Pressure Pulsator to Study the Low-Frequency Characteristics of a Liquid Rocket Engine

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Abstract - This paper presents the activities performed during the development of a pressure pulsator that was designed for the investigation of the low-frequency dynamic characteristics, such as the transfer function, of a liquid rocket engine (LRE). A cam-type pressure pulsator, which can generate sinusoidal pressure oscillations at frequencies up to 166 Hz, was designed and fabricated. A BLDC motor of 250 Watts was used to actuate the pulsator. Sinusoidal pressure oscillations were generated from 10 Hz to 130 Hz in steps of 10 Hz via control of the motor rotational speed. High-quality sinusoidal pressure oscillations were acquired successfully up to 100 Hz.

Keywords: Pressure Pulsator, LRE.

1. Introduction

A cam-type pressure pulsator is used to evaluate the low-frequency instability of an LRE and also acquire the transfer function of an LRE or a part of the hydraulic system, such as a regulator. The cam-type pressure pulsator can generate sinusoidal pressure oscillations of low frequency less than 100 Hz [5]. Alternatively, a disk-type pulsator is used for the study of the dynamic characteristics of an LRE's injectors because the disk-type pulsator can generate pressure oscillations higher than 1 kHz [1~4]. However, the pressure oscillations generated by the disk-type pulsator have not only a target frequency but also many other frequencies because of the interference between holes on a disk. Therefore, cam-type pulsators (which can generate cleaner pressure oscillations compared to disk-type pulsators) are generally used when target frequencies are lower than 100 Hz for the study of the low-frequency characteristics of an LRE or a propellant feeding system of a rocket [5]. Shnyakin [5] reported that the pressure oscillations generated by a cam-type pulsator showed good agreement with the mathematic sinusoidal oscillations, with discrepancies within 6%.

Jung [7] simulated a cam-type pulsator including a hydraulic test facility using mathematical models to determine the key design parameters of the pulsator. He used transfer matrix and impedance methods [6] in frequency domain simulations and AMESim commercial code in time domain simulations. He showed that almost perfect sine waves could be generated by the pulsator and that an orifice installed at the inlet line of the pulsator could effectively adjust the amplitude of the sinusoidal waves.

In this paper, a cam-type pressure pulsator driven by a BLDC motor is introduced as shown in Fig. 1, which has been designed and fabricated for the investigation of the low-frequency dynamic characteristics of an LRE. Performance evaluations of the pulsator were fulfilled experimentally in the low-frequency domain.

2. Design of Pulsator

Fig. 2 shows the configuration of a cam and a nozzle. Two circular cams with radius 'R' have eccentricity 'e'. This structure can make the flow area between the nozzle and the cam change as a sinusoidal wave, in accordance with the cam rotation. Assuming that the radius of the cam is large enough compared to clearance 't', the flow area between the cam and nozzle is expressed as Eqn.(1), where 'd' is the flow diameter of the nozzle.

$$A = \pi \cdot d \cdot t \tag{1}$$

The relationship between clearance 't' and rotational angle 'θ' is expressed as Eqn. (2).

$$t = \mathbf{C} - \sqrt{(\mathbf{R^2} - \mathbf{e^2}) + (\mathbf{e} \cdot \cos\theta)^2} - \mathbf{e} \cdot \cos\theta \qquad (2)$$

$$\mathbf{t} = \mathbf{C} - \mathbf{R} - \mathbf{e} \cdot \cos\theta \qquad (3)$$

Alternatively, a perfect sinusoidal wave for clearance 't' is expressed as Eqn.(3), which is different from Eqn.(2). Nevertheless, the discrepancy of 't' can be ignored if the eccentricity 'e' is small enough in Eqn.(2). In this study, the pulsator is designed to have the discrepancy of 't' to be less than 0.3%.
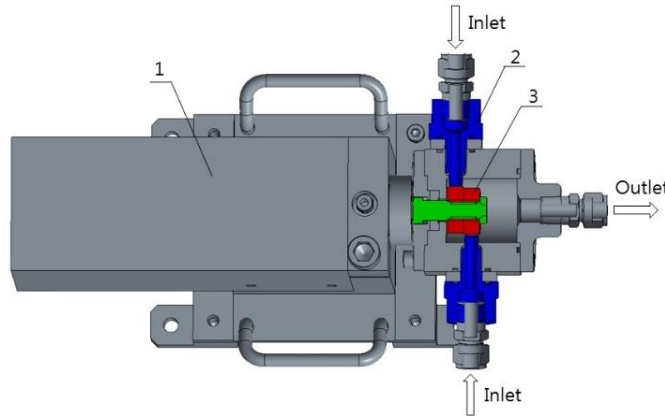
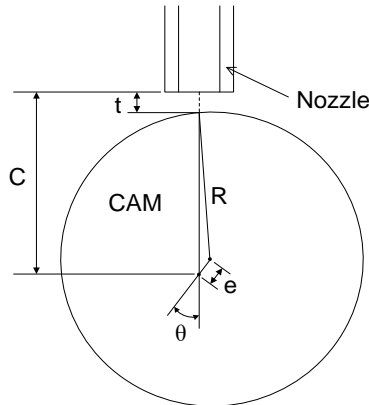Fig. 1: Cam type pulsator (1-BLDC motor, 2-nozzle, 3-cam)

Fig. 2: Configuration of cam and nozzle

3. Fabrication of the Pulsator and Controller

The pulsator and controller were fabricated as shown in Fig. 3. A 250-watt BLDC motor specified in Table 1 is used to drive the pulsator. The motor is equipped with an encoder for precise control of the rotational speed.

The controller can control the rotational speed of the motor up to 10,000 rpm, corresponding to a pulsator frequency of 166 Hz. The controller comprises an embedded real-time controller (such as NI-cRIO-9075) and a motor driver (amplifier). In addition, the controller can acquire data on not only the motor status but also the pressure and flow rate of the hydraulic lines in a test facility. A computer communicates with the controller via TCP/IP, gives control orders to the controller and takes data from the controller at a sampling rate of 2 kHz. The control S/W is programmed using LabVIEW, as shown in Fig. 4.
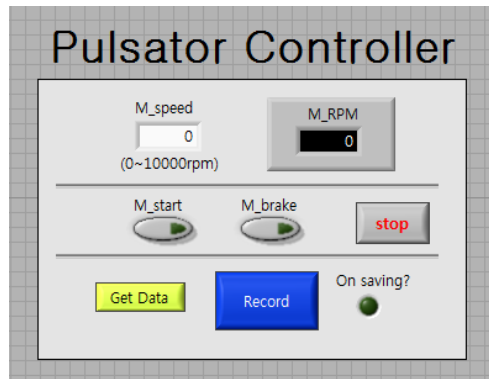
Fig. 3: Controller (left) and pulsator (right).

Fig. 4: GUI of pulsator control S/W.

Table 1: Specification of BLDC motor (Maxon EC45).

Specification	Unit	Value
Input Voltage	V	48
Power	Watt	250
Nominal speed	RPM	10,000
Nominal torque	mNm	316
Number of pole pair	-	1

4. Experiment and Performance Evaluation of the Pulsator

Experiments were performed on a test facility, as shown in Fig. 5. The purpose of the experiments is to evaluate the performance of the pulsator before an LRE test. The pressure capacity of the test facility is 180 bar. A run tank was filled with water and pressurized by nitrogen gas. The main hydraulic line was equipped with a regulator (throttle valve) and an orifice. The by-pass line was equipped with a pulsator and an orifice. The amplitude of pressure sinusoidal oscillations was well manipulated by adjusting the flow diameter of the orifice in front of the pulsator, as reported by Jung [7].
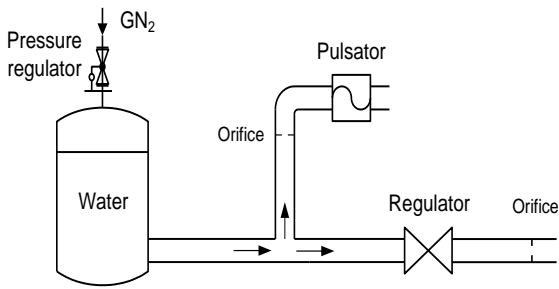
Fig. 5: Schematic diagram of test facility and test setup.

Sinusoidal pressure oscillations were generated from 10 Hz to 130 Hz in steps of 10 Hz via control of the motor rotational speed. The inlet pressure of the regulator was measured at a sampling rate of 2 kHz. Representative test results of pressure oscillations and FFT are shown in Fig. 6-9. High-quality sinusoidal pressure oscillations were acquired successfully up to 100 Hz. Except for harmonic frequencies of the target frequency, other frequencies were not found. When the frequency was higher than 100 Hz, as shown in Fig. 9, the amplitude of the 2nd harmonic frequency increased.
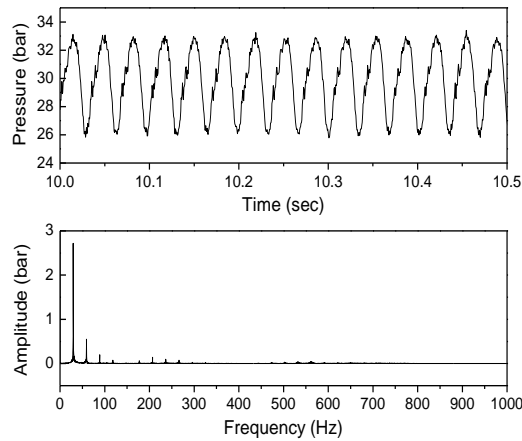

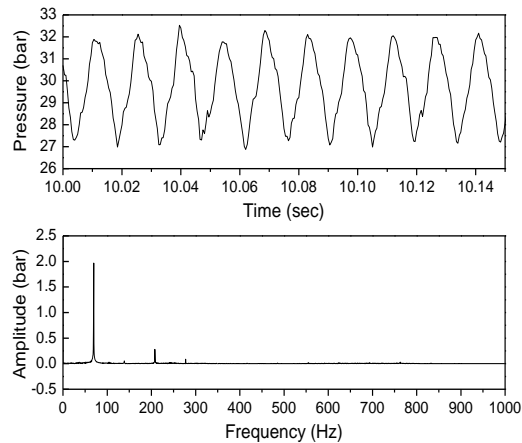Fig. 6: Pressure wave and FFT (30 Hz).
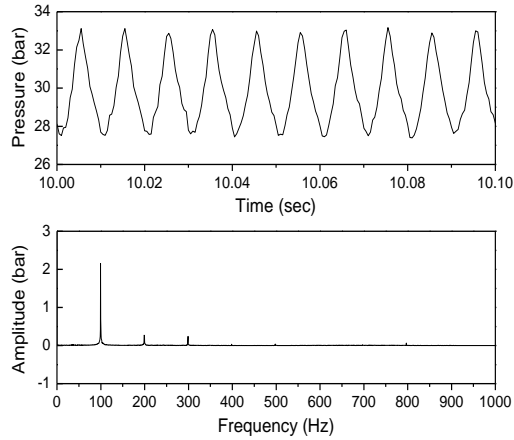

Fig. 7: Pressure wave and FFT (70 Hz).

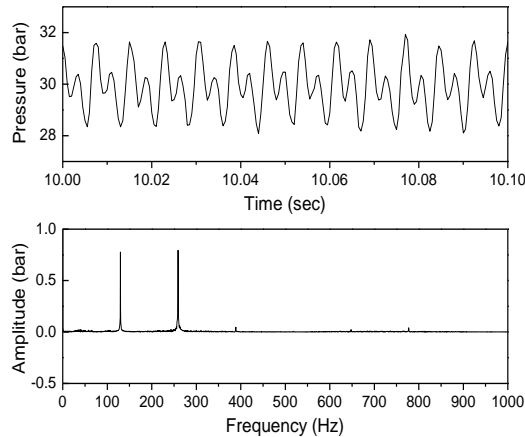ICMIE 108-4

Fig. 8: Pressure wave and FFT (100 Hz).

Fig. 9: Pressure wave and FFT (130 Hz).

6. Conclusion

The design and performance evaluation of a cam-type pulsator were summarized in this paper. High-quality sinusoidal pressure oscillations were acquired successfully up to 100 Hz. Other frequencies, except for harmonic frequencies of the target frequency, were not found. In addition, the amplitude of the 2nd harmonic frequency of the target frequency was found to be negligible up to 100 Hz.

The pulsator introduced in this paper can be used effectively for not only the study of the low-frequency dynamic characteristics but also acquiring the transfer function of an LRE or a propellant feeding system.

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