A FLUID TRANSIENT ANALYSIS FOR THE PROPELLANT FLOW WITH AN UNSTEADY FRICTION IN A MONOPROPELLANT PROPULSION SYSTEM

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단일추진제 추진시스템의 비정상 마찰을 고려한 과도기유체 해석

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A fluid transient analysis on the Koreasat 1 & 2 pipeline system is conducted through numerical parametric studies in which unsteady friction results are compared with quasi-steady friction results and show relatively accurate prediction of the response curve with the unsteady friction. The code developed and used in this analysis has finished verification through comparing with the original Zielke model, the full and recursive convolution model and quasi-steady model as a reference. The unsteady friction is calculated by the recursive convolution Zielke model in which a complete evolution history of velocity field is no longer required so that it makes the fluid transient analysis on the complicated system possible. The results show that the application of quasi-steady friction to model cannot predict the entire response curve properly except the first peak amplitude but the application of unsteady friction to model can predict reasonably the response curve, therefore it is to know the characteristics of the propulsion system.

Key Words: 과도기유체(Transient Flow), 비정상 마찰(Unsteady Friction), 단일추진제(Monopropellant)

1. INTRODUCTION

Pressure transients in a spacecraft propulsion system have the potential damage to spacecraft integrity and on-orbit functionality. It also can result in a catastrophic disaster, i.e., the loss of spacecraft. For examples, the Compton Gamma Ray Observatory (CGRO) had experienced a severe waterhammer transient in propellant priming[1] and the Mars '98 Lander descent propulsion system had conducted a series of subsystem level testing and a detailed set of waterhammer analyses to ensure system integrity and functionality[2].

Many different methods have been developed to analyse pressure (or fluid) transients in a propellant propulsion system. One of the most popular methods is using the method of characteristics, which is to transform two partial differential equations (PDE) of continuity and momentum conservations into four ordinary differential equations (ODE) that are solved numerically with a variety of boundary and initial conditions and system topologies [3,4,5].

The conventional approach to incorporate the frictional effects into the unsteady governing equations for pipe flow has generally used a steady state friction approximation using Darcy-Weisbach friction factor. Many experimental studies have been conducted to validate the steady state friction approximation. But these studies have shown that the steady state friction approximation is only correct at the first couple of pressure rises which is the highest pressures typically and is most detrimental to piping systems. These studies have also shown that the fluid acceleration plays an important role in damping. The first

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접수일: 2006년 1월 19일, 심사완료일: 2006년 3월 7일.

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pressure rise after a transient event is nearly independent of the frictional dissipation in pipe flow. Hence the numerical simulation gives reasonable agreement with only the first rises when the conventional approach is implemented. The remaining frictional damping is caused by the fluid acceleration and is known as the unsteady friction or the frequency-dependent friction[4]. To cope with such difficulty, unsteady friction models such Zielke and its derivative models and Vardy-Brown model have been incorporated into the pressure transient analysis[7,8]. The author have followed these models and tried to improve the existing model[9,10]. With this approach, the more precise prediction of the pressure evolution has been achieved for a long period. Furthermore it is beneficial to design a fluid device, i.e., orifice, to reduce the transient pressure head oscillations.

A fluid transient analysis for the propellant flow in a satellite propulsion system is needed to verify the design of propulsion system. This work is not to verify the design of propulsion system of Koreasat 1 & 2 but to identify it through parametric studies and to understand it more deeply by conducting a fast Fourier transform (FFT) analysis on the results. Main parameter is the thruster valve operation time, and given conditions are pipeline materials and number of pressure drop devices (i.e. filters, latching isolation valves, etc.) and pipelines and their lengths. All 50 lines and 50 junctions are fully considered in a model to analyze fluid transients. A constant value of the Darcy-Weisbach friction factor f (steady state friction factor) is used in most of commercial software packages for water hammer analysis, but the unsteady friction effects are considered in this work.

2. UNSTEADY FRICTION MODELS

The method of characteristics transformation of the unsteady pipe flow equations as Eqs. (1) and (2) gives the water hammer compatibility equations which are valid along the characteristic line[3]:

$$H_x + \frac{1}{g} V_t + h_f = 0 \qquad (1)$$

$$H_t + \frac{a^2}{g} V_x = 0 \qquad (2)$$

- along the C+ characteristic line (Δx/Δt = a)

$$H_{i,t} - H_{i-1,t-\Delta t} + \frac{a}{gA}\left(Q_{i,t} - Q_{i-1,t-\Delta t}\right) + \frac{f\Delta x}{2gDA^2} Q_{i,t}\left|Q_{i-1,t-\Delta t}\right| = 0 \qquad (1)$$

(3)

- along the C-characteristic line (Δx/Δt = -a)

$$H_{i,t} - H_{i+1,t-\Delta t} - \frac{a}{gA}\left(Q_{i,t} - Q_{i+1,t-\Delta t}\right) - \frac{f\Delta x}{2gDA^2} Q_{i,t}\left|Q_{i+1,t-\Delta t}\right| = 0 \qquad (2)$$

(4)

in which H = piezometric head, Q = flow rate, Δx = reach length, t = time, Δt = time step, a = water hammer wave speed, g = gravitational acceleration, f = Darcy-Weisbach friction factor, D = pipe diameter and i = node number. At a boundary (reservoir, valve), the boundary equation replaces one of the water hammer compatibility equations. The rectangular grid system is used in this work.

2.1 FULL CONVOLUTION ZIELKE MODEL

The original Zielke model[6] is a full convolution model and requires mass memory and computation time and has been modified by several researchers to get better in the computational efficiency and/or to enlarge its application to the transient turbulent flow conditions[7]. On account of space consideration the original Zielke model is described briefly here. As an alternative the unsteady friction factor used in Eqs. (1) and (2) can be suggested as a sum of the quasi-steady part and unsteady part as shown in Eq. (5). The unsteady part of friction term is related to the weighted past velocity changes at computational section:

$$h_f(t) = \frac{fV(t)\left|V(t)\right|}{2gD} + \frac{16\nu}{gD^2}\int_0^t \frac{\partial V}{\partial t^*} W_0\left(t - t^*\right) dt^* \qquad (5)$$

The approximate weighting function was defined as

$$W(\tau) = \begin{cases} \sum_{i=1}^{6} m_i \tau^{\frac{1}{2}i-1} & \textit{for} \;\; \tau \le 0.02 \\ \sum_{i=1}^{5} e^{-n_i \tau} & \textit{for} \;\; \tau > 0.02 \end{cases}$$

$$\tau = \frac{4\nu}{D^2}(k - j)\Delta t \qquad (6)$$

in which j and k = multiples of the time step Δt, W = weights for past velocity changes, ν = kinematic viscosity of the fluid, τ = dimensionless time, and coefficients $\{n_i, i = 1, \cdots, 5\} = \{26.3744, 70.8493, 135.0198, 218.9216, 322.5544\}$ and $\{m_i, i = 1, \cdots, 6\} = \{0.282095, -1.25, 1.057855, 0.937500, 0.396696, -0.351563\}$.

2.2 Recursive Convolution Zielke Model

The recursive convolution model is a approximate model and can do efficient and accurate calculation of Zielke model and Vardy-Brown model[8].

The weighting function is approximated by a finite sum of N exponential terms

$$W_{app}(\tau)=\sum_{k=1}^{N} m_k e^{-n_k\tau} \tag{7}$$

The unsteady head loss becomes

$$h_f(t)=\frac{fV(t)|V(t)|}{2gD}+\frac{16\nu}{gD^2}\sum_{k=1}^{N} y_k(t) \tag{8}$$

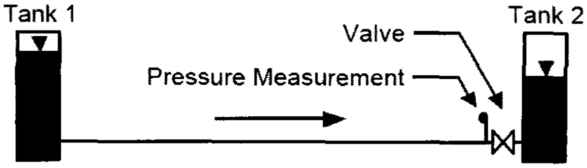
where the recursive variables y_k are defined as

$$y_k(t)=\int_0^t \frac{\partial V}{\partial t^*} m_k e^{-n_k K(t-t^*)} dt^* \tag{9}$$

and where the constant K (= $4\nu/D^2$) converts the time, t, into the dimensionless time, τ. It is a numerical method for the efficient implementation of weighting function unsteady friction models that is based on that of Kagawa et al.[11] and is further improved by Vitkovsky et al.[8]. In contrast to Kagawa et al.[11], Vitkovsky et al.[8] considered the component y_i at time t + $2\Delta t$ so that the calculation is sampled from one MOC diamond grid only and produces an efficient recursive expression for the component y_k and hence h_f.

Table.1 Best fit exponential sum coefficients for Zielke weighting function[8]

	10 Coefficient Fit		
k	n_k	m_k	τ_{mk}
1	26.5976	1.02700	1.00×10^{-1}
2	78.6005	1.31342	5.70×10^{-2}
3	202.234	2.14832	2.00×10^{-2}
4	540.226	3.70620	7.20×10^{-3}
5	1501.07	6.37762	2.47×10^{-3}
6	4267.16	10.9363	8.43×10^{-4}
7	12286.9	18.7309	2.87×10^{-4}
8	35639.2	32.0736	9.52×10^{-5}
9	103956	55.1523	2.82×10^{-5}
10	309336	99.4544	7.05×10^{-6}



Laminar Flow Simulation Details

L = 36.088 m; H_2 = 25.0 m, V_0 = 0.12 m/s, a = 1324.356 m/s; D = 25.4 mm; g = 9.81 m/s^2; $\nu = 39.67\times10^{-6}$ m^2/s; ρ = 998.2 kg/m^3, **Re** = 76.8

Fig. 1 Flow Simulation Details[8]

$$y_k(t+2\Delta t)=e^{-n_k\Delta\tau}\left\{e^{-n_k\Delta\tau}y_k(t)+m_k\left[V(2\Delta t)-V(t)\right]\right\} \tag{10}$$

It is worth to note that there is no convolution and the complete history of velocities is now not required; but it needs the storage of N extra variables $y_1, \cdots, y_N$ at each space location. For details see for references[8,11].

3. FLUID TRANSIENT ANALYSIS

3.1 Model Validation

The model validation is conducted through a comparison with results of the standard water hammer algorithms and experimental data[8]. In Fig. 1 the flow simulation details are presented.

Computational results from the present models (full convolution and recursive convolution model) and the original Zielke model are compared and depicted in Fig. 2 and its FFT results that to show differences of power spectral density in Fig. 3. All of Computational results meet the result of well-proven Zielke model but the result of quasi-steady friction model agree well for only the first period of the transient (4L/a).

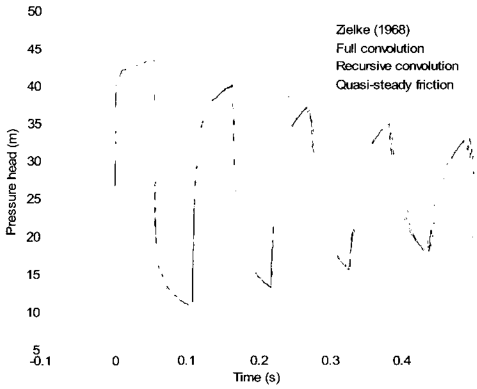


Fig. 2 Model validation case: Pressure oscillation

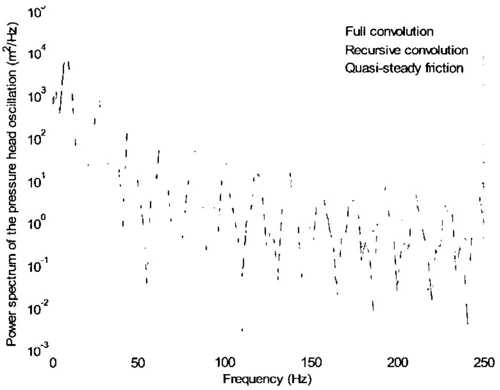


Fig. 3 Model validation case: FFT results

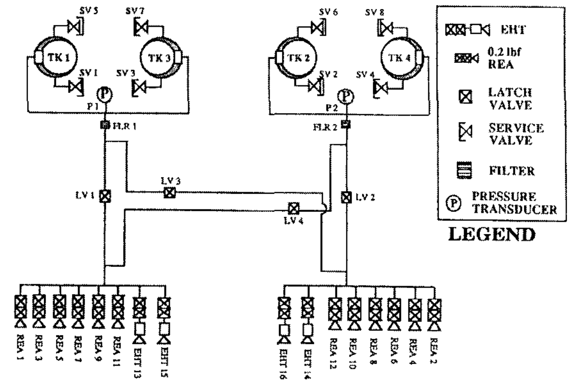


Fig. 4 Schematic of propulsion system

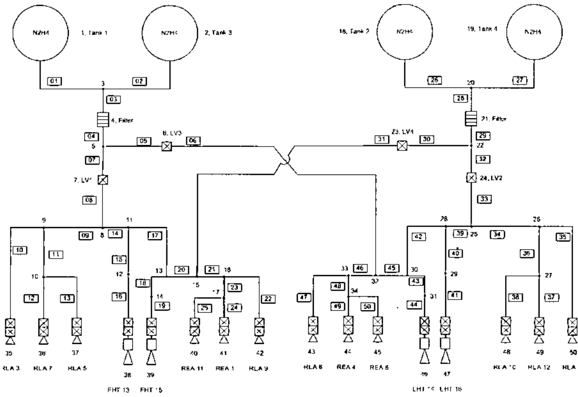


Fig. 5 Computational model diagram

3.2 PROPULSION SYSTEM OF KOREASAT 1 & 2

It shows the schematic of propulsion system of Koreasat 1 & 2 in Fig. 4.

It is a hydrazine monopropellant blowdown subsystem. It is divided two independent half-systems each capable of performing all thrusting maneuvers and each half-system consists of two 0.5 m diameter tanks supplying fuel for six 0.9 N catalytic rocket engine assemblies (REAs) and two 0.4 N electrothermal hydrazine thrusters (EHTs). A Ti all-welded manifold network include latching valves, fill and drain valves, filters, pressure and temperature instrumentation, and thermal control equipment. Each half-system will have a normally-open latch valve (LV1 and LV2) which can be closed in the event of leak to isolate the tanks of half-system from its thrusters. The cross-over lines are normally closed off by the latching valves (LV3 and LV4), which can be opened if one thruster set must be isolated due to leakage [12]. All 50 lines and 50 junctions are considered in a model to analyze fluid transients as shown in Fig. 5.

3.3 THRUSTER VALVE OPERATIONS

The thruster inlet pressure range of the REAs is from 400 to 80 psia and EHTs, 350 to 85 psia as shown in the Table. 2. The response times of thruster valve are usually less than 20 ms, in this work 20, 10 and 1 ms are considered as parameters shown in the Table. 4. Other conditions are the pipeline materials, Ti-3Al-2.5V and 304L SS, an on/off duty cycle of 250 ms on/750 ms off.

Table. 2 Operation and allowable inlet pressure ranges

Thruster	Operation inlet pressure range (psia)	Allowable inlet pressure range (psia)
REA	400 - 80	420 - 70
EHT	350 - 85	350 - 80

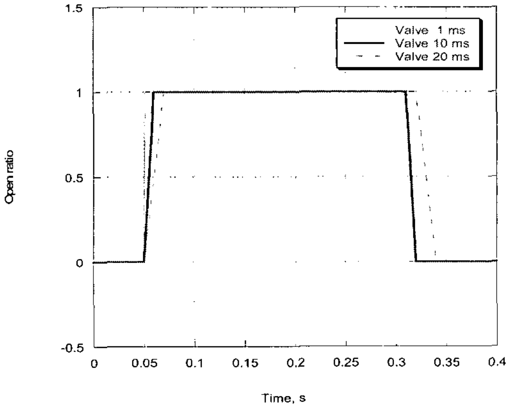


Fig. 6 Thruster Valve Opening/Closing Operations

In the Table. 3 the specific impulse requirements is shown.

Parametric studies are conducted according to the Table. 4. In Fig. 6 the thruster valve opening/closing times are shown with 250 ms On/750 ms Off.

3.4 RESULTS

The calculations are conducted for the opening and closing thruster valves of REA 5, 6, 7, and 8 (Station aquisition: East) at the operation inlet pressure ranges of 400 psia and 80 psia with quasi-steady friction and unsteady friction. But this section shows only the results of REA 8 because of similarities of the results.

It is difficult to identify the frequency components by looking at the original signal. A common use of Fourier transforms is to find the frequency components of a signal in a time domain. Converting to the frequency domain,

Table. 3 Specific Impulse Requirements

Feed Pressure Range (psia)	Duty Cycle (s)		min Isp (s)
	On	Off	
350 - 300	0.25	0.75	192
350 - 300	3.00	9.00	216
350 - 100	All others		113
350 - 100	1.0	83.2	137

Table. 4 Case Studies

Pressure (psia)	Thruster valve opening/closing time (ms)		
400	20	10	1
80	20	10	1

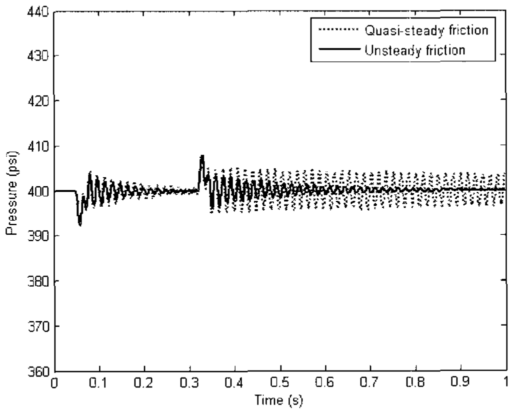


Fig. 7 Pressure oscillation of 20 ms & 400 psia.

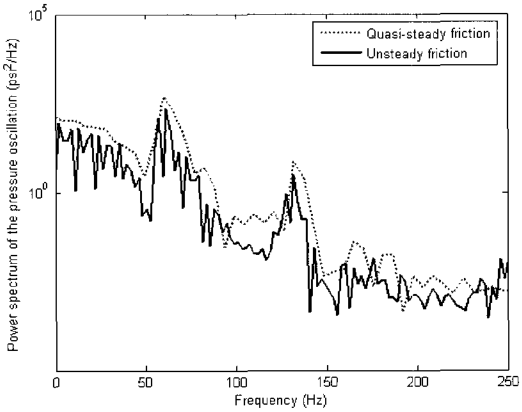


Fig. 8 PSD of 20 ms & 400 psia.

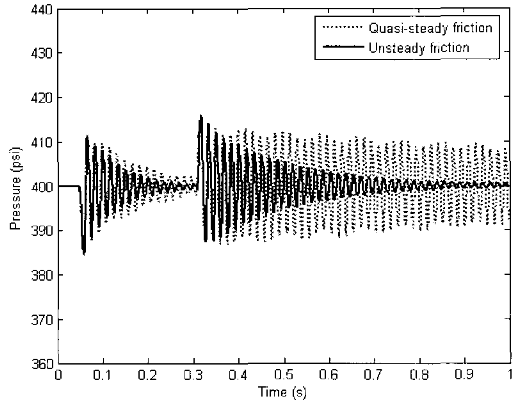


Fig. 9 Pressure oscillation of 10 ms & 400 psia.

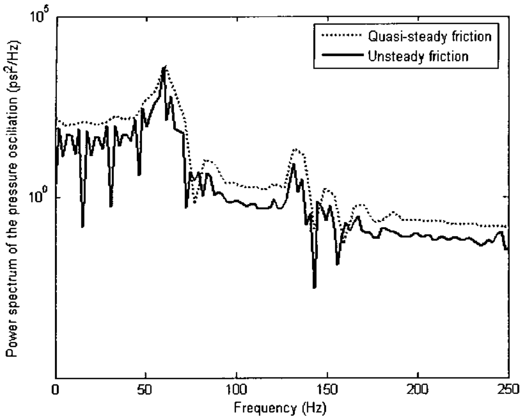


Fig. 10 PSD of 10 ms & 400 psia.

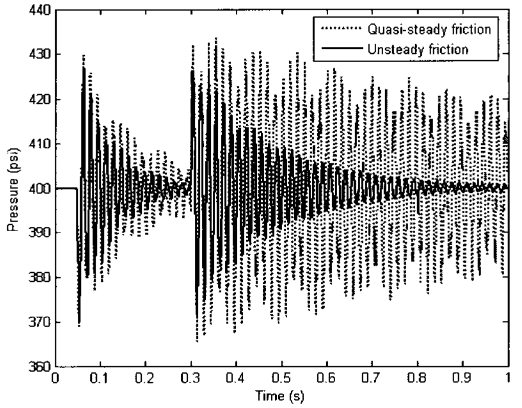


Fig. 11 Pressure oscillation of 1 ms & 400 psia.

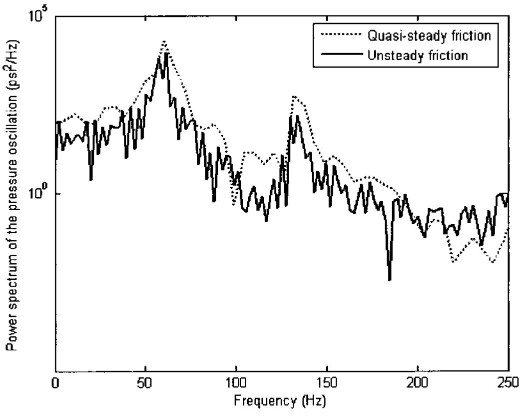


Fig. 12 PSD of 1 ms & 400 psia.

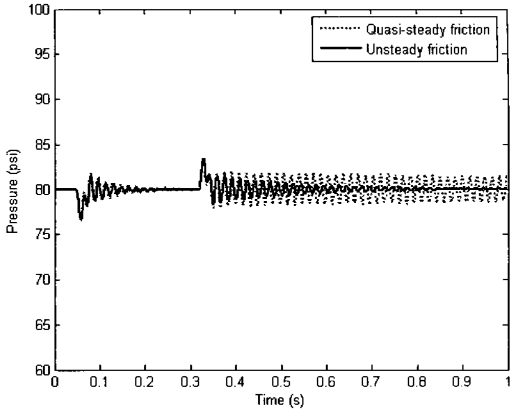


Fig. 13 Pressure oscillation of 20 ms & 80 psia.

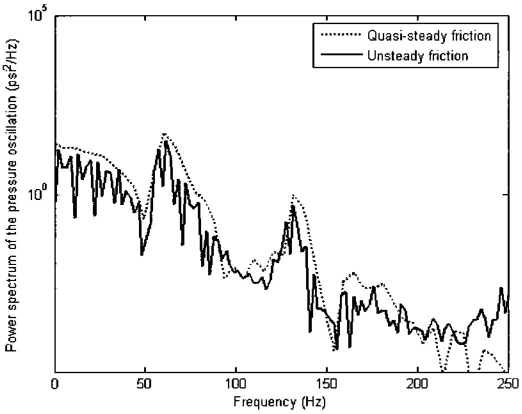


Fig. 14 PSD of 20 ms & 80 psia.

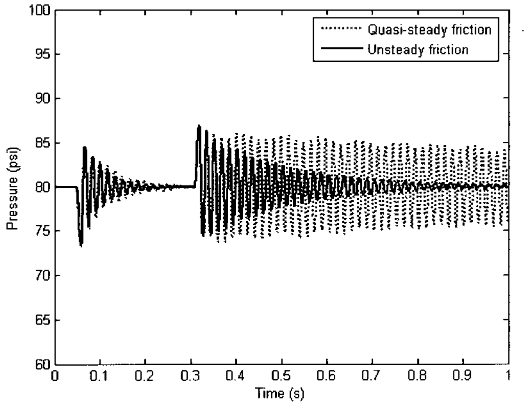


Fig. 15 Pressure oscillation of 10 ms & 80 psia.

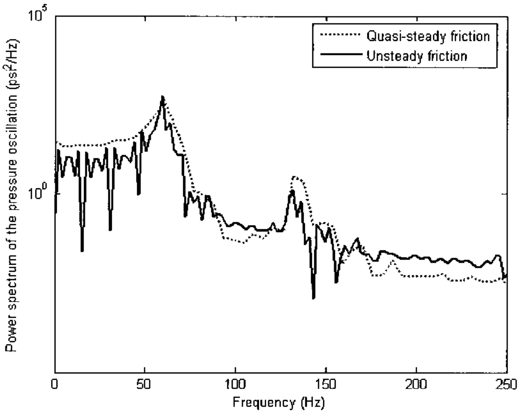


Fig. 16 PSD of 10 ms & 80 psia.

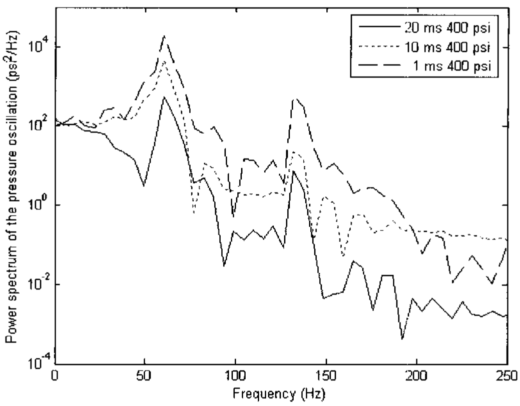


Fig. 19 QS PSD of 400 psia & 20, 10, 1 ms.

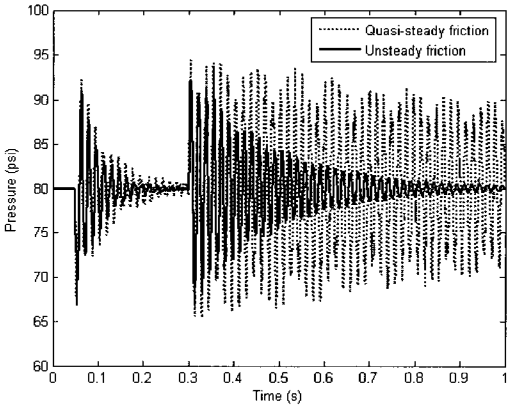


Fig. 17 Pressure oscillation of 1 ms & 80 psia.

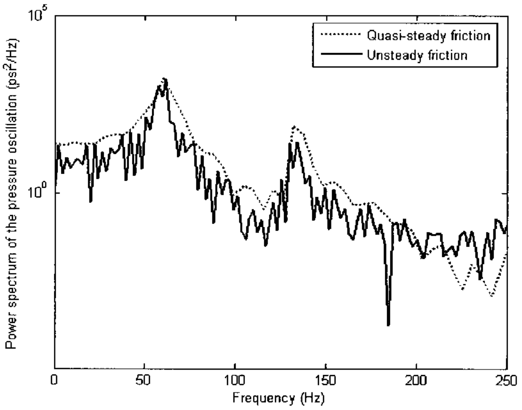


Fig. 18 PSD of 1 ms & 80 psia.

the discrete Fourier transform of the pressure oscillation data is found by taking the 512-point fast Fourier transform (FFT).

3.4.1 Pressure Oscillation and Frequency Components

The inlet pressure of thruster valve oscillates due to thruster valve opening/closing of 20 ms as shown in Fig. 7. On opening valve the pressure oscillation begins and then the oscillation amplitude of inlet pressure attenuates as fast as that of unsteady friction does and it goes to a steady state. On closing valve the inlet pressure of quasi-steady friction oscillates but attenuates at very slow rate. Because there is no other mechanism to be considered than the pipeline friction. But the inlet pressure of unsteady friction attenuates faster than that of quasi-steady friction does because the effect of unsteady friction is added. The frequency contents of quasi-steady friction and unsteady friction are shown in Fig. 8 and show clearly the difference in the power spectral densities (PSD) between quasi-steady friction and unsteady friction.

This similar patterns appears in the rest of results as shown from Fig. 9 to 18. As expected when the thruster valve opening/closing time gets short the amplitude of pressure oscillation gets higher and in 1 ms condition as a worse case it exceeds the allowable inlet pressure range. As the inlet pressure of thruster valve is reduced to 80 psia the effect of unsteady friction is still so strong that the amplitude of pressure oscillation of unsteady friction case gets attenuated faster than that of quasi-steady friction case.

These results show that the use of quasi-steady friction cannot predict the response curve except the amplitude but

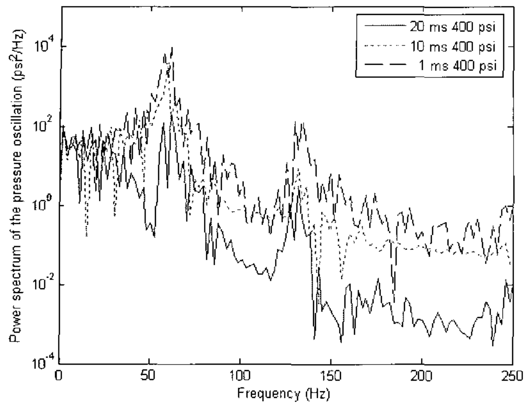


Fig. 20 US PSD of 400 psia & 20, 10, 1 ms.

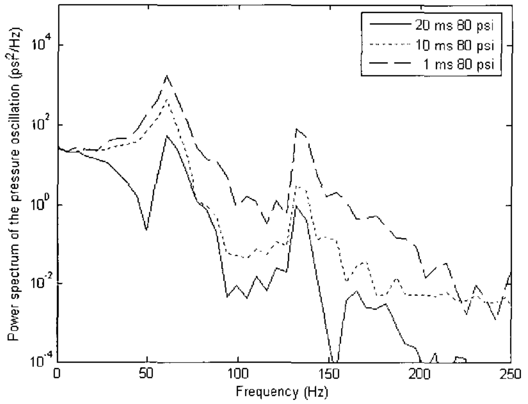


Fig. 21 QS PSD of 80 psia & 20, 10, 1 ms.

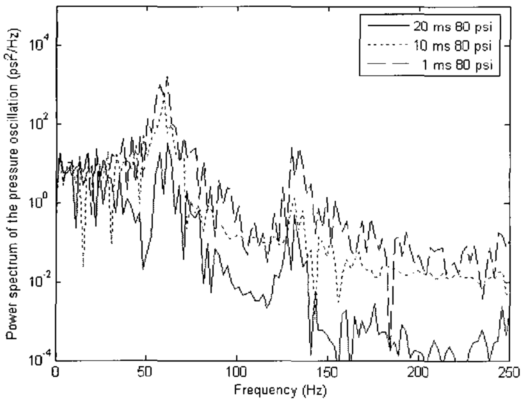


Fig. 22 US PSD of 80 psia & 20, 10, 1 ms.

the use of unsteady friction can predict the response curve reasonably and be able to be closer to the real situation.

3.4.2 QUASI-STEADY AND UNSTEADY PSDs

The Quasi-steady and unsteady frictions power spectral density results are compared as shown in Fig. 19 to 22 to find whether the change of frequency components occur because of the changes of valve operation time. Results show that shorter the valve operation time causes the greater response amplitude of pressure oscillation without changing the peak frequencies.

4. CONCLUSION

This work is done to identify fluid transient phenomena of Koreasat 1 & 2 propulsion system through numerical parametric studies in which a comparison between the quasi-steady friction and unsteady friction results is made. The valve operation time and unsteady friction are the dominant parameters to analyse the fluid transient phenomena. The results show that the shorter operation times cause the greater the response amplitude of pressure oscillation.

The results show that the use of quasi-steady friction cannot predict all the response curve properly except the peak amplitude but the use of unsteady friction can predict the response curve reasonably.

ACKNOWLEDGEMENT

The author gratefully acknowledges the financial support of the Ministry of Science and Technology of Korea and appreciates Dr. Anton Bergant and Dr. Vitkovsky, J.P who willingly provide their computational and experimental data.

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