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Noninvasive Fill Testing of Sealed Pressure Vessels

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A simple method for testing the pressure inside a sealed vessel without breeching the vessel wall is presented. The method is based on the impulse response of the vessel. Specific hardware implementations are presented. The device can be cost competitive with normal pressure sensors and can be implemented on pressure vessels currently in service. The pressure sensor has been demonstrated in multiple hardware configurations. All relevant components are considered cryogenic and vacuum capable.

For some pressure vessels, it is desirable to have a pressure transducer that does not breech the vessel wall. This is true for pressure vessels used in defense applications where it is desirable to have a shelf life greater than 10 years. In these cases, the port required for a gage would reduce the reliability of the system by creating a potential leak path. Pressure vessels containing highly corrosive materials are another application where it is desirable to have a pressure gage with no wetted components. The following discussion documents the design and implementation of a pressure transducer that meets these requirements by determining pressure via vessel impulse response.

Theory of Operation. In 1962, R. R. Archer described the effect of uniform stress states on the natural frequencies of spherical shells.[1] His work predicts that the natural frequencies of the pressure vessel should increase with internal pressure. In the mid-1990s, workers at TRW constructed and patented a device that monitored this change with a complex electronic circuit that sweeps through the frequency range of interest and provides a readout of selected resonant frequencies.[2] Their device was to be implemented on the pressure vessels in airbag restraint systems equipped with pressurized gas vessels. That technology has since been made obsolete by gas generator systems. However, their idea and implementation was ingenious, but cumbersome. The method described here is an advancement of their previous work. The use of the complex electronics is replaced by a simple impulse test. A schematic illustration of the method is presented in Figure 1.

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 tap is sufficient. The output of the accelerometer is amplified and filtered as required. The signal is of little value in the time domain. However, when processed to the frequency domain, the resonant frequencies of the vessel are readily apparent. Typical output for the pressure vessel used in this study is presented in Figure 2. The 9 kHz region is expanded and presented as an insert. The quality of the data and the accuracy of the frequency response are evident. The signal-to-noise ratio is seen to be 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. FEA predicts this mode will occur at 9844 Hz in a nonpressurized bottle. Clearly, modeling is not suitably accurate for calibrating the transducer. Calibration can be done with either a single bottle by varying fill pressures or, as in our case, evaluating various bottles with fixed fill pressures. Calibration results for the vessel used in this study are shown in Figure 3.

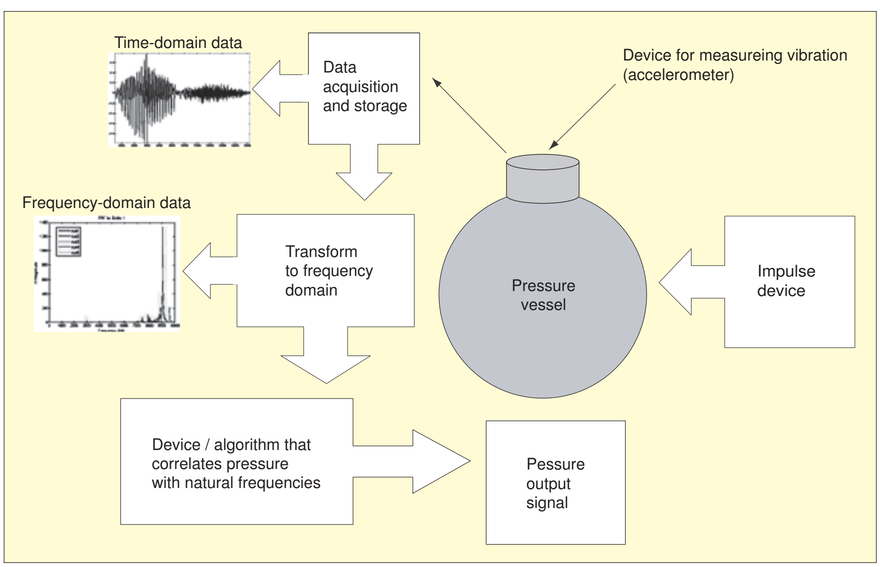

Figure 1. Schematic illustration of the method

Implementations. The method can be implemented with various hardware configurations. The most straightforward but least portable is a simple spectrum analyzer. This could include a dedicated unit or a virtual instrument run from National Instrument's LabView with a data acquisition card. This allows PC-based implementation. Some signal processing is required to avoid aliasing. With the recent release of the compact flash format data acquisition card, a simple hand-held device has been demonstrated. It uses the HP iPAQ with the NI 6004 compact flash card programmed with National Instruments PDA code. Typical screen output is shown in Figure 4.

The most portable and perhaps most useful device is a dedicated microprocessor-based unit. The schematic of a demonstrated device is shown in Figure 5. Modest signal processing and power circuitry accompanies a PIC 18F452 microprocessor. In this case, the output is a series of LEDs that provide a bar graph type display of the fill pressure. The device is equipped with an interface port so that the gage can be calibrated for individual bottles if desired. Provision is also made for temperature compensation of the pressure reading.

Accuracy and Resolution. Signal processing in the frequency domain provides extremely high accuracy and reliability. In addition, available accelerometers are extremely accurate and precise even when implemented as MEMS (Micro-Electro Mechanical Systems) technology. The accuracy of the method is limited chiefly by the calibration procedure. The frequency response of individual bottles is considered well defined and not subject to large variations with time unless significant corrosion processes are at work. If the method is calibrated for a bottle design as opposed to a single bottle, inaccuracies would be observed due to bottle-to-bottle dimensional and residual stress variations. Inaccuracies due to temperature variations are not an issue with hardware implementations that allow temperature compensation. In complex systems, there is always a chance of resonant frequencies from nearby structures compromising the signal. Care must be taken to avoid this mechanical cross-talk.

The resolution of the method is limited by the signal processing algorithm. The Nyquist criterion for sampling speed must be met. Consideration must also be given to signal aliasing since real structures will contain significant amounts of high frequency components. The frequency resolution is ultimately deter-

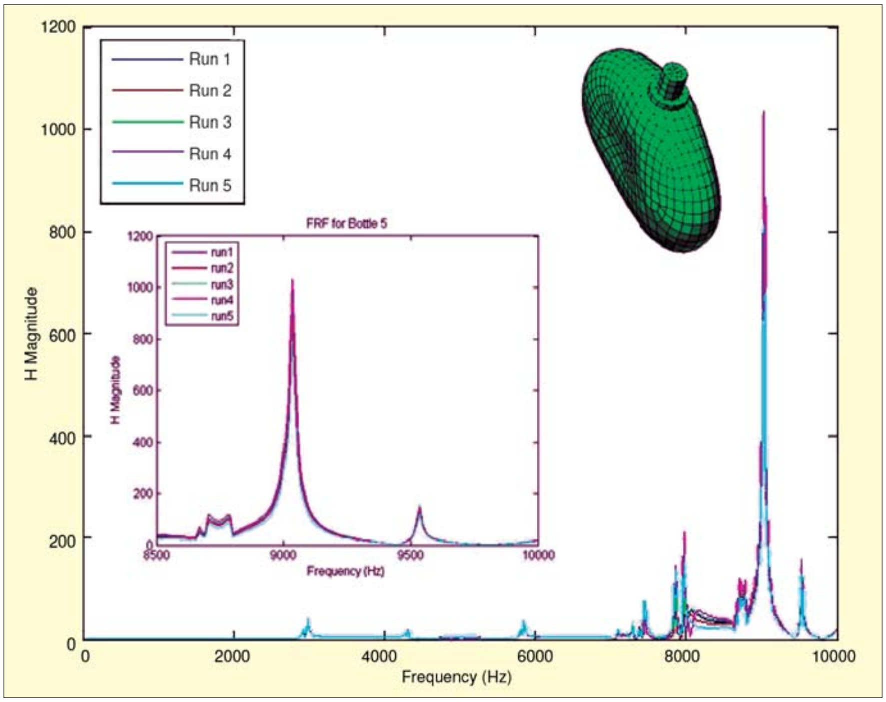

Figure 2. Frequency response of the bottle used in this study.

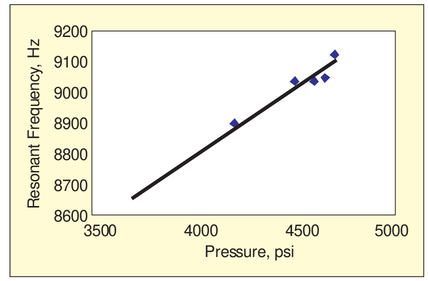

Figure 3. Calibration curve for different bottles of the same design. Deviations at high pressure are due to inaccurate fill pressures.

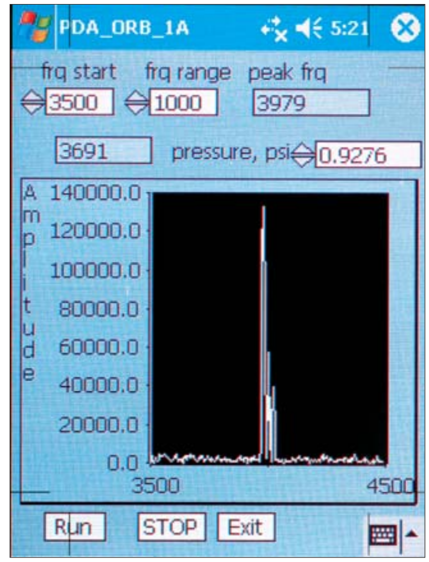

Figure 4. PDA deployment

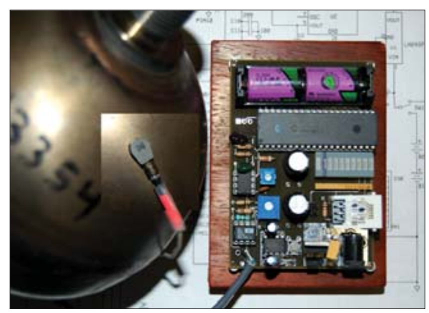

Figure 5. Instrumented pressure vessel and circuit board.

mined by the sample size, which can be made arbitrarily large, with current DSP (Digital Signal Processor) technology. In the case of the PIC18F452, the on-board memory is restricted to about 1400 words, which limits frequency resolution to twice the resonant frequency divided by 1400. Useful limits on the frequency resolution are on the order of 0.1 Hz which would imply a sample size of roughly 200,000 data points for the 9 kHz peak shown in this study. At these sample sizes, the time to perform the digital Fourier transform becomes a limiting factor for some dedicated microprocessor-based systems.

Conclusions. The ability to measure pressure and/or fill in a sealed vessel without breeching the vessel wall is demonstrated. The method relies only on the impulse response of the vessel and the variation of resonant frequencies with internal stress.

1. R. R. Archer, "On the influence of Uniform Stress States on the Natural Frequencies of Spherical Shells," Trans of the ASME Journal of Applied Mechanics, September, 1962, pp. 502-505.
2. Bronowocki, A. J., et al., US Patents 5,591,900 and 5,351,527.

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