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IMPULSE RESPONSE PRESSURE TRANSDUCER

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Abstract

A pressure transducer that does not breech the vessel wall is described. The transducer determines pressure by monitoring the change in the impulse response of the pressure vessel as a function of the change in internal pressure. The method is demonstrated on multiple vessels of the same design and construction. The technique is implemented with dedicated laboratory hardware, PC and PDA based systems and a fully embedded microcontroller with accuracy and cost that rivals current technology.

INTRODUCTION

The most reliable, single-fill pressure vessel would have only one (fill) port. Any additional ports, e.g., for a pressure gauge would reduce the reliability of the system by creating potential leak paths. And yet, it may still be desirable to have knowledge of the internal pressure. In this case, it would be desirable to determine pressure without breeching the vessel wall. Similarly, pressure vessels containing highly corrosive materials are applications where it is desirable to have a pressure gauge with no wetted components. The following discussion describes the design and implementation of a simple pressure transducer that meets this requirement.

Others have considered this problem. Tittmann [1] has recently described a pressure gauge that does not breech the vessel wall. Bronowacki, et al [2] has described a similar device. Other workers have reported pressure transducers based on acoustic emission [3], and angle beam ultrasonic methods [4]. Still other studies have reported on use of acoustic resonances. [5] All these devices are apparently based on the detection of variations produced in the gas that are read externally sometimes through interaction with the vessel walls.

The pressure transducer reported here is implemented using impulse response. Previously reported devices have relied on electronic circuitry using sine sweeps and peak detection. Here the frequency response is determined using an impulse stimulus and the digital Fourier transform. This simplifies the electronics and allows easy implementation of a microprocessor based embedded system. Evidence of successful implementation of the device is presented on a series of bottles all of the same design and construction.

EXPERIMENTAL EVALUATION AND RESULTS

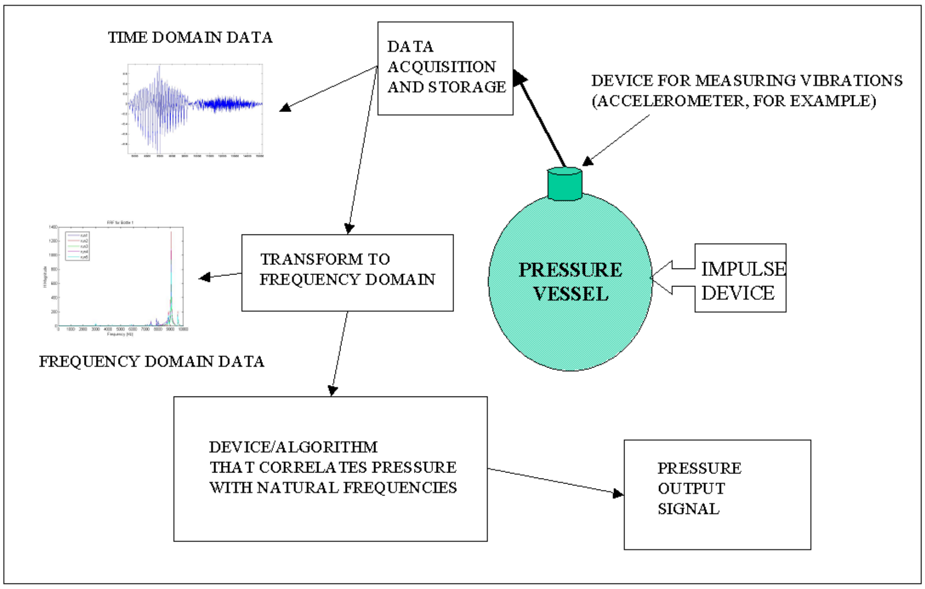

Figure 1—Experimental technique

Figure 1 summarizes the experimental technique. An accelerometer is mounted to the pressure vessel. A somewhat arbitrary device is used to impact the vessel. The suitable impact device need only excite the resonant frequencies of interest and only a very light impact is sufficient. The output of the accelerometer is amplified and filtered. The signal is of little value in the time domain. However, when processed to the frequency domain, the resonant frequencies of the system are readily apparent. Typical frequency response functions for the pressure vessels used in this study are presented in Figure 2. The 9 kHz region is expanded and presented as an insert. The quality of the data is evident. The signal to noise ratio is greater than 1000 and the consistency of the peak value is better than 1 Hz for the 9 kHz peak. Amplitude/phase evaluation identified the most probable mode of the 9 kHz peak as the flattening mode displayed in Figure 2.

Empirical calibration can be done with either a single bottle by varying fill pressures or, as in this case, evaluation of various bottles with fixed fill pressures. Six 'identical' vessels were used in this study. The vessel dimensions and construction material are given in the section on theoretical predictions. The vessels were pressurized with Nitrogen to preset levels, sealed and weighed. Calibration results for the vessel used in this study are shown in Figure 3. Possible methods of theoretical calibration are discussed below.

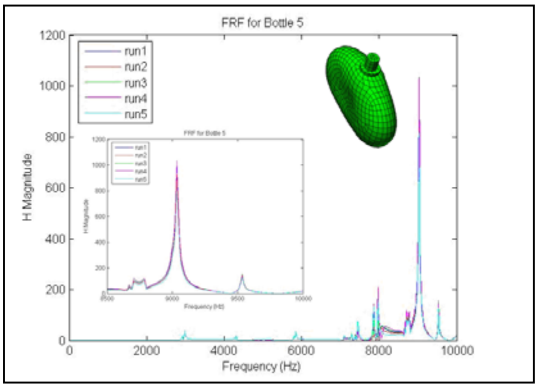

Figure 2—Typical impulse response

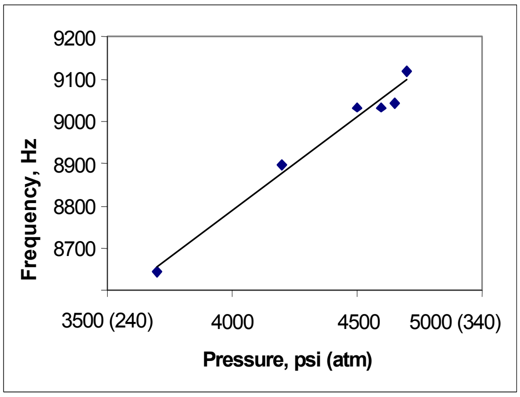

Figure 3—Empirical calibration curve

THEORETICAL PREDICTIONS

Theoretical predictions of the impulse response are now discussed. Modelling is based on the response of a spherical gas resonator, the natural frequencies of a spherical shell and the combination and interaction of both. All three possibilities are considered. We will first discuss the modes of a spherical gas resonator as described by Morse and Feshbach [6]. The natural frequencies are the roots of the following expression.

$$j'_n(z) = 0, \quad (1)$$

where $j_n(z)$ is the spherical Bessel function. If z_{ns} is the s th root, the frequency is given by $(c\, z_{ns})/(2\,\pi\, a)$ with c representing the speed of sound in the gas and a the resonator radius. Predicted frequencies are charted in Figure 4 for the 250 atm, (3700 psig) pressure vessel. Experimental peak positions are also shown. Using the acoustic impedance method, Morse and Feshbach describe the system interaction of a membrane with the gas resonance using the following transcendental expression.

$$[j_o(ka)/j_1(ka)] = (\rho s\, h/\rho\, a)\,(ka) - (4\, E\, h/\rho\, c^2\, k\, a^2), \quad (2)$$

where ρs = shell density, ρ = gas density, E = shell modulus, h = shell thickness, and $k = \omega/c$. Equation 2 applies to free symmetric vibrations. Predicted frequencies based on Equation 2 are shown in Figure 4. Very little shift in the resonant frequencies is predicted for symmetric vibration modes. Real gas effects are included with the equation of state provided by Wagner and Span. [7]

The natural frequencies for the vessel (independent of pressure and gas resonance) were estimated from expressions provided by Blevins. [8] The first symmetric vibration mode is estimated to be 20.7 kHz. The first bending mode is predicted to be 9.54 kHz.

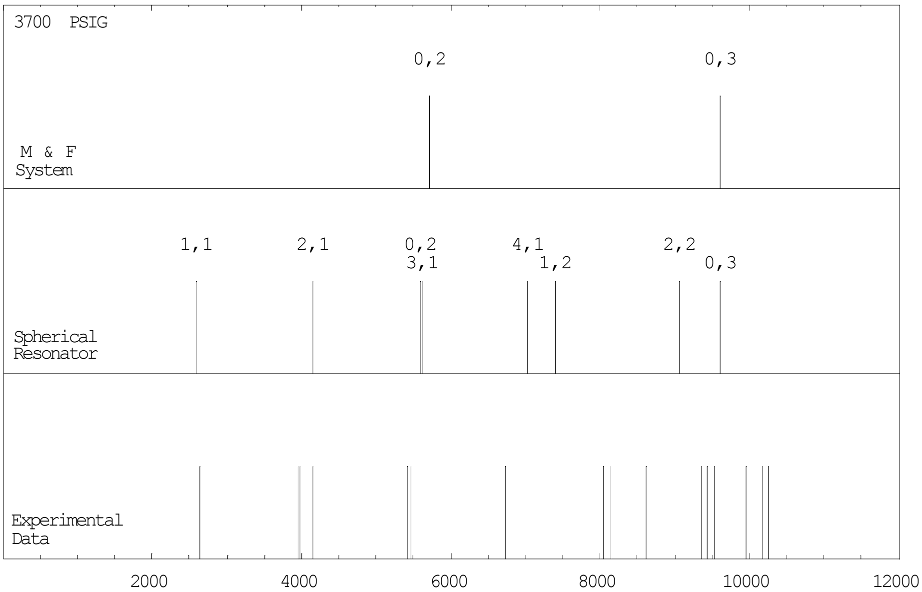

Figure 4—Comparison of theoretical and experimental natural frequencies

The natural frequencies of a spherical shell are expected to increase as the membrane stress increases. R. R. Archer described the effect of uniform stress states on the natural frequencies of spherical shells. [9] An estimate of the expected frequency shift with internal pressure is made based on his work. We first define the following parameters. The values for the pressure vessel used in this study are provided.

ρ_s = density of the shell material (mass/volume) = 7.8E03 kg/m^3 (0.287 lb/in^3)
h = thickness of shell = 3.43E-03 meters (0.135 inches)
a = spherical radius = (0.0635 meters) 2.5 inches
p = internal pressure = 0 to 30 MPa (0 to 4500 psig)
$D = E\, h^3/12(1-\nu^2)$ where

E is the elastic modulus = 200 GPa (30E06 psi)

$\nu = 0.3$

f = frequency in cycles/second

Extrapolation of Archer's result is required. Archer's work suggests a linear relationship between non-dimensional natural frequency and non-dimensional stress resultant. The proportionality constant is estimated to be 0.2. This suggests the following relationship.

$$\Delta f = (0.2)\ 2\ \pi\ (p\ a/2)\mathrm{Sqrt}[1/(\ \rho\ D\ h)] \quad (3)$$

With the values given, the expected frequency change for the vessels used in this study is 0.75 Hz/atm or 0.5%.

A finite element analysis was performed on the vessel design used in this study. The analysis did not include the effect of internal pressure on the natural frequencies so no information was generated that could be used to calibrate the change in frequency with change in pressure. However, the analysis did provide some information on expected mode shapes and an estimate of their natural frequencies. This information coupled with careful phase and amplitude analysis was used to assign experimentally observed frequencies to predicted mode shapes. For example, FEA predicts the flattening mode will occur at 9844 Hz.

DISCUSSION

Experimental –v- Theoretical Natural Frequencies

The match between predicted and actual frequencies is reasonable below 5 kHz but poor at higher frequencies. Further, the experimentally observed peak shift is 4.9% for the 9 kHz peak over the 250 to 320 atm pressure range examined here. Based on Equation 1, the resonant frequencies are proportional to the change in speed of sound in the gas. The speed of sound in Nitrogen changes by 9.2% over the pressure range 250 to 320 atm, which does not match the experimental results. On the other hand, the shift in natural frequency predicted from Archer's work is too low as previously described. Additional work is required to match theory and experiment.

Limitations

The method described has some limitations. The equipment used to measure the frequency response determines the resolution. This is not a serious limitation based on the availability of current dedicated digital signal microprocessors. The accuracy of this method is controlled by variations in bottle dimensions and perhaps gas composition. Tighter control of these variations allows more accurate determination of internal pressure. In addition, certain modes will have nodes or places or zero displacement. Still other locations might be adversely affected by attachment boundary conditions. For example, monitoring a natural frequency associated with the movement of the fill boss could be adversely affected by the way the bottle is attached to its manifold.

As modeling and numerical procedures improve, it may become possible to calibrate the transducer from theoretical predictions. This is not yet feasible. However, with an embedded microprocessor, it is possible to calibrate individual bottles during fill. The calibration can be stored in memory and referenced as required. This would provide accuracy equaling current technology.

Hardware Implementation

Hardware level devices have been demonstrated in our lab. These range from dedicated spectrum analyzers to fully embedded systems. One such system uses a data acquisition card on a PDA running LabView software. An example output is shown in Figure 5. We have also demonstrated a fully embedded system based on a PIC microcontroller. A picture of this device is shown in Figure 6.

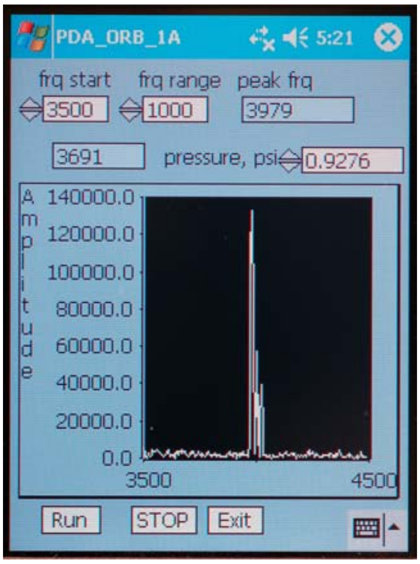

Figure 5—PDA implementation

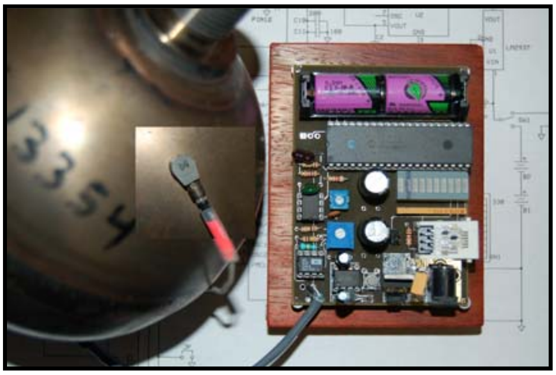

Figure 6—Fully embedded system

SUMMARY

A device/technique is demonstrated that can be used to measure the pressure inside a pressure vessel without breeching the vessel wall. It is based on monitoring the change in frequency response produced by a change in the internal pressure. Once calibrated, the technique can be implemented with dedicated laboratory hardware, a PC or PDA based system or a fully embedded microprocessor. The cost and accuracy are equivalent to existing technology.

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