1978

Investigation of Pressure Transducer Adapter Dynamics

A. B. Buchholz

Follow this and additional works at: https://docs.lib.purdue.edu/icec

https://docs.lib.purdue.edu/icec/277
INVESTIGATION OF PRESSURE TRANSDUCER ADAPTER DYNAMICS

A. Bruce Buchholz, S.I.T., Mechanical Engineer  
Research Division, Carrier Corporation  
Carrier Parkway, Syracuse, NY 13221

ABSTRACT

A widely-used technique for reciprocating compressor research is to use miniature pressure transducers to measure cylinder pressure. A great deal of useful information on cylinder processes can be obtained in this manner, providing that the information is accurate. These transducers must often be mounted outside the cylinder, in adapters, due to space constraints and interfering structures (such as inlet, vee, or the crankcase). It is an established fact that the internal passages and volumes of an adapter affect the pressure signal; thus, it is imperative that the characteristics of each adapter system be known in order to prevent improper interpretation of the data. This report discusses pressure transducer-adapter systems, includes recommendations for design, and describes procedures for testing them.

NOMENCLATURE

General

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>speed of sound</td>
</tr>
<tr>
<td>d_h</td>
<td>diameter of adapter hole</td>
</tr>
<tr>
<td>d_c</td>
<td>diameter of cavity between the end of the connecting passageway and the transducer diaphragm</td>
</tr>
<tr>
<td>f</td>
<td>frequency (Hz)</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz (cycles/second)</td>
</tr>
<tr>
<td>l_h</td>
<td>length of adapter hole</td>
</tr>
<tr>
<td>l_c</td>
<td>length of adapter cavity</td>
</tr>
<tr>
<td>P_c</td>
<td>cylinder pressure</td>
</tr>
<tr>
<td>P</td>
<td>pressure</td>
</tr>
<tr>
<td>R</td>
<td>ratio of V_2/V_1</td>
</tr>
<tr>
<td>S_h</td>
<td>cross-sectional area of adapter hole = ( \pi d_h^2/4 )</td>
</tr>
<tr>
<td>S_c</td>
<td>cross-sectional area of adapter cavity = ( \pi d_c^2/4 )</td>
</tr>
<tr>
<td>sec</td>
<td>seconds</td>
</tr>
<tr>
<td>ms</td>
<td>milliseconds</td>
</tr>
<tr>
<td>mS</td>
<td>microseconds</td>
</tr>
<tr>
<td>u</td>
<td>gas velocity</td>
</tr>
<tr>
<td>V_h</td>
<td>volume of adapter hole</td>
</tr>
<tr>
<td>V_c</td>
<td>volume of adapter cavity (between end of adapter hole and transducer diaphragm)</td>
</tr>
</tbody>
</table>

Greek

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>density</td>
</tr>
<tr>
<td>( \omega )</td>
<td>frequency or speed (rad./sec)</td>
</tr>
</tbody>
</table>

INTRODUCTION

A largely experimental program was undertaken to examine current design practices and procedures involved in setting up pressure transducer adapter systems in conjunction with reciprocating compressors. Adapters become a necessity when space constraints or interfering structures preclude the direct use of even miniature pressure transducers. Normally, this means creating a connecting passage from the top of the cylinder (preferably near the center), through the head and into an adapter which can accept the transducer chosen for the tests. In practice, this might be accomplished by using a drilled out suction "tee" bolt which is threaded at the end to mate with the adapter, as shown in Figure 1. While other adapter systems could be used, most would have operating characteristics similar to those used here, and would be modeled as in Figure 2.

Since adapters may be a necessity, it should be recognized that they are known to affect the "true" pressure signal, predominately through resonance, magnitude variations, phase shifts, and roll off. Resonance is that condition where the magnitude of the pressure wave is greatly amplified by the reinforcement of the wave reflected in a passageway at its natural frequency. Resonance is usually not hard to detect as it often results in severe fluctuations of the output. It can be avoided or corrected through adapter redesign, damping or filtering. Unfortunately, flapping of compressor valves causes pressure fluctuations which are desired data, yet which can be mistaken for resonance. Thus, it is important to know how a particular adapter behaves in order to prevent useful information from being mistakenly damped or filtered.

The pressure transducers mentioned here were all of a strain-gaged diaphragm type. Piezoelectric-type transducers were not included as they do not provide a DC level for recording the absolute magnitude of a pressure signal.

275
Whereas resonance is caused by frequency effects, other sorts of magnitude errors can be found in adapted signals due to capacitive and inductive effects of the adapter system and pressure medium acting with a mass spring effect. Due to the gas dynamics, magnitude errors may be affected by the type of refrigerant chosen, oil in the system, or general adapter dimensions.

Phase shift and roll-off of the adapted signal are more difficult to detect. Phase shift means an actual time lag (or lead) of the peak points of the adapted signal from what they actually should be. This is extremely important in conducting digital calculations of cylinder work, as an error of a few degrees of crank angle in the pressure signal can cause large errors in the pressure-volume diagrams. Roll-off describes a change in the slope of the output signal from the actual wave. It primarily affects the steep portions of the compression and expansion signals. Both of these errors are associated with the mass-spring effect of the adapter signal, although phase shift also takes into account the time delay caused by having the pressure wave travel a longer distance in order to reach the transducer diaphragms.

Errors due to the latter three conditions above are illustrated in Figure 3, which compares (in exaggerated form) an output signal from a pressure transducer mounted in an adapter to the "actual" induced (reference) wave.

2.0 CURRENT DESIGN PROCEDURE

Most currently-available literature uses acoustic theory to predict resonant frequencies in adapters. Treatment of transient responses is more limited, but is examined by such authors as Nagao and Ikegami (Ref. 4).

Behavior of the gas inside the adapter system is described by equations derived from the conservation of mass and momentum. It is commonly assumed by most authors that the gas behaves as an ideal gas, following the adiabatic law. (This may be questioned in actual practice.) The cross-sectional area of the adapter hole (A1) is assumed to be constant for its entire length, which is reasonable, since this is the most practical way to manufacture one. For frequency response, the change in gas density along the canal (dp/2ax), and the change in the square of the velocity of the gas along the canal (au2/2ax), are assumed to be zero. The transfer function, G (jw), in the frequency domain is valid only for a linear system, neglecting the dropping of all u2 terms.2 Since the design of most adapter systems will be largely influenced by space constraints, which are likely to vary for every application, designing a complete adapter system from scratch is not examined. Instead, predictable results from certain dimensional changes are listed below, as well as verified findings of several authors:

1) The connecting tube between the transducer diaphragm and cylinder has to be of such a length that within the frequency range of expected pressure fluctuations, no resonances occur in the measuring system.

2) The shorter the adapter tube length, the higher the resonant frequency.

a. The greater the adapter tube diameter, the higher the resonant frequency.

b. Severely reducing diameter can severely damp the system (reduce wave amplitude and frequency effects).

3) The damping factor increases with increasing V2/S1d1 (Ref. 4).

4) Introducing an orifice along the adapter hole (throttling) causes the system to act as a low-pass filter, reducing high frequency amplitude, but not greatly affecting the natural frequency of the system (Ref. 2). If an orifice is used, one with a diameter 0.36 times the diameter of the adapter hole (d1) provides the best combination of phase shift and magnitude accuracy (Ref. 2 and 4).

5) If the degree of vibration damping exceeds a limit, improved accuracy cannot be achieved by reducing the amplitude of the oscillation because of the lag induced in the indicated pressure.

6) Frequency response is a function of V2/S1i1 and is independent of any damping coefficient (Ref. 4). Note that a reduction in V2/V1 or in i1 will raise the resonant frequency (Ref. 2).

7) Total volume in the adapter system works as the storage of potential energy (namely capacitance). This volume is nearly equal to V1 + V2 (Ref. 4). The relative effect of V2 is potentially much greater than V1.

8) In applying acoustic theory to determining resonant frequency, a correction factor (πd1/4) should be added to the adapter hole length (i1) to account for the inertia of the gas in the tube. For most adapter systems, this correction will be insignificant as it is normal for i1 >> d1 (Ref. 2).

9) In frequency analysis, Helmholtz resonant equations are only valid for large values of V2/V1 and will not be accurate if V2/V1 < 3 (Ref. 2). In simplified form, the classical Helmholtz equation would reduce to f = \frac{c}{2\pi V1} \frac{1}{\sqrt{R}} where R = \frac{V2}{V1}, c = speed of sound for medium.

2 The transfer function, G (jw), is defined here as the pressure signal, Y (jw), from the adapted transducer (or excess pressure in the cavity) over the pressure recorded by the reference transducer, X (jw), (or that pressure in the cylinder) j = \sqrt{-1}.
3.0 TEST PROGRAM

While reference literature is available on the subject of pressure transducer adapter design, there are a number of shortcomings related to the configurations considered, the effects of damping and experimental verification. Perhaps most important there are fabrication constraints and assembly variables that introduce large deviations from the actual design. For these reasons a test program was undertaken to obtain a better understanding of adapter use and provide a means for improving design and examining future systems in sufficient depth to insure the obtaining of meaningful data.

3.1 Test Apparatus

In order to experimentally study adapter system behavior, test devices had to be designed to adequately compare test results from a reference transducer mounted flush in a cylinder head with results from a transducer mounted in an adapter system. Two types of experimental techniques were proposed. The first involved imposing a step change in pressure upon both the reference transducer and the transducer adapter system simultaneously, using a shock tube and comparing the response of the two transducers. The second method was to introduce a variable frequency signal upon both transducers simultaneously. For ideal test comparison, it was necessary that both test techniques use the same relative configurations. To accomplish this, a common test head (Figure 4) was designed to be used with both a shock tube and a frequency test unit. This test head was tapped to provide similar placement of a reference transducer and one of a series of adapter systems. In this manner, one test set-up could accommodate all the possible adapters to be examined and compare them in exactly the same way.

3.1.1 Shock Tube

In order to produce a step input pressure wave, a shock tube was constructed utilizing mylar burst diaphragms. A digital oscilloscope and X-Y plotter were used to record results from the two transducers simultaneously.

The shock tube was designed to be used with various atmospheres (air, nitrogen, R-22, or R-12). Initial pressures ranged from 0 to 160 psig on the high side, and -14.7 to 0 psig on the low side. Rise time to 100% of the peak wave was on the order of 0.00185 seconds. For either nitrogen or R-22, the magnitude of the initial wave could be maintained near 120 psig. No temperature control was attempted for any of the tests conducted in this test program, although the transducers themselves were of a temperature compensating type.

3.1.2 Frequency Test Unit

Testing for frequency response using pressure transducers was hindered by the minimum distinguishable pressure differential of the transducers used (on the order of 122.43 [A] or approximately 0.037 psi [rms]). This ruled out the possibility of using small acoustic speakers to drive the frequency system. Instead, a large 60-watt horn driver was mounted in a frequency test unit that could accept the common test head.

The natural frequency of the transducers was so high (on the order of 350 kHz) that it played no role in the observed frequency results. No resonant frequency was expected from the driver system attachment while utilizing air. Output from the transducers was observed using both a digital scope and a mechanical impedance/transfer function analyzer rack. All the adapter systems were observed over a frequency spectrum of 50 - 5050 Hz.

3.1.3 Adapters

Adapters were made up to allow any combination of dimensional changes under consideration, including one with an orifice (mechanical low pass filter). All the systems could have their internal cavity volume decreased by adding a Teflon or copper washer between the end of the transducer and the base of the adapter hole. All could add extra volume to this cavity by inserting washers between the transducer's external sealing point and the adapter. The systems could also have oil injected into the adapter hole to study the effect of a possible accumulation of compressor oil in an adapter during actual compressor operation.

3.2 Test Program Results

The shock tube tests proved to be a very useful tool for examining transducer-adapter systems in that they provided a very realistic method for studying the dynamic mass-spring effects. The digital scope allowed accurate numerical analysis of phase and magnitude shifts, while at the same time providing a general wave form comparison for roll-off and damping of the adapted vs. the reference wave. For example, Figure 5 shows shock tube wave form comparisons for five waves: (A) is the reference wave. (B) is the adapted wave from a typical adapter with a small cavity volume (less than .002 in.³) between the end of the connector hole and the transducer diaphragm. Note the overshoot error in magnitude and the capacitive effect due to energy storage by the adapter cavity. (C) is a wave from the same system as (B), except that a Teflon washer was added between the transducer and the connector hole to fill in the cavity volume. Note that the equipment integrity was verified through a series of tests in which transducer location was varied. Rotating the test head showed that there was no shock wave discontinuity. The transducers were statically calibrated on the shock tube and were found to be identical. As a check of their dynamic characteristics, the position of the transducers were reversed during several of the tests and were found to give the same results.
wave form is a close replica of the "true" wave; phase shift is negligible, and capacitive effects are greatly reduced. (D) shows wave results from an adapter system utilizing the optimum orifice studied. While the magnitude is fairly close, there is a substantial phase shift, and the wave form slope is much different in nature. (E) shows the effects of introducing a very "large" cavity volume \( V_2 \), which causes severe damping, large magnitude errors, phase shift, and roll-off. As an indication of the relative importance of even minor internal dimensional changes, the "large" cavity volume \( V_2 \) mentioned here and used for illustrative purposes because it was so extreme, was .00948 cubic inches. Trends from these and many more similar tests were used to make up the design recommendations in Section 4.0.

Numerical analysis of the shock tube tests showed that the velocity of propagation of the shock wave was 13,335 ips in air, and approximately half that (5,855 ips) in R-22 at room temperature. The approximate delay in starting time for the adapted waves in air was 10 μs/24 in. of tube length, implying a wave velocity of 24,000 ips; this should be equivalent to Mach 1.78. The approximate delay in starting time for R-22 was roughly twice as long. There was a direct correlation between starting time lag and the lengths of the adapter hole for the tests conducted in air and R-22.

Magnitude errors using R-22 ranged from 4 to 7% for tests using the internal washers to 7 - 31% without them. Phase shifts due to starting time lag for most of the adapters were not crucial, corresponding to the equivalent of less than one degree of crank angle for an operating compressor. Orifices were found to reduce high frequency effects for systems thus affected, but phase shift was always substantial, ranging from the equivalent of 7 to 9 degrees of crank angle. This is far too much to be considered as useful data for P-V diagrams, etc.

The high frequency tests conducted duplicated the findings of other authors and generally provided the results expected from acoustic theory. When frequency problems (resonant points) were encountered, it was found that they could be alleviated through general dimensional changes, or by the use of an orifice as a last resort.

4.0 CORRELATION OF ADAPTER DESIGN AND PRACTICAL USAGE

An important point in the transducer-adapter study is that very small internal changes in the adapter can influence the performance of the system. As noted in Section 3.2, the "large" internal volume caused by adding two external copper washers was on the order of .00948 in.³, and this proved to be extreme during testing. Indeed, the reduction in the normal cavity volume (Figure 5, Curves B and C), resulting from the addition of an internal washer, was only .00157 in.³ and, as shown, had significant effects.

While "clean" designs can be put on paper, they may be difficult to manufacture. The model adapter systems used in this test program were carefully built, one-piece sections, with only tolerance limits affecting dimensional stability. Actual adapters are made of several parts, each carrying manufacturing or assembly variations. The adapter hole is often drilled through the valve bolt, which limits the diameter. The minimum length of the bolt is determined by the length necessary to fasten the valve assembly. In practice, an adapter section is screwed onto the drilled out valve bolt; and a transducer is then screwed into the adapter. In both instances, dimensional changes are possible due to assembly practices.

Producing satisfactory adapter systems requires two stages. First, a basic adapter system must be designed so that it is compatible with the system to be tested, including any known frequency constraints. At the same time and probably more important, if the compressor to be tested is expected to generate large amplitude pressure variations, the transducer-adapter system must be designed to give maximized performance in terms of accurate magnitude levels and phase shift.

Once designed, the system should be built, tested, and calibrated to define the degree of expected performance.

4.1 Design Guidelines

From the results of this test program, the following guidelines are provided for the design and use of transducer-adapter systems. It will be assumed that the transducer is placed at the end of a cylinder, not in the cylinder walls, as this would affect interpretation of pressure results in other ways.

1. Adapter hole length should be kept as short as possible. This will maximize the lowest resonant frequency and decrease the response time of the system to an incoming wave.

2. Adapter hole diameter should be as large as possible, maximizing the resonant point.

3. Maintain the smallest cavity volume \( V_p \) that is possible. This is probably the most important point in the use of adapter systems. This will raise the resonant frequency, provide more accurate indications of magnitude, reduce time lag or phase shift, and decrease energy storage (capacitive) effects significantly.

In order to accomplish this, the adapter section must be designed internally so that the pressure transducer used can screw down flush to its bottom. To insure a proper mating condition, a pliable internal washer should be used between the rim of the transducer and the adapter to fill excess volume. To make this design effective, the bottom of the hole must be machined flat, necessitating a bore, and not the normally-used drill-tap routine (see Figure 6).

This system will also allow a much simpler ballpark prediction of the system's resonant frequency, as it will make the pipe organ frequency equation much more valid, while
almost completely ruling out the use of the Helmholtz equation. (During this test program, the actual resonant frequencies were located between the predictions from these two extremes, as expected.)

4. Avoid using throttling devices, orifices, restrictions, etc. While they were shown to be effective in reducing and filtering high frequency effects and in maintaining accurate magnitude peaks, they distorted wave forms and caused phase shifts.

Relatively small errors in time and wave form are considered more significant than small errors in magnitude, especially when dealing with unknowns. In this test program, an orifice believed to be the "optimum" for the adapter design resulted in a phase shift that varied the equivalent of between 

5. No allowance for the presence of compressor oil in the adapter system need be made in the design. A coating of oil on the surface of the transducer diaphragm was shown to have little, if any, effect on adapter output.

6. Once a basic configuration is designed, a model adapter system should be fabricated and tested versus a reference system using a shock tube in either air or the refrigerant to be used. Testing in air, or N₂, will magnify magnitude effects through greater wave velocities; but this may be an advantage for observational purposes.

If refrigerant is used, it must be remembered that under actual operating conditions its properties will change with both pressure and temperature. Resonant frequencies at the possible extremes can be calculated.

7. If results from the bench tests are not satisfactory, dimensions should be altered using the guidelines above.

REFERENCES


Figure 1 - Pressure Transducer Adapter System

Figure 2 - Modeled Adapter System
Figure 3 - Response Error Definition

Figure 4 - Common Test Head Unit
REFERENCE WAVE
B-E VARIOUS TYPES OF ADAPTED WAVES

A - Reference Wave
B - Adapter with Small Cavity Volume (less than .002 in.³)
C - Adapter with Teflon Washer used to Fill Cavity in B
D - Adapter with Orifice .36(d) of B, C
E - Adapter with "Large" Cavity Volume (.00948 in.³)

Figure 5 - Sample Shock Tube Test Results

Figure 6 - Proper Adapter Design