TRACEABLE DYNAMIC PRESSURE MEASUREMENT BASED ON MACRO DEFINITION OR MICRO INTERPRETATION

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Abstract - Traceable dynamic pressure measurement is the primary problem faced by dynamic pressure metrology. Various traceable dynamic pressure measurement methods are described and analyzed, which include inertia force, hydrostatic pressure, shock wave theory, laser-piston, refractive index, spectroscopy and so on. Based on the characteristics of various methods and the practices of dynamic pressure calibration researches in CIMM, they are grouped into three categories, which are macro definition of pressure, fluid state equation and fluid physical properties. The latter two are related to the microscopic characteristics of the fluid, and rarely used by static pressure metrology. The advantages and disadvantages of the three categories are compared. The inertial force method is an easy and reliable dynamic pressure measurement method under the existing conditions. The method based on the physical properties measurement, including the laser-refractive index method and spectroscopy method, directly measures the pressure medium's own characteristics and may be able to achieve a wider measurement range and higher dynamic measurement accuracy, which is an important development trend.

Keywords: Dynamic pressure, Traceable measurement, Pressure's macro definition, Thermodynamics, Laser measurement.

1. INTRODUCTION

The pressure in the practical test is often expressed as dynamic form. Dynamic pressure measurement in the engine, explosion, construction, railway, medical and other fields have a wide range of applications, such as pressure fluctuations in the engine combustion chamber, the bridge surface pulsating pressure, human blood pressure [1,2]. Dynamic calibration of pressure sensors or measurement systems is a guarantee of dynamic pressure measurement's accuracy. The dynamic pressure calibration methods are basically divided into three types according to the dynamic excitation signal: step pressure, periodic pressure (mainly sinusoidal pressure), impulse pressure (mainly half-sine pressure). The step pressure calibration, which is represented by shock tube and fast-open device, is the most mature technology. Their amplitude traceable measurement methods are based on shock wave velocity's measurement or platform pressure's static measurement. By for the increasingly used sinusoidal pressure or impulse pressure generators, reference sensors are usually used. The dynamic pressure's traceability has become the primary bottleneck for the development and application of dynamic pressure calibrations. The problem has been paid attentions to by researchers. EURAMET and NIST have strengthened the researches of the optical method for the traceable dynamic pressure measurement [3,4,5].

In this paper, the principles, applications and characteristics of various traceable dynamic pressure measurement methods are analyzed , which are based on the macroscopic definition of pressure or microcosmic interpretation from thermodynamics. According to the characteristics and requirements of dynamic pressure calibration, various methods are classified. The advantages and disadvantages of various methods and the scope of application are analyzed from the perspective of the research practice of dynamic pressure calibration technology. The development trend of traceable dynamic pressure measurement is also prospected.

2. DYNAMIC PRESSURE MEASUREMENT BASED ON THE MACRO - DEFINITION OF PRESSURE

Static pressure primary standards are basically piston pressure gauges or liquid pressure gauges. The traceable measurement of static pressure is mostly based on the macro definition of pressure.

$$P=F/S$$

Where F and S are the active force and the area between the piston and the fluid.

Researchers are also using this method to realize traceable measurement of dynamic pressure. The liquid impulse pressure calibration by laser interferometry is one typical application. In the calibration devices the drop-weight's acceleration is measured by laser interferometer and the active force is mainly from the inertial force, which is calculated from $F = M \times a$. The traditional way of drop-weight's acceleration is measured by an accelerometer [6]. In recent years, researchers have used laser interferometer to measure the acceleration (Italian INRIM, Finnish MIKES, etc.) [7, 8, 9] with higher precision, higher resolution and higher dynamic characteristics, so that the dynamic pressure is directly traced to mass, time and so on.

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Beijing(CIMM) has also studied the impulse pressure calibration by laser interferometry based on the macro-definition of pressure[10]. The impulse pressure amplitude's measurement range is (10 ~ 500) MPa, and the impulse width is (5 ~ 9) ms. As the impulse width is not so little, the device is mainly used to calibrate the piezoelectric pressure sensors' amplitude sensitivity. The device's object is shown in Figure 1, in which there is no cushion between the weight and the piston. The direct impact needs higher requirement for the impulse width control, but also eliminates the inertia force of the cushion for the measurement. Through the theoretical and experimental analysis of the influence of pressure and acceleration distribution and friction, the uncertainty of the calibration of amplitude sensitivity of piezoelectric pressure sensor is analyzed, and the uncertainty of expansion is less than 1.8%. The curve for calibrating (KISTLER 6213B) is shown in Figure 2. It is now being studied to extend the measurement range of the device to (5 ~ 800) MPa.
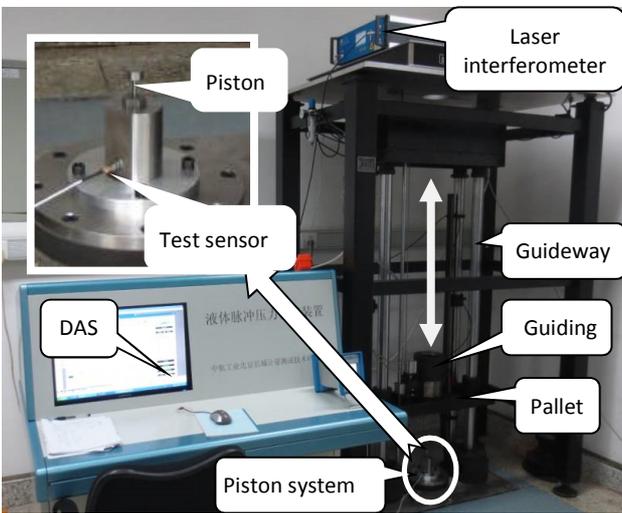

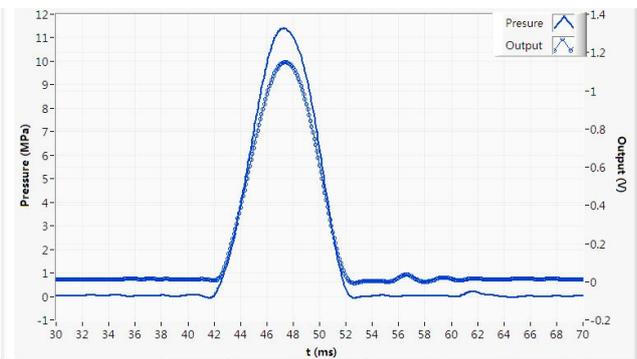Fig.1. Liquid impulse pressure calibration device by laser interferometry.

Fig.2 Impulse pressure signals measured by sensor and laser interferometry

The dynamic pressure can be clearly traced to the basic parameters in the dynamic pressure measurement method based on the macro-definition of pressure, and the calibration device is easy to achieve. However, the dynamic pressure measurement range and accuracy in this method are limited by the acceleration distribution in the inertial mass, the motion friction and so. For example, the impulse width should be less than 1ms and it requires the entire impulse waveform instead of the peak only to be measured when the impulse pressure is used to measure the sensors' frequency response or dynamic model. The uneven distribution of the inertia mass' acceleration and the pressure, dynamic response of the mechanical structure will be more significant when the impulse width is smaller, and the relative impact of the motion friction will be greater on the smaller pressure. One more prominent limitation is that the method cannot be used for dynamic pressure measurement where there is significant static pressure, and it needs to be combined with a particular type of dynamic pressure generator.

In addition, the hydrostatic pressure method ($p = \rho g h$) is also used for the measurement of underwater acoustic pressure and low frequency sinusoidal pressure such as the vibrated liquid column method[11] and the inclined water column method[12], which is extended from the macroscopic definition of pressure. But the method can only be used for low-frequency small-scale dynamic pressure calibration because of the fluctuations of surface, the surface tension, etc.

3. DYNAMIC PRESSURE MEASUREMENT BASED ON FLUID STATE EQUATION

For the fluid medium with changeless mass, the fluid state equation establishes the relationship between volume, pressure and temperature. There is the following equation of state for the ideal gas.

$$pV = \frac{m}{M}RT$$

Where p, V, m, M and T are the pressure, volume, mass, molar mass and thermodynamic temperature of the gas respectively, and R is the Avogadro constant.

Therefore, the dynamic pressure can be calculated from the change of volume for the dynamic pressure generators with variable volume (such as sinusoidal pressure generators or impulse pressure generators with piston systems). Of course, this pressure is interpreted by thermodynamics with molecular motion.

The change of the volume is calculated from the piston displacement's measurement in the variable volume closed cavity by laser interferometry. According to the known initial volume and the average pressure, the pressure change is obtained based on the adiabatic gas model. Then the dynamic pressure traceable measurement is realized. NPL and other NMIs have achieved low-frequency sound pressure calibrations [13,14,15] using this method. CIMM has studied the micro sinusoidal pressure calibration technology under low pressure or negative pressure using this method [16].

A piston-in-cylinder device actuated by vibrator is used to generate micro sinusoidal pressure form 1Hz to 500Hz in an pressure chamber with air and the average pressure can be adjusted from negative pressure to low positive pressure. Raster system measures the piston's static and dynamic displacement. Amplitude and phase of sinusoidal pressure is

calculated from absolute pressure, displacement and other known quantities. So the pressure's amplitude and phase can be traced to the basic quantities such as length, mass, etc. The device's structure is showed in figure 3.
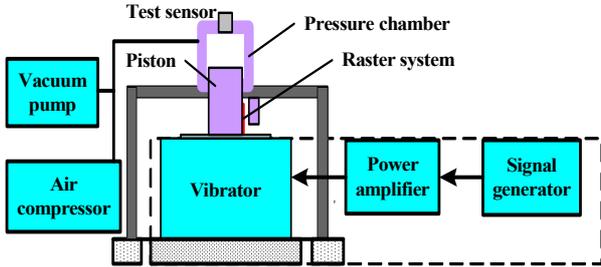

Fig.3. Structure of micro sinusoidal pressure calibration device

The calculation is also corrected for wave motion, gas leakage and heat-conduction. The sinusoidal pressure normalized amplitude-frequency characteristics caused by the pressure fluctuation effect is shown in figure 4. The first-order resonant frequency is about 1200Hz and its influence cannot be ignored at 500Hz. Calibration results of the 8510B-2 are showed on figure 5 with the amplitude sensitivity's measurement uncertainty less than 2% and the phase uncertainty less than 2°.
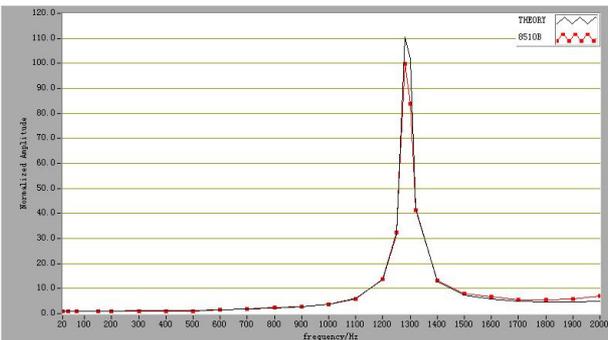

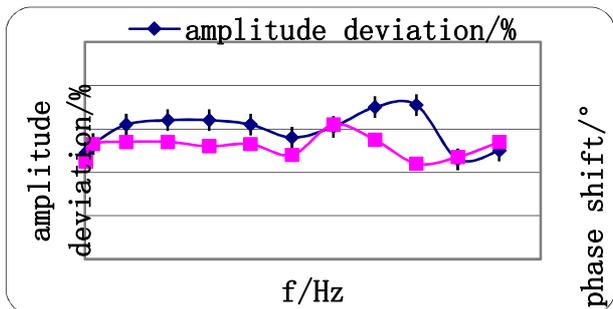Fig.4. Normalized amplitude of the pressure chamber

Fig.5. Calibration results of 8510B-2

However, the effect of heat conduction and leakage limit the application of the method at low frequencies, and the fluctuation effect affect the high frequency application. And the method is confined to the dynamic pressure excitation sources with variable volume.

In the dynamic pressure standards with shock tube the shock wave theory is widely used to traceable measurement of the step amplitude [1,2,17,18]. The state equation of adiabatic gas is one of the most important theories in the shock wave theory. This method is also used in the Φ100 shock tube in CIMM[19] with the reflected shock step pressure from 10kPa to 10MPa. The sensor's amplitude sensitivity calibration uncertainty is less than 2.5% (k = 2). The device is shown in figure 5. It is being studied to extend the reflected shock step pressure to less than 1 kPa.

Fig.6. Φ100 shock tube in CIMM

The shock tube is also used to carry out the high frequency characteristic analysis [20] and the dynamic modeling [21,22] of the pressure sensors due to its extremely fast rising time. However, the problems of tracking the pressure step process and the fluctuation of the platform fluctuation have not been solved. It can not give full play to the frequency response calibration and system model.

The liquid state equation is also used for dynamic pressure measurements, which are mainly related to the volume elastic modulus. PTB et al. have proposed to measure the volume change of the liquid by laser interferometry to trace the impulse pressure to the static pressure [23], but the subsequent study did not proceed. South Korea's et al. conducted a study on the use of density for liquid step pressure tracing [24]. However, the elastic modulus of the actual liquid is very susceptible to the influence of the temperature and the gas mixed. The instability of the liquid elastic modulus limits the practical use of the method, and the method.

4. DYNAMIC PRESSURE MEASUREMENT BASED ON FLUID PHYSICAL PROPERTIES

The physical properties of the fluid itself, especially the optical properties, are determined by the type and microstructure of the fluid, such as refractive index or dielectric constant, spectral characteristics, and so on. The change in pressure causes change in the microstructure of the fluid, resulting in changes of refractive index, spectral characteristics. This relationship can be used for dynamic pressure measurements and trace directly to the basic quantities or static pressure.

4.1 Dynamic pressure measurement based on refractive index

The refractive index is the intrinsic physical property of the fluid. Based on the reliable relationship between the pressure and the refractive index of gas or liquid and the high precision measurement of the refractive index, the traceable dynamic pressure measurement can be realized. The application of the method in dynamic pressure calibration has been paid more and more attention.

NRLM (NMI of Japan) has studied the refractive index-based gas square wave pressure measurement by laser interferometry [25]. The research was based on the empirical formula of Edlen, and the static pressure experiment was carried out. The experiment results show that there is a good linear relationship between the pressure change and the refractive index change within 100kPa. The temperature change caused by the pressure change will also make the air refractive index changes. The researchers temporarily reduced the square wave frequency (0.125Hz below) to remain enough time for the temperature's stability and avoid the impact of temperature. The method of determining the temperature change of medium is the focus of further research.

CIMM has studied the refractive index-based gas sinusoidal pressure measurement by laser interferometry[26]. The calibration device uses an outlet modulation type sinusoidal pressure generator from 1Hz to 3kHz. The laser beam passes through the pressure chamber of the generator. The structure of the device is shown in figure 7.
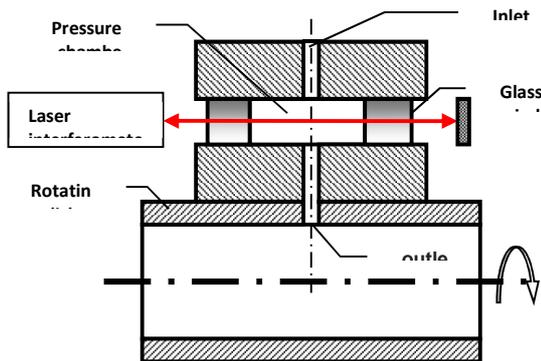

Fig.7. Structure of gas sinusoidal pressure device by laser interferometry.

The relationship between the optical path and the pressure is established by the in situ static calibration, and the optical path is used as the intermediary to make the dynamic pressure trace to the static pressure. In situ static calibration results show that there is a very good linear relationship between the refractive index n-1 and the pressure within 2.5 MPa, which is shown in figure 8. However, due to the lack of measurement and correction of the temperature change, there is a clear inconsistency in the dynamic calibration results between low frequency and high frequency. This problem remains to be further studied.
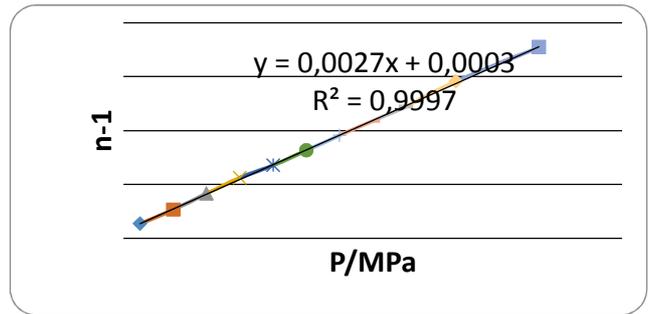

Fig.8 Relationship between refractive index and pressure.

NIST developed one photon measurement static pressure standard using the refractive index based gas pressure measurement principle and Fabry-Perot (FP) interference technology. Its measurement range is from a few mPa to 100kPa. The measurement accuracy is about 0.005% at 30kPa in a constant temperature environment. The photon pressure standard is expected to replace the existing highest level pressure standards such as liquid pressure gauges [27]. The results show that the refractive index based gas pressure measurement model itself has a very high accuracy and repeatability, so the main problems in the dynamic pressure measurement will come from temperature changes and refractive index measurement methods.

PTB studied the liquid impulse pressure measurement based on refractive index by laser interferometry, with water as the pressure medium. Static pressure calibration in situ is also used to establish the relationship between pressure and optical path. The basic principle was analyzed and the preliminary experiments have been completed. But the obvious nonlinear problem remains to be further studied [28, 29].

CIMM applied this method with water's refractive index by laser interferometry to high frequency sinusoidal pressure calibration [30]. Based on the Lorentz-Lorenz equation, hydromechanical characteristics of water and analysis of the optical path, the theoretical pressure-optical path length relation is obtained. Static pressure experiment is designed to test and verify the l-p relation. From the experiment results, there is also obvious nonlinearity in the l-p relation, which is possibly caused by the mixed gas or the glass window's shift. Sinusoidal pressure generator with PZT, resonant water cylinder and heterodyne interferometer are used in the dynamic experiment to test the measurement method. The schematic diagram and set-ups of the dynamic pressure experiment are showed in figure 9 and figure 10.
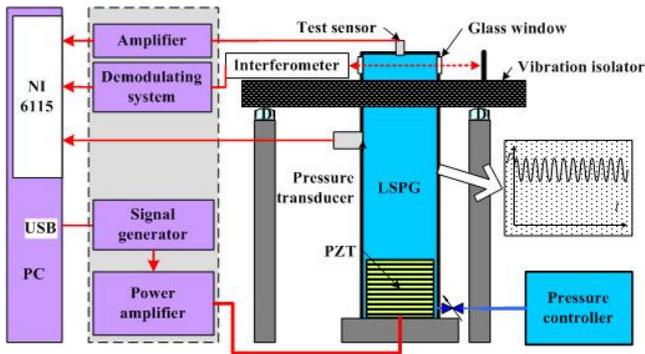
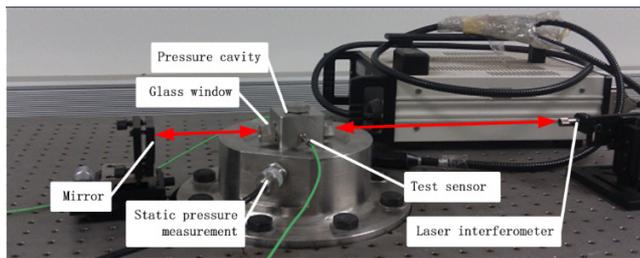Fig.9. Schematic diagram of the dynamic pressure experiment.

Fig.10. Dynamic pressure experiment set-ups with laser interferometer

The pressure amplitude and phase measured by the heterodyne interferometer are close to the results measured by the high resonant frequency pressure sensor below 10 kHz. But above 10 kHz, the deviations are much bigger and the repeatability is bad, which is showed in figure 11. The disturbing components for dynamic measurement are put forward and theoretical analyzed. The possible reasons include the less pressure amplitude and the geometric deformation and windows' vibration, but not the temperature's change and the pressure maldistribution. So it should to strengthen the amplitude of the sinusoidal pressure and compensate of the optical measurement length in the following study.
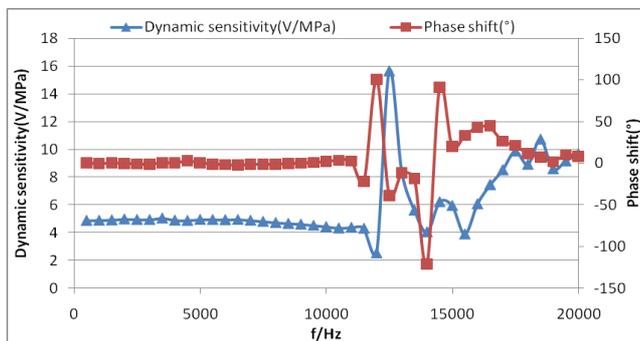

Fig.11. Dynamic experiment results of 112B10

For the measurement method of the liquid dynamic pressure by the refractive index, the temperature change caused by the pressure change is relatively small and can be neglected to a certain extent. Therefore, the liquid refractive index measurement method has a certain advantage compared

with the method of measuring the refractive index of gas on the effect of temperature. However, due to the very large deviation between the refractive index of the liquid and the gas, the relative optical path change caused by the movement of optical windows is more serious.

4.2 Dynamic pressure measurement based on spectral analysis

Form 1980s NIST has been committed to measure the entire process of the step pressure in shock tube through spectrum measurement. The originals scheme is the measurement of step pressure and temperature changes through coherent anti-Stokes Raman spectroscopy (CARS). Its principle and results of static pressure experiments was reported [31]. But the method has been abandoned by NIST because of its significant nonlinearity and expensive ancillary equipment. In recent years, NIST has begun to study the use of molecular absorption spectroscopy to achieve the dynamic pressure of the shock tube [32, 33]. The stage goal is the sampling rate ≥100kHz and dynamic pressure measurement uncertainty ≤5%. Molecular absorption spectroscopy techniques are widely used in the gas composition analysis and temperature measurement. The tunable semiconductor laser absorption spectroscopy technique (TDLAS) based on wavelength modulation spectroscopy (WMS) is used to calculate the pressure by measuring the absorption line of 1571 nm (6366 cm^{-1}) of CO_2. Static pressure measurement has been achieved at (20 ~ 100) kPa.A with the maximum error of 3.1%. Now NIST is carrying out the temperature compensation method. Since the absorption spectrum method itself has measurement capability of gas temperature, the method itself may be possible to complete the compensation of the temperature in the dynamic pressure measurement. However, according to the static experiment results, the linetype measurement method is not so accurate.

4.3 Brief summary

Assuming that there is no any dynamic delay between the pressure and the physical properties of the fluid, the dynamic problem of these methods will mainly come from the instruments and methods used in the measurement of the corresponding physical properties, such as laser interferometers and spectrometers. With the progress of correlative instruments, such methods in the dynamic pressure measurement will have a very large space of upgrade.

5. COMPARISON OF TRACEABLE DYNAMIC PRESSURE MEASUREMENT METHODS

Various dynamic pressure measurement methods described above are compared from traceability, applicable dynamic pressure generators, pressure measurement range, measurement accuracy, and dynamic response.

1) Traceability

The trace path of dynamic pressure measurement based on the macroscopic definition of pressure is very clear. The dynamic pressure measured based on the fluid state equation

is the thermodynamic pressure, which need take into account the non-ideal state of the equation.

The method based on the refractive index or absorption spectrum utilizes the correlation between these physical properties and pressure, and the theoretical trace path to the basic quantities is very complicated. It is more convenient for the practical application to use the physical properties as the intermediary to trace the dynamic pressure to the static pressure.

2) Applicable dynamic pressure generator

The dynamic pressure measurement method based on the macroscopic definition of pressure or the fluid state equation needs to consider the dynamic pressure generator's principle and structure, especially for the latter. The method based on the refractive index or absorption spectrum has nothing to do with the principle and structure of the dynamic pressure generator, but it is necessary to consider the pressure medium's usability. This is not the key problem for the measurement standards.

3) Pressure measurement range

The pressure measurement range based on the macroscopic definition of pressure or the fluid state equation has some limitations. The method based on the fluid state equation is more suitable for small amplitude gas dynamic pressure and large amplitude liquid dynamic pressure because of the non-ideality and non-linearity. The force and movement caused by the static pressure need to be avoided or canceled in the method based on the macroscopic definition. For the method based on the refractive index or the absorption spectra, non-linearity is also an important factor limiting the measurement range.

4) Measurement accuracy

There is relatively high theoretic accuracy in the pressure measurement based on the macroscopic definition of pressure, the gas state equation or the refractive index. The actual use of the method based on the liquid state equation may be greatly affected by the repeatability. And the method based on the absorption spectrum needs to be further optimized to improve the pressure measurement accuracy.

5) Dynamic response

The dynamic measurement ability of hydrostatic pressure method is bad. The dynamic pressure measurement method based on the macroscopic definition of pressure or fluid state equation has some limitations on the high frequency dynamic measurement. The dynamic pressure optical measurement methods based on the refractive index and the absorption spectrum have infinite high dynamic response capability on the measurement mechanisms, and their dynamic measurement capability will be mainly limited by the measurement instruments and methods of refractive index and absorption spectra.

It can be seen from the above analysis that the dynamic pressure measurement method based on the pressure macroscopic definition or the gas state equation can solve some traceable dynamic pressure problems to a certain extent,
but there are some limitations in the measurement range and dynamic measurement capability. The dynamic pressure optical measurement methods based on the physical properties such as refractive index and absorption spectrum are optical direct measurement methods. They don't depend on the principle of dynamic pressure generator. They have the advantages of high dynamic, wide measurement range and high resolution. So they are promising traceable dynamic pressure measurement methods. Of course, the impact of temperature changes and other outstanding issues remain to be resolved.

6. SUMMARY AND OUTLOOK

Traceable dynamic pressure measurement is the primary problem faced by dynamic pressure calibration technology, which is very different from static pressure measurement and more difficult. The principle, application and characteristics of three kinds of traceable dynamic pressure measurement methods based on pressure macroscopic definition, fluid state equation and fluid physical property are analyzed and compared systematically. The results show that each method has its own advantages and disadvantages, and the measurement method based on the physical properties of the fluid is an important development trend.

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