Dynamic characterisation of pressure transducers using shock tube methods

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Abstract. This paper describes the results obtained from a range of dynamic pressure transducers in response to a rapid step pressure input. The testing was carried out in a pair of instrumented shock tubes at NPL. The results demonstrate a wide variation in the results obtained from different combinations of transducer, instrumentation, and mounting arrangement.

1. Introduction
In a wide range of industrial applications, accurate measurements of rapidly-changing pressures are required. One specific example is pressure measurement within automotive engine cylinders to improve understanding of the combustion process, enabling optimisation of engine efficiency [1]. The sensitivity of pressure measurement systems for such applications is currently determined by calibration against static pressure standards, primarily because dynamic pressure standards of the required amplitude and frequency content are not readily available.

Users will routinely calculate a time series of assumed pressure values from their system’s output, using its statically-derived sensitivity, even in highly-dynamic applications. It is important to appreciate the magnitude of the possible resultant errors. One method of determining the system’s dynamic characteristics, and hence the potential measurement errors, is subjecting it to a known step change in pressure and recording its subsequent output. This paper reports on the outputs from various pressure measurement systems subjected to known pressure steps generated using a shock tube method.

2. Shock tubes
Ideal gas theory predicts that a practically-instantaneous pressure step of calculable magnitude will be generated at the end face of a shock tube at the instant that a shock wave, which has propagated within the tube, reflects off this end face. The principle of operation of a shock tube used to generate such a pressure is given in [2].

A pressure transducer mounted in the end wall of the tube with its diaphragm flush to the end face will experience, within a few nanoseconds, a step pressure rise \( \Delta p \), the magnitude of which can be calculated solely from the shock front’s Mach number \( N_{Ma} \) and the initial pressure \( p \) in the shock tube’s driven section. The Mach number is the ratio between the shock velocity \( v_s \) and the speed of sound \( c \) in the driven gas. The speed of sound is a function of the gas’s adiabatic index \( \gamma \), its absolute temperature \( T \), its average molar mass \( M \), and the molar gas constant \( R \). The pressure step \( \Delta p \) is given, for diatomic gases (such as nitrogen and oxygen) with an adiabatic index of 1.4, by (1). As all tests reported on in this paper used air at room temperature and pressure as the driven gas, variation of the generated pressure step to determine system response at different pressure levels was achieved by changing the shock...
velocity. Shock velocity can be increased either by increasing the initial pressure in the shock tube’s driver section (by strengthening the diaphragm) or by using a lighter driver gas (such as helium) - both techniques were used in these tests.

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\Delta p = \frac{14p(2N_{Ma}^4 - N_{Ma}^2 - 1)}{3(N_{Ma}^2 + 5)}
\]

where: \( N_{Ma} = \frac{v_s}{c} \) and \( c = (\gamma RT/M)^{1/2} \)

NPL has developed two shock tubes, a plastic tube with a maximum internal pressure of 1.4 MPa and a steel tube with a maximum internal pressure of 7 MPa. The construction, commissioning, and validation of the plastic tube are described in detail in [2]. Other than the construction material and resultant maximum pressures, the main differences between the plastic and steel tubes are that the steel tube uses Hypalon® fabric, rather than brass sheet, as its diaphragm material and that the steel tube’s pressure control manifold is constructed using solid, rather than flexible, pipework. In order to reach reflected pressure steps of up to 6.5 MPa, it is necessary to use helium as the driver gas.

In both tubes, the shock velocity is derived from the time taken for the shock front to travel a set distance, measured using the outputs from pressure transducers mounted at known positions in the side wall of the tube. In the plastic tube, these positions are defined by holes machined in an aluminium block firmly strapped to the tube; for the steel tube, the transducer locations are machined into bosses welded onto the tube wall and their positions determined on a co-ordinate measuring machine.

3. Methodology

To commission the shock tubes and to investigate their performance, a Kistler 603B piezoelectric pressure sensor, designed for highly-dynamic measurements, and a Kistler 5064C charge amplifier (with its low-pass filter option disabled) were used. The voltage output signal from the charge amplifier was acquired using a National Instruments PXI-5922 24-bit flexible-resolution digitiser.

For many of the commissioning tests, the absolute value of the pressure step was neither required nor calculated, as it was simply the difference in transducer output between tests that was of interest. As similar diaphragms did not rupture at exactly the same pressure in each test, comparison between test results was facilitated by normalising the output traces to a value of unity as the initial peak response.

4. Commissioning tests

The repeatability of the pressure measurement system and, by extension, the input pressure signal in each tube were demonstrated by subjecting the 603B sensor to three pressure steps of approximately 1.1 MPa. For each tube, the resulting three traces virtually overlaid each other. Similarly, a comparison of the traces obtained from the two tubes showed them to be in excellent agreement, clearly demonstrating that the shapes of the input pressure signal were virtually identical.

When located in the tube’s end wall, the vibration of the sensor’s mount, excited by the shock front, is transmitted to the sensor and can have a significant effect on its output, despite its in-built vibration compensation system, as shown in figure 1 which displays the results of tests performed in the plastic tube on the sensor held in mounts of three different materials [3]. The use of a plastic mounting adapter to isolate the sensor from its metallic mount reduces the amount of vibration transmitted into it, the success of this approach being demonstrated in figure 2. Similarly, separate tests in the steel tube using the plastic adapter in steel and brass flanges gave almost identical results.

An analysis of the uncertainty associated with the magnitude of the pressure step is given in [4] and concludes that the major uncertainty contribution is associated with the measurement of the speed of the shock front. Recent results suggest that, contrary to the ideal theory, the shock front is decelerating prior to impacting the end wall. The magnitude of the pressure step therefore needs to be calculated from an extrapolated velocity value, and the uncertainty associated with this extrapolation becomes the major contributor to the pressure step uncertainty, leading to an expanded relative uncertainty of up to 2 %.
5. Test results

The commissioning test work demonstrated that both tubes are capable of generating repeatable calculable step pressures. These inputs have been used to determine the normalised response of the following pressure measurement systems to such rapid changes in pressure:

- Kistler 6052C piezoelectric sensor (with a Kistler 5064C charge amplifier)
- Kistler 4005BA piezoresistive sensor (with a Kistler 4665B amplifier)
- Simea Optic prototype optical sensor (further details can be found in [5])

Typical traces from these three sensors are given in figure 3 (with a timescale to demonstrate the trace normalisation point) and figure 4 (with a timescale to aid comparison with the other figures).

Four further sets of tests resulted in sensitivity values, derived for different pressure steps calculated from (1), for a further three pressure measurement systems:

- Dytran 2300C7 piezoelectric sensor (with a Dytran 4102C current source power unit) – figure 5
- Kulite HEM-312 piezoresistive sensor (with a Texas Instruments INA128 amplifier, gain 220, frequency response 100 kHz, settling time 15 µs) – figure 6
- Kistler 603B piezoelectric sensor, firstly with a Kistler 5064C charge amplifier (figure 7) and secondly with a Kistler 5015A charge amplifier (figure 8), both with the low pass filter option disabled – in each figure, ten responses are plotted (three at the lower two pressures and two at the higher two pressures)
Figure 5. Sensitivity of Dytran 2300C7 sensor

Figure 6. Sensitivity of Kulite HEM-312 sensor

Figure 7. Sensitivity of Kistler 603B sensor with 5064C charge amplifier

Figure 8. Sensitivity of Kistler 603B sensor with 5015A charge amplifier

6. Conclusions

- The material in which the sensor is mounted can greatly affect its dynamic characteristics.
- Different types of pressure measurement system, even when explicitly marketed as being suitable for dynamic or high frequency measurement, can show wildly different response characteristics.
- The instrumentation employed and settings selected can radically affect the measured output from the same sensor subjected to the same input.
- For some sensors, the shape of the response curve is affected by the magnitude of the pressure step.

In summary, great care should be taken in the selection of a pressure measurement system and, for confidence in the measurements it makes, the whole system should be dynamically characterised.

References

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