Dynamic calibration of pressure sensors at low frequencies using liquid step pressure generator with special spool valve

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Abstract

This study presents a dynamic pressure calibration technique using a liquid step pressure generator for evaluating the dynamic response of conventional pressure sensors at low frequencies. The technique is sufficient to display the transient response of pressure sensor in the time and frequency domains. Besides the system identification process, the dynamic calibration depends on a pressure generator, which determines a range of the calibration. In this study, the liquid step pressure generator was developed with a spool valve to generate a step pressure in a liquid situation. The sensing cavity, where maintains the liquid step pressure, is the main feature of the generator. Its extremely small volume limits the pressure transient caused by fluid in the generator, so the rise time and the bandwidth of the liquid step pressure reaches 30.0 µs and 10.4 kHz, respectively. The experimental results not only display the performance of the liquid step pressure generator, but also reveal the dynamic characteristics of three different pressure sensors based on the least squares method.

Keywords: Dynamic pressure calibration, transient response, liquid step pressure, pressure sensors, spool valve

1. Introduction

For a dynamic pressure measurement, the dynamic characteristics of pressure sensors almost dominate the accuracy of their pressure signals, so pressure sensors should be calibrated dynamically before using them. Dynamic pressure calibration is an approach to identify the dynamic characteristics of pressure sensors in the time or frequency domains. Besides a signal processing of system identification, the approach depends on a pressure generator which realizes a reference pressure signal to stimulate a test sensor. The performance of the pressure generator determines a range of the calibration, and it should cover a wide range of harmonics of interest.

Pressure generators are commonly divided into two types – periodic and aperiodic pressure generators based on their waveform. Periodic pressure generators usually employ a rotating valve to generate periodic pressure by continuously switching a fluid passage between on and off, such that the transient response of the generated pressure increases as its rotation rate increases, but the rotation rate are limited by the increment of fluid temperature [1]. Hydraulic and pneumatic square pressure generators have been used to study the dynamic characteristics of pressure sensors in the frequency domain based on the frequency response method [2, 3]. The main drawback to generating periodic pressure is that the bandwidth frequency of period pressure is too low to examine modern pressure sensors. Aperiodic pressure generators are superior to periodic pressure generators in the bandwidth frequency of generated pressure. The generators generate aperiodic pressure with a high bandwidth frequency between a few kHz and hundreds of kHz. Step and impulse pressures are the typical aperiodic pressure, and pneumatic step pressure has been adopted to be a standard pressure in dynamic pressure calibration in France [4]. Shock tubes and quick-opening
devices are the common aperiodic pressure generators which generate step pressure by connecting a low-pressure chamber to a high-pressure chamber rapidly.

A choice of pressure generators adopted in dynamic pressure calibration depends on the context of the actual measurement of test pressure sensors. This work presents that a liquid step pressure generator, aperiodic pressure generator, using a reformed spool valve attempts to conduct the dynamic pressure calibration of pressure sensors, which are often adopted in liquid situations. In fact, it is difficult to generate a liquid step pressure with short rise time by general aperiodic pressure generators because the quick-opening mechanism of the generators involves a change in volume, which brings a serious problem of pressure drop in liquid situations. Therefore, aperiodic pressure generators generate pneumatic pressure instead of liquid pressure. However, the liquid step pressure generator in this study provides a liquid step pressure with a short rise time, and it certainly increases a range of dynamic pressure calibration in liquid situations.

2. Description of liquid step pressure generator

Figure 1 presents the structure of the liquid step pressure generator that utilizes a reformed spool valve, which comprises a spool and alloy housing. There are three lands on the spool, and it forms a low-pressure chamber and a high-pressure chamber with the housing. Unlike conventional sealing in spool valves, contact sealing is adopted to improve the sealing capacity in the generator. The spool is reciprocated in the housing by an external impact force, which is responsible for the quick-opening motion for the generator.

Sensing cavity, where a step pressure is maintained, is the main feature of step pressure generators, and its volume almost dominates the pressure transient of the generated step pressure. Therefore, the sensing cavity should be as small as possible to limit the pressure transient. The sensing cavity in this study is around 0.1 cm³. Besides the sensing cavity, the design of the sensing ports at the end of the sensing cavity ensures that the reference pressure signal detected by a reference pressure sensor is the same as the pressure signal detected by a test pressure sensor. For general step pressure generators using poppet valves, their reference pressure sensors are far from test pressure sensors, so the measurement uncertainty increases in dynamic pressure measurement. However, the distance between the reference pressure sensor and the test sensor in this study is around 0.3 mm, such that the reference signal can be regarded as the input signal of the test pressure sensor in the dynamic pressure calibration. Moreover, the design of the adopter in the test sensing port is considered to install a test pressure sensor with different exterior.

The principle of the generation of the liquid step pressure is that the sensing cavity with a low pressure suddenly connects to the high-pressure chamber. Figure 1 shows the spool at an initial position, where the sensing cavity connects to the low-pressure chamber, and two
chambers are charged. After the pressure charge, two pressure chambers are isolated by external control valves to prevent a detrimental effect from the fluid in the connecting lines. Then, the spool is shifted toward lift the second position, where the high-pressure chamber connects to the sensing cavity, and it is moved by an impact. Figure 2 plots a side view of the sensing cavity at the second position. The liquid step pressure is rapidly generated in the sensing cavity when the high-pressure chamber is suddenly connected to the sensing cavity, and the pressure sensors simultaneously record the pressure. The amplitude of the liquid step pressure $P_s$ is a little lower than the high pressure because it is a sum of low pressure in the sensing cavity and high pressure in the high-pressure chamber. However, the extreme small sensing cavity, the reference sensing port setting opposite the test sensing port, and the quick-opening mechanism are employed to obtain liquid step pressure with a short rise time.

However, the quick-opening mechanism and extreme small sensing cavity are adopted to obtain a liquid step pressure with a short rise time, and the geometric and dimensional tolerances of the generator are strictly controlled to seal the passages in the generator.

3. Transient response of pressure sensors

Film resistors, strain gauges, metal alloys, or polycrystalline semiconductors are commonly used in regular pressure sensors as the resistive media. These materials conduct current or electricity based on geometric deformations in their structure. The dynamic pressure calibration must be applied to verify the realized pressure because the deformations are not exactly proportional to a pressure change. The unit-step transient response of conventional pressure sensors can be presented by a mass-spring model with mass, $m_s$, stiffness, $k_s$, and viscous damping, $c_s$. In the dynamic pressure calibration, the generated step pressure passes through the sensing cavity before the test sensor receives it, such that the signal the test pressure sensor detected reflects not only the transient response of the sensor but also the pressure transient of the fluid in the sensing cavity. Thus, the unit-step transient response received by the sensor should be represented by a modified model, which includes the pressure transient of the fluid.

![Fig. 3. Transient response model in the pressure generator.](image)

Figure 3 plots the modified model. The fluid properties are defined by suffix f, and its transfer function can be described by Eq. 1

$$\frac{X_f(s)}{F(s)} = \frac{c_f s + k_f}{(m_f s^2 + c_f + k_f)(m_s s^3 + (c_s + c_f) s + k_f + k_s) - (c_f s + k_f)^2}$$

(1)

To obtain the dynamics of the sensor, the mass of the fluid should approach to zero based on Eq. 1, but it is difficult to generate a step pressure without pressure transient. However, liquid medium was adopted in this study because of its high bulk modulus, as compared to gas medium. Furthermore, the pressure signal measured by a test pressure sensor is regarded as the output signal, and the reference signal is regarded as the input signal in the dynamic pressure calibration. The dynamic characteristics of the test pressure sensors are obtained by a comparison of the input and output signal based on the least squares method [5].
4. Experimental setup and design

Figure 4 shows the experimental setup, comprising the liquid step pressure generator, a hydraulic pressure system, and the measurement system. The liquid step pressure generator using the spool was reciprocated by an external piston with a displacement sensor, and its spool velocity was fixed at 1.5 m/s. The hydraulic pressure system provided the low-pressure chamber and high-pressure chamber with stable pressure. The low and high pressures were fixed at 0.1 MPa and 3.0 MPa, respectively. Moreover, the fluid temperature was always at 26–28°C detected by thermocouple to maintain fluid properties. Finally, the measurement system included a reference piezoelectric pressure sensor and an analyzer were adopted. Three test pressure sensor A, B, and C, were calibrated orderly, and these sensors were installed in the generator with different adapters. Moreover, the sampling frequency of the measurement system was fixed at 64.0 kHz and, the number of the sampling points was set to 2048. All signals were transferred to a computer.

5. Results and discussion

Figure 5 shows the transient response of the generated liquid step pressure in the time domain and its frequency response in the frequency domain. The transient response converges toward a steady state in 0.3 ms. Its rise time is roughly 30.0 µs which is shorter than earlier researches [2, 6], and the bandwidth frequency is around 10.4 kHz. The generator certainly expands a range of the dynamic pressure calibration.

Figure 6 displays the transient response of three test pressure sensor to the liquid step pressure in the time domain. The damping vibration of sensor B and C act as the underdamped vibration, but the vibration of sensor A is close to a critically damped or overdamped vibration without an overshoot. The irregular damping vibration of the pressure sensors could be caused by air bubbles in the fluid and deformation of materials in the
pressure sensors; however, it reveals the dynamic reactions of the pressure sensors in the time domain. According to the transient response of the pressure sensors, the frequency response of the pressure sensors are obtained by the comparison of the input and output signals based on the least squares method. Figure 7 demonstrates the frequency response of the pressure sensors in the frequency domain by a bode diagram. Obviously, sensor C has the largest bandwidth than other two sensors, but its resonant peak is roughly 4.0 dB at the resonant frequency of 2.1 kHz. Additionally, Sensor A has no resonant peak. The phase of the frequency response displays the phase margin of the pressure sensors, which clearly indicates the stability of the pressure sensors.

![Bode diagram of three test pressure sensors.](image)

6. Conclusion
The liquid step pressure generator using an innovative spool valve was developed to calibrate dynamically three different pressure sensors based on the least squares method. The extremely small sensing cavity limits the interference caused by the pressure transient of fluid in the generator, and the symmetric installation of the test and the identical reference pressure sensors ensures that the same liquid step pressure is received by both pressure sensors. The generator expands the range of dynamic pressure calibration in liquid situation, and its bandwidth reaches 10.4 kHz. Moreover, the Bode diagram clearly indicates the dynamic characteristics of three pressure sensors, and sensor C has the best performance in dynamic situations. Hence, the liquid step pressure is suitable pressure for identifying and calibrating pressure sensors at low frequencies.

References