Application of shock tube in calibrating dynamic pressure transducers

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Abstract. The step pressure generated by shock tube was used for calibration of dynamic pressure transducers. First, the performance of the shock tube based calibration installation was theoretically predicted. The influence of Mach number to the step pressure and the duration of the step pressure plateau was analyzed by numerical calculation. Second, the performance of the calibration installation was tested, whose result showed that the minimum and maximum value of the step pressure generated by the calibration installation was 9.60kPa and 1.101MPa, respectively, the maximum value of the rise time of the step pressure was 0.7μs, the minimum value of the duration of the step pressure plateau was 4.14ms, the fluctuation of the step pressure plateau was better than ±2%, and the maximum value of the 2nd order expand uncertainty of the step pressure was 3.52%. The test result verified that the calibration installation met the requirements of the previous design and correlative verification regulations. Last, the sensitivity and syntonic frequency of standard pressure transducers were tested by the calibration installation. The result was in accord with the factory technical parameters.

1. Introduction

It was important and essential to calibrate dynamic pressure transducers termly [1, 2]. Shock tube was used for the calibration of dynamic pressure transducers because it was an ideal generator of step pressure [3-6]. According to the ‘Verification Regulation of Dynamic Pressure standards’ [7], the shock tube based dynamic pressure standard should meet all demand of performance index showed in table 1.

| Performance index of shock tube based dynamic pressure standard. |
|---------------------------------------------------------------|
| Range of the step pressure                               | 15kPa~1MPa         |
| Rise time of the step pressure τₚ                           | <1μs               |
| Duration of the step pressure plateau τₜ                   | >4ms               |
| Fluctuation of the step pressure plateau                   | Within ±2%        |
| 2nd order expand uncertainty of the step pressure Uᵦᵣ(k=2) | <4% (k=2)         |

This paper studied the theoretical design, manufacture, actual test and verification of shock tube based calibration installation for dynamic pressure transducers which met the demand of table 1. The
influence of Mach number on the 2nd order expand uncertainty of the step pressure generated by the calibration installation was specially studied.

2. Theoretical prediction
Figure 1 showed the schematic diagram of the shock tube based calibration installation for dynamic pressure transducers. The hardware consisted of a shock tube, a vacuum pump, a high pressure gas resource, two pressure transmitters, three transducers for velocity measurement, a temperature transmitter, two data sampling cards and a industrial personal computer, etc. The software was a data sampling and data processing system which calculated the parameters of the calibrating transducers.

Figure 1. Schematic diagram of the shock tube based calibration installation for dynamic pressure transducers.

Figure 2. Flow field divisional of shock tube based calibration installation.
The typical flow field division of shock tube was shown in figure 2, in which the flow field of section 5 was used for calibration of dynamic pressure transducers. When the working gas in the shock tube was air with normal temperature, the step pressure generated by the reflected shock wave of the flow field of section 5 could be calculated by [7]:

$$\Delta p_5 = \frac{7}{3} \left( M_s^2 - 1 \right) \left( 4M_s^2 + 2 \right) / \left( M_s^2 + 5 \right) \cdot p_1$$

Where Mach number $M_s$ of the shock wave was calculated according to the signal of transducers for measurement of the velocity of the shock wave, and initialized pressure of low pressure section $p_1$ was measured by the pressure transmitter and then recorded by the data sampling and data processing system.

Previous work [4] designed the parameters of the shock tube based calibration installation and predicted its performance, as shown in table 2.

**Table 2.** Parameters and performance prediction of shock tube based calibration installation.

| Parameter                              | Value       |
|----------------------------------------|-------------|
| Length of the high pressure section    | 2m          |
| Length of the low pressure section     | 5m          |
| Initialized pressure of high pressure section $p_4$ | 24.27kPa 1.62MPa |
| Initialized pressure of low pressure section $p_1$ | 2.86kPa 0.19MPa |
| Step pressure                          | 15kPa 1MPa  |
| Mach number                            | 1.557       |
| Duration of the step pressure plateau $\tau$ | 9.85ms   |
| Fluctuation of the step pressure plateau | Within ±2% |
| $2^{nd}$ order expand uncertainty of the step pressure $U_4(k=2)$ | 2.92% (k=2) |

The numerical calculation result showed the influence of Mach number of the shock wave to the duration of the step pressure plateau and the step pressure generated by the shock tube based calibration installation. When Mach number of the shock wave decreased, the duration of the step pressure plateau [8] increased as shown in figure 3(a), the step pressure decreased however.

![Figure 3](image1.png) ![Figure 3](image2.png)

**Figure 3.** (a) Influence of Mach number to the duration of the step pressure plateau; (b) Influence of Mach number to the step pressure.

3. **Performance test**

Because of real gas effect [9], the Mach number of the shock wave would decrease, which would lead to changes as predicted in figure 3. The actual performance of the shock tube based calibration installation could precisely obtained only through actual test.
Table 3 showed the actual performance of the calibration installation in three different step pressure and corresponding test conditions. When step pressure was 9.6kPa (<15kPa), 288kPa (15kPa~1MPa) and 1.101MPa (>1MPa), all the rise time of the step pressure \( t_r \) was less than 1\( \mu \)s, all the duration of the step pressure plateau \( \tau \) was more than 4ms, all the fluctuation of the step pressure plateau was within \( \pm 2\% \), and all the 2\(^{nd}\) order expand uncertainty of the step pressure was less than 4\%. Thus the actual performance met the demands showed in table 1, but not as good as predicted in table 2. Compared with the predicted value, the actual Mach number \( M_s \) and duration of the step pressure plateau \( \tau \) decreased, the actual initialized pressure of low pressure section \( p_1 \) increased, and the actual 2\(^{nd}\) order expand uncertainty\[10\] of the step pressure increased as well.

| Actual initialized pressure of high pressure section \( p_4 \) | 33kPa | 591kPa | 1.93MPa |
|---------------------------------|--------|--------|---------|
| Actual initialized pressure of low pressure section \( p_1 \) | 4.36kPa | 190kPa | 316kPa |
| Material of the film | Vegetable parchment film | 100\( \mu \)m polyester film | 75\( \mu \)m polyester film plus 250\( \mu \)m polyester film |
| Burst quomodo of the film | Heating up via a resistance wire | The pressure differential \( p_4 - p_1 \) |
| Temperature \( T \) | 22.43\( ^\circ \)C | 20.04\( ^\circ \)C | 20.05\( ^\circ \)C |
| Mach number \( M_s \) | 1.36 | 1.23 | 1.43 |
| Step pressure \( \Delta p_5 \) | 9.60kPa | 288.16kPa | 1.101MPa |
| Rise time of the step pressure \( t_r \) | 0.3\( \mu \)s | 0.7\( \mu \)s | 0.7\( \mu \)s |
| Duration of the step pressure plateau \( \tau \) | 4.14ms | 6.45ms | 4.72ms |
| Fluctuation of the step pressure plateau | Within \( \pm 2\% \) |
| 2\(^{nd}\) order expand uncertainty of the step pressure | 3.25\% | 3.52\% | 3.05\% |

4. Test of standard transducers
Three dynamic pressure transducers were tested by the shock tube based calibration installation. Figure 4 showed the response of transducer PCB 113B26, one of the tested transducers, and its corresponding frequency spectrum. The rise time of the transducer was obtained from figure 4(a); the syntonic frequency of the transducer was obtained from figure 4(b). The sensitivity of the transducer was calculated when the step pressure and the voltage amplitude of the response of the step pressure was obtained.
Figure 4. (a) Response of the transducer PCB 113B26 when $\Delta p_2 = 1.101$MPa; (b) The corresponding frequency spectrum.

Table 4 showed all the tested transducers and the test result. The rise time and syntonic frequency given by the manufacturer were approximate range and value, respectively. The test values of the two parameters were reasonable to the value given by the manufacturer. And the test values of sensitivity of the transducers were close to the value given by the manufacturer. The maximum error was 4.08%.

| Test number | 1          | 2          | 3          |
|-------------|------------|------------|------------|
| Model of the transducers | PCB 113b21 | PCB 113b26 | PCB 113b28 |
| Range of the transducers | 1379kPa | 3447.5kPa | 344.75kPa |
| Sensitivity of the transducers | 3.6mV/kPa | 1.46mV/kPa | 14.7mV/kPa |
| Rise time | <1$\mu$s | <1$\mu$s | <1$\mu$s |
| Syntonic frequency | ~500kHz | ~500kHz | ~500kHz |
| Tested syntonic frequency | 482.10KHz | 485.50KHz | 355.12KHz |
| Tested rise time | 0.6$\mu$s | 0.7$\mu$s | 0.8$\mu$s |
| Tested sensitivity | 3.60mV/kPa | 1.45mV/kPa | 15.30mV/kPa |

5. Conclusion
A shock tube was applied to calibration of dynamic pressure transducers, based on which a calibration installation was designed and manufactured. The performance of the calibration installation was theoretically predicted and actually tested. It was verified that the the Mach number of the shock wave generated by the calibration installation would decrease because of real gas effect. Thus to reach the same step pressure, the actual initialized pressure of low pressure section should be higher than theoretical prediction. The actual performance of the calibration was not as good as prediction, but still met the demands of corresponding verification regulations. Three transducers were tested by the calibration installation. The test result was consistent with the values given by manufacturer, which verified the availability of the calibration installation.

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References
[1] HUANG Jun-qin, Measurement System Dynamics and Its Applications, Beijing, National
Defense Industry Press, 2013: 5-6

[2] Damion J. P. Dynamic calibration of pressure sensors. LNE REPORT. 2007.

[3] ZHANG Da-you. The Application of Shock tube in Testing and Calibrating the Performance of Pressure Sensor. Journal of Astronautic Metrology and Measurement, 2004, 24 (4): 24-27.

[4] YAN Lai-jun, ZHANG Long, ZHANG Xu, et al. Design of Measurement and Control System for Shock Tube Based Calibration Installation of Dynamic Pressure Transducer. Proceedings of IEEE 13th International Conference on Electronic Measurement and Instruments (ICEMI), 2017, 3, pp. 319-324.

[5] Revel G. M. Pandarese G. Cavuto A. The development of a shock-tube based characterization technique for air-coupled ultrasonic probes. Ultrasonics, 2014, 54(6): 1545-1552.

[6] Wisniewiski D. Second generation shock tube calibration system. International Journal of Acoustics and Vibration, 2012, 17 (3): 133-138.

[7] JJG 624-2005: ‘Verification regulation of dynamic pressure transducers’, 2005

[8] JJG 1142-2017: ‘Verification Regulation of Dynamic Pressure standards’, 2017

[9] ZHANG Jing ping, FU Zhou dong. The Calculation of Shock Wave Speed in the Presence of Real Gas Effect and Shock Attenuation. ACTA METROLOGICA SINICA, 2000, 21(1): 45-50.

[10] LI Qiang, WANG Zhongyu, WANG Zhuoran. Uncertainty evaluation for the dynamic calibration of pressure transducer. Journal of Beijing University of Aeronautics and Astronautics, 2015, 41(5): 847-856.