Design and Optimization of Symmetrical Pulsating Pressure Generator Based on Gas Medium

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Abstract. In order to realize pulsating pressure in wide frequency and pressure range, this paper designs a symmetrical pulsating pressure generating device structure, which solves the problem of offset movement of the piston movement due to offset pressure and the problem of bias pressure retention. In addition, the main factors that limited the performance of the pulsating pressure generating device are analysed in detail, and the pulsating pressure generating demand in a wide frequency range is realized by segmentation processing.

1. Introduction
In recent years, the requirements of supersonic wind tunnel and other gas media, high frequency and high pressure dynamic pressure test with offset pressure have been increasing. Before measuring dynamic pressure, the pressure sensor first needs dynamic pressure calibration. Therefore, the research on dynamic calibration technology of such pressure sensors is of great significance [1-3]. For dynamic pressure calibration, the key lies in how to generate a pressure signal with stability, good repeatability, accurate amplitude and time index of signal, and convenient traceability to the international standard system of units (SI).

From the signal form, the pressure source of dynamic pressure calibration can be divided into three types: pulse pressure signal, step pressure signal and continuous period pressure signal. Step pressure and pulse pressure are adjustable frequency range is relatively narrow, and continuous in the form of a periodic signal is more close to the actual measurement of dynamic pressure signal, and its energy concentration, output stability, deterministic signal is good, can carry on the frequency sweep to the pressure sensor calibration and other characteristics, can get more accurate frequency response of the sensor or system, is a kind of static calibration methods [4-6], become the focus of the dynamic pressure calibration direction. Sinusoidal excitation signals are commonly used in continuous period pressure calibration. Corresponding to pressure sensors, sinusoidal pressure signals containing offset pressure are pulsating pressure signals. The conduction medium of pulsating pressure can be divided into liquid medium and gas medium. Generally speaking, since the compressibility of liquid medium is far less than that of gas medium, the pressure generation mode of liquid medium has great advantages in generating high frequency and high pressure pulsating pressure signals. However, pressure sensors used in wind tunnel testing, engine performance testing and other occasions should not be calibrated with liquid medium. Therefore, it is very important to study the generating device that can generate high frequency and high pressure pulsating pressure in the gas medium.

2. Structural Design of Pulsating Signal Generator
As shown in Fig. 1(a), the whole device consists of three main parts: a cylinder, a vibrating table and a biasing pressure applying structure. The piston rod is rigidly connected with the table of the shaking
table through the flange, so that the linear reciprocating vibration generated by the shaking table can directly drive the piston movement, making the volume of the air chamber on both sides of the piston in the cylinder change and generating pulsating pressure. The pressure sensor is sealed on the cylinder head by a specially designed mounting base to ensure that the additional volume brought by the installation of the sensor is as small as possible. A volume-matching unit is designed in the symmetrical position of the cylinder head to keep the pressure distribution on the end cover symmetrical. Similarly, the open valve of the offset pressure-applied design needs to be as close to the cylinder as possible to prevent the introduction of unnecessary initial cavity volume. In order to improve the piston movement origin deviation and gas leakage caused by offset pressure, a symmetrical gas pulsation pressure generator is designed and implemented in this paper. When the piston is at the original position of movement, both sides of the piston have the same offset pressure. Therefore, the force on the piston is balanced, which solves the problem of balance origin deviation. At the same time, due to the same pressure on both sides of the piston, the gas leakage problem has been improved. Finally, the schematic model of symmetrical gas pulsation pressure generator is obtained as shown in Fig. 1(b).

![Figure 1](image)

**Figure 1.** Device structure: (a) is structure block diagram; (b) is mechanical diagram

3. Optimization of Structural Parameters

In the symmetrical gas pulsation pressure generator, the initial offset pressure $P_s$, the initial volume $V_{20}$ of the air chamber and the volume change $V_{42}$ caused by reciprocating vibration of the piston are the three key parameters that determine the peak-to-peak (P-P) value of the pulsation pressure. In this paper, according to the demand of pulsating pressure (Table 1), the vibration displacement of the vibration table will be analysed by referring to the selection of the vibration table, and the main parameters of the cylinder will be designed accordingly. Vibration table is the power source of piston vibration and one of the core components of pulsating pressure generator. The main technical indexes that can be achieved, such as maximum thrust, maximum acceleration and maximum displacement, directly affect the design of pulsating pressure generating device in all aspects, and are also the main factors restricting the amplitude and frequency of pulsating pressure. According to the requirements of pulsating pressure, the vibration table with the technical parameters as shown in Table 2 is selected in this work.

| Table 1. Gas pulsation pressure generation requirements |
|-------------------------------------------------------|
| **Pulsating pressure frequency: 5 Hz ~ 100 Hz**       |
| Offset pressure (KPa) | P-P pressure (KPa) | Offset pressure (KPa) | P-P pressure (KPa) |
| 30 | 5 | 30 | 0.5 |
| 100 | 10 | 100 | 1 |
| 450 | 20 | 450 | 2 |


Table 2. Main technical parameters of vibration table

| Technical index                  | Parameters | Unit |
|----------------------------------|------------|------|
| Frequency range                  | 5~5000     | Hz   |
| Rated sinusoidal thrust           | 2.94       | kN   |
| Maximum acceleration             | 980        | m/s² |
| Maximum speed                    | 2          | m/s  |
| Maximum displacement             | 40         | mm   |
| Mass of moving parts             | 3          | kg   |

The peak range of $L_{dz}(f)$ of unilateral displacement of cylinder piston vibration at a certain frequency can be expressed as:

$$L_{dz, \text{min}}(f) \leq L_{dz}(f) \leq L_{dz, \text{max}}(f)$$  \hspace{1cm} (1)

Where, $L_{dz, \text{min}}(f)$ is the minimum unilateral displacement of cylinder piston at a certain frequency under the condition of guaranteeing the quality of vibration waveform. It is limited by the nonlinear characteristics of the vibration table, the accuracy of the vibration measuring sensor and the ambient noise level. $L_{dz, \text{max}}(f)$ is the maximum unilateral displacement of the cylinder piston at a certain frequency, which is limited by the maximum thrust of the vibration table.

$$L_{dz}(t) = L_{dz} \cdot \sin(2\pi \cdot f \cdot t)$$  \hspace{1cm} (2)
$$v_{dz}(t) = 2\pi \cdot f \cdot L_{dz} \cdot \cos(2\pi \cdot f \cdot t)$$  \hspace{1cm} (3)
$$a_{dz}(t) = -(2\pi \cdot f)^2 \cdot L_{dz} \cdot \sin(2\pi \cdot f \cdot t)$$  \hspace{1cm} (4)
$$L_{dz, \text{max}}(f) = \frac{F_{\text{max}}}{(2\pi f)^2 M}$$  \hspace{1cm} (5)

Where, $F_{\text{max}}$ is the maximum thrust of the shaking table, $M$ is the mass of moving parts (including load mass) of vibration table, $f$ is the vibration frequency. The vibration velocity and acceleration are bounded due to the restriction of vibration table index, so the range of vibration amplitude at the specified frequency is limited. If the maximum thrust is 3000 N and the load is 3 kg, the mass of the moving part is 6 kg and the maximum acceleration is about 50 g. Within 1 Hz to 100 Hz, there is the maximum amplitude-frequency curve as shown in Figure 2(a), and within 100 Hz to 500 Hz, there is the maximum amplitude-frequency curve as shown in Figure 2(b). The maximum amplitude of the vibration table from 5 Hz to 500 Hz is constrained as shown in table 3. It can be seen that with the increase of frequency, the vibration table will work under the limitation of maximum displacement, maximum velocity and maximum acceleration successively.

![Figure 2. Maximum amplitude-frequency curve: (a) within 1 Hz to 100 Hz, (b) within 100 Hz to 500 Hz.](image-url)
Table 3. Vibration table maximum amplitude constraints

| Frequency (Hz) | Piston maximum unilateral amplitude (mm) | Maximum speed (m/s) | Maximum acceleration (g) |
|---------------|----------------------------------------|---------------------|--------------------------|
| 500           | 0.05                                   | 0.157               | 50 (upper limit)         |
| 100           | 1.25                                   | 0.785               | 50 (upper limit)         |
| 25            | 12.8                                   | 2 (upper limit)     | 32                       |
| 5             | 20 (upper limit)                       | 0.628               | 2                        |

When the vibration frequency \( f = 5 \) Hz, if the peak-to-peak pulsating pressure with a peak-to-peak value of 5 kPa is to be generated under the bias pressure 30 kPa, the static-static pressure ratio should be 0.083, and the unilateral equivalent length of the cylinder should not be shorter than \( 5/0.083 \approx 60 \) mm. At 100 Hz, even when the vibration amplitude reaches the maximum, the equivalent length of the cylinder side shall not be longer than \( 1.5/0.083 \approx 15 \) mm. Therefore, the symmetrical cylinder of a single length cannot meet the requirements of pulsating pressure from 5 Hz to 100 Hz. It is necessary to further segment the frequency range and design the size of the symmetrical pulsating pressure generating device respectively. Among them, the cylinder with 195 mm length on one side is required to complete the pulsating pressure from 5 Hz to 30 Hz. The cylinder with 15 mm length on one side is used to complete the pulsating pressure generation requirements from 20 Hz to 100 Hz. Similarly, at 500 Hz, in order to generate the peak-to-peak pulsating pressure of 500 Pa at 30 kPa, the ratio of station-static pressure should reach 0.83%. Then, the equivalent length of one side of the cylinder should not be longer than \( 0.05/(0.83\%) \approx 6 \) mm. A cylinder with a unilateral length of 6 mm is selected to complete the pulsating pressure generation requirements from 100 Hz to 500 Hz.

The theoretical calculation results are respectively simulated and verified. Taking a cylinder with a unilateral length of 15 mm as an example, the pulsating pressure that can be generated within the frequency range of 20 Hz to 100 Hz is shown in Figure 3(a). Where, the black line box represents the demand for pulsating pressure at different frequencies. The red curve (the innermost part) represents the amplitude-frequency relationship of pulsating pressure generated by vibration of the vibration table when the maximum acceleration is 0.5 g. The blue curve (outermost) represents the amplitude-frequency relationship of pulsating pressure generated by vibration of the shaking table at a maximum acceleration of 50 g.

It can be seen that under the bias pressure of 30 kPa and 100 Hz, the maximum output acceleration of the vibration table is 50 g, corresponding to the maximum unilateral amplitude of 1.25 mm. At this time, the positive peak value of the pressure is 2.7 kpa, the negative peak value is 2.3 kpa, and the negative peak value is less than \( 5 \text{kPa}/2 = 2.5 \) kpa. Therefore, it is necessary to shorten the effective length of the cylinder and increase the negative peak pressure. The unilateral length of the cylinder was corrected to be 13 mm, and the simulation was conducted again. At this time, under the bias pressure of 30 kPa and 100 Hz, the maximum output acceleration of the vibration table is 50 g, corresponding to the maximum unilateral amplitude of 1.25 mm. At this time, the positive peak value of pressure is 3.2 kpa, the negative peak value is 2.6 kpa, and the negative peak value is greater than \( 5 \text{kPa}/2 = 2.5 \) kpa, which meets the preliminary requirements.
Figure 3. Amplitude-frequency curve under offset pressure of 30kPa. (a) The initial length of air cavity is 15 mm, (b) The initial length of air cavity is 13 mm

As shown in Figure 4, at the 450 kPa offset pressure and 25 Hz, the minimum acceleration of sinusoidal vibration of the shaking table is guaranteed to be 0.5 g, corresponding to the minimum unilateral amplitude of 0.2 mm, corresponding to the positive peak value of 7.03 kpa and the negative peak value of 6.82 kpa, which also meet the pulsating pressure of the peak value of 20 kPa.

Figure 4. Amplitude-frequency curve under offset pressure of 450 kPa within the 13 mm air cavity

Similarly, three symmetrical cylinders with effective lengths, as shown in Table 4, were finally determined to meet the requirements of pulsating pressure from 5 Hz to 500 Hz.

| Effective unilateral length of cylinder | Working pressure | Frequency range | Maximum speed |
|----------------------------------------|-----------------|----------------|--------------|
| 6 mm                                   | 10 kPa – 750 kPa| 20~500 Hz      | 2 m/s        |
| 13 mm                                  |                 | 10~300 Hz      |              |
| 195 mm                                 |                 | 5~50 Hz        |              |

4. Conclusion
In this work, the constraint conditions of various parameters of the pulsating pressure generator are analysed in detail, and the requirements for pulsating pressure generation in a wide frequency range
are realized through piecewise design, and the feasibility of the structure is determined through simulation analysis, which provides a theoretical basis for the realization of the pulsating pressure generation device.

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6. References
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