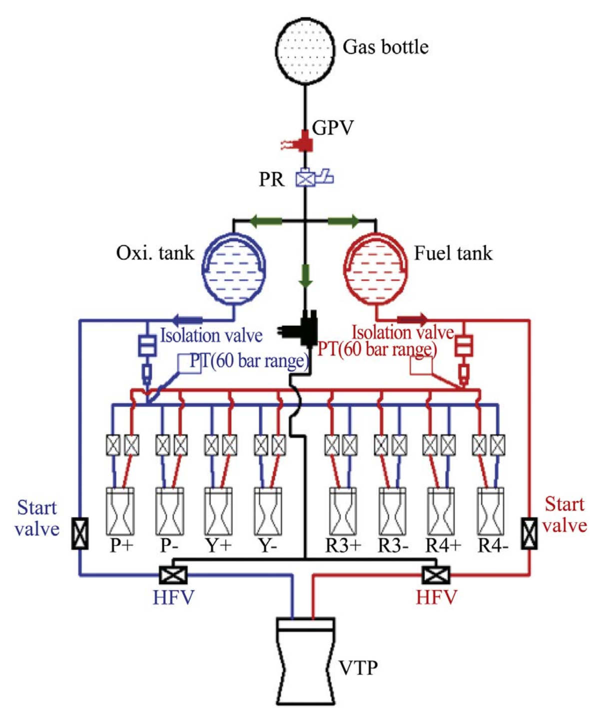

Fig. 1 Layout of RCS & VTP.

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