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A Digital Signal Processor Based Controller for Inventory Confirmation Using Mass-Spring Devices

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A DIGITAL SIGNAL PROCESSOR BASED CONTROLLER FOR INVENTORY CONFIRMATION USING MASS-SPRING DEVICES

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ABSTRACT

Successful inventory confirmation measurements in SNM storage monitoring scenarios require electronic systems that are capable of long-term, reliable operation. Reliability can be improved by using systems with a minimum of inaccessible active components. A resonant weight pad has been designed to determine item mass with only two passive components located at the SNM storage point. During operation, the resonant weight pad and the monitored item become a mass-spring system, whose resonant frequency is related to the item's mass. This paper describes a Digital Signal Processor (DSP) based control system that is capable of determining resonance and correlating it to a mass value. In addition, the control system provides a communication link between the weight pad and a host processor.

INTRODUCTION

Mass is one measurement used to quantify the physical properties of SNM (Special Nuclear Material) within Modular Storage Vaults (MSVs) or Rackable Can Storage Boxes (RCSBs). The data is used to prove that the mass property of the SNM stays within predefined limits. In the case of mass measurements, variation outside those limits indicates tampering with the SNM. Resonant weight pad technology provides not only an indication of change in mass, but can also indicate tampering by reacting to changes in center of mass or density (due to removal and replacement or material substitution). The technology provides mass measurement with only two buried passive electronic components, both of which are noted for their insensitivity to temperature or humidity and long term durability.

The design goal of the controller is to provide a robust and accurate system that will control a resonant weight pad, determine resonant frequency, convert the resonant frequency to mass, and finally communicate the results of the measurements back to a host processor. This design must work with hardware already designed and/or operating. These requirements and constraints, along with physical layout of MSVs and/or RCSBs define the scope of this project.

BACKGROUND

Mass-Spring Device (Resonant Weight Pad)

To better understand the operation of the controller, it is necessary to provide a brief explanation of the resonant weight pad itself. The device operates as a simple mass-spring system governed by the differential equation

$$m\frac{d^2x}{dt^2} + \alpha\frac{dx}{dt} + kx = F\ . \tag{1}$$

The solution of this equation reveals that if the motion of the mass-spring system is sensed and the spring constant is known (or experimentally derived) then the resonant frequency can be determined by analysis of the magnitude and phase information [1]. Since the solution determines that the resonant frequency (ω) is defined as,

$$\omega = \sqrt{\frac{k}{m}}\ , \tag{2}$$

the mass can be directly calculated.

Drawings of the weight pad are shown in Figure 1. The pad consists of two voice coils (each one is similar to a speaker voice coil) sandwiched between two stainless steel plates, separated by a cantilever spring arrangement. The larger (center) coil is driven by a sinusoidal current source. The signal in the coil induces an EMF that opposes or attracts the magnet (opposition or attraction is a function of the polarity of the drive signal and the wiring of the mechanical assembly). Because the magnet is permanently attached to the top plate, the sinusoidal signal induces piston motion (see Figure 1). This voice coil will be denoted as the driving coil for obvious reasons. The second (smaller) voice coil is driven by the mechanical system. In this case, the motion of the magnet through the coil produces a voltage proportional to the velocity of the upper plate. This voice coil will be denoted as the pickup coil.

The resonant weight pad is well adapted to a MSV/RCSB type of environment because it uses only two passive electronic components. The two coil and magnet assemblies are essentially the same as speaker voice coils, which have been observed to operate continuously for several decades under normal conditions. This design allows placement of the support electronics outside of the hole, ensuring easy repairs or upgrades without disturbing the material.

Modular Storage Vault (MSV) and Rackable Can Storage Box (RCSB)

MSVs and RCSBs are concrete blocks used to store material. Each block contains multiple storage holes that hold one container and a mass measurement device. Generally, the container is set on top of the weight pad and is stored indefinitely in this configuration. The MSVs, RCSBs and material containers dictate the physical size of the weight pad. For proper operation, the base of the storage container must be extremely stable. Any rocking or vibrations that are transmitted through the storage container will cause faulty mass readings. Ideal materials include concrete and granite. If the base of the hole is metal, it should be securely anchored to the structure from both the sides and bottom to prevent a drum head effect.

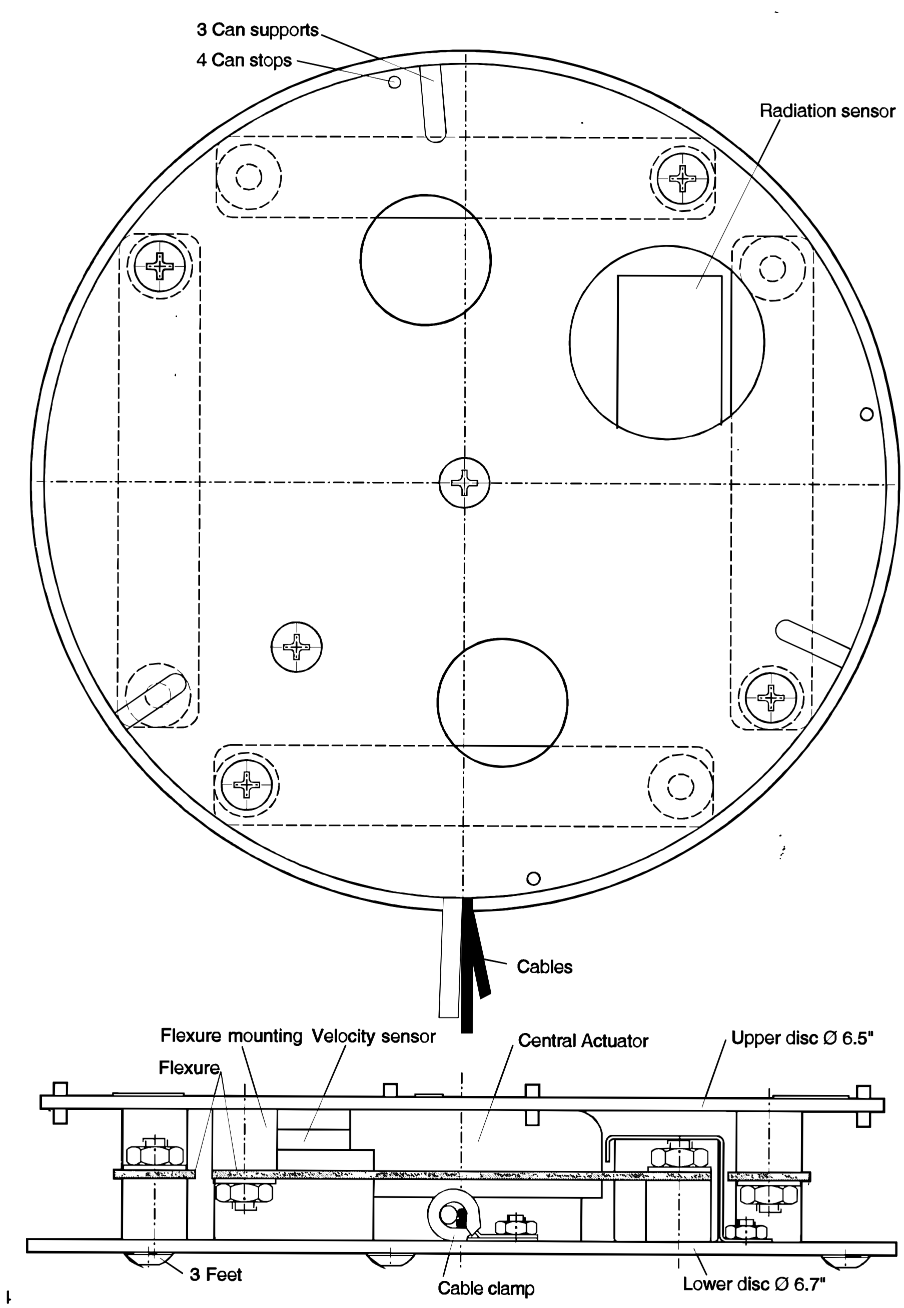

Figure 1, Resonant Weight Pad Assembly [2]

CONTROLLER DESIGN DISCUSSION

Mass Determination Algorithm

The goal of this controller is to determine the resonant frequency of a mass spring system. To accomplish this requires four steps. First, generate and drive the mass-spring system with an excitation signal. Second, record the generated signal. Third, use the data to calculate the resonant frequency. Fourth, convert the frequency to mass based on previous calibration data. Each of these steps will be discussed in detail.

Signal Generation

The driving signal used must excite the weight to produce sufficient displacement, which in turn produces a voltage in the pickup coil that can be recorded and used for processing. The resonant frequency is obviously unknown, so all frequencies must be initially excited. One way of exciting the system at a wide range of frequencies is a chirp function,

$$A\sin(2\pi f \frac{t^2}{2})\,. \tag{3}$$

Based on the known mass range and the spring constants of the weight pad, resonant frequencies are expected in the range of 5-60 Hz. Logically, the chirp function's power spectrum has energy in that range. The chirp's length in time is a function of the resolution needed to determine the resonant frequency. This is important because it defines the rate at which sequential mass measurements can be made. For a resolution of 62.5 mHz, the chirp takes 16 seconds to complete.

The basic chirp given in (3) does not address gain issues. At all times, the acceleration produced by the driving signal must not exceed the acceleration of gravity, g (9.8 m/s^2). If A is optimized to produce adequate displacement with large mass, then acceleration will exceed g when measuring small mass. The result is shaking or buzzing of the container as separation occurs between the pad and container or the pad and MSV/RCSB. When this happens, data from the pickup coil is corrupted and the resonant frequency determination algorithm fails.

In order to be certain that the container and top plate of the weight pad do not separate during excitation, it is necessary to drive the weight pad with a current waveform such that the peak acceleration does not exceed 1*g*. The same is true to guarantee that the bottom plate does not lift off the bottom of the MSV/RCSB. Consequently, the weight system was modeled by equation (1), and the peak acceleration, velocity, and displacement were computed. The weight pad parameters were taken from the manufacturer's literature: spring constant 80,000 N/m, voice coil force constant 11 N/amp. The coefficient of the velocity term in the differential equation was calculated to be 7.9 N-s/m by measuring the shape of the resonance at 18.8 kg.

The differential equation was solved by 4^{th} order Runge-Kutte numerical integration over the interval from 0 to 16 seconds, using 8192 steps, with a chirp driving function covering 0 to 80 Hz. The resulting peak acceleration scales with the amplitude of the chirp and the results of the calculation are shown in Chart 1, expressed as m/s^2/amp. The chirp amplitude is modulated with the inverse of the fitted function adjusted to get a peak acceleration of 0.5*g* with a maximum drive within the specifications of the output amplifiers.

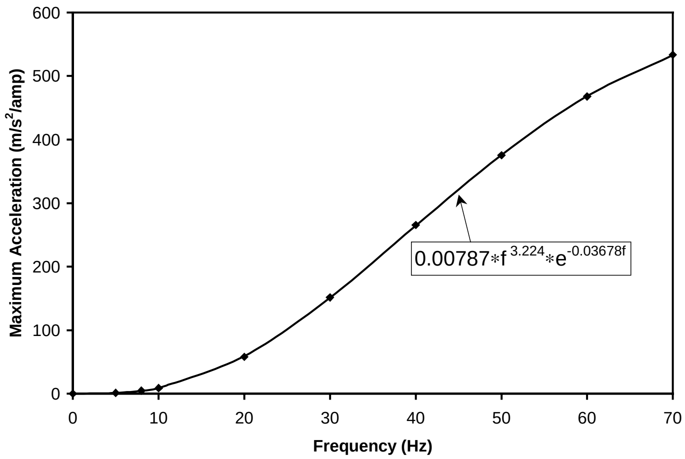

Chart 1, Peak Acceleration as a Function of Resonant Frequency

Signal Recording

Analysis requires a copy of both the transmitted drive signal and the recorded pickup signal. The drive signal is typically output at a high sampling rate (i.e. 2560 Hz), well above the Nyquist rate for the given bandwidth (about 60 Hz). It will be seen later that the determination of resonant frequency is based on the phase relation of the output and input signals. Introducing a smoothing filter on the output data would allow lower output sampling rates, but would also introduce a phase shift that would corrupt the measured result. To somewhat counteract the lack of a smoothing filter, a high output rate is used to more closely approximate an analog sinusoid. Because the driven system is a mechanical mass-spring system, it will not respond (measurably) to the steps cause by the quantized outputs because they are too far away from the system resonance.

For similar reasons, anti-aliasing filtering causes problems during recording of the pickup signal. Typically, the signal is passed through a low pass filter to band-limit the signal before sampling. However, filtering the input introduces a detrimental phase shift. By not low pass filtering, aliased artifacts are present, but because the aliased signals are low-level noise they do not significantly alter the spectrum.

Resonant Frequency Determination

The frequency determination is based on the transfer function of the output Fast Fourier Transform (FFT) and the input FFT. The magnitude of the FFT transfer function (FFTTF) for a typical mass is shown in Chart 2. This data gives a clear indication of the system resonance by a single sharp peak. The sampling rate and FFT length determine the resolution. Because the frequency resolution is directly proportional to the mass resolution, an ideal system would have very high frequency resolution. Increasing the resolution is possible by increasing the sampling rate and/or the FFT length. The sample rate is limited by hardware (both speed and ultimately memory), and the FFT size is limited by hardware memory. In practice, the only option available is to increase the effective resolution by interpolating the data for a more accurate value of the true resonance. Examination of the phase data in Chart 3 reveals the transition at the resonant frequency. This transition curve is somewhat linear near resonance, providing the ideal curve to interpolate.

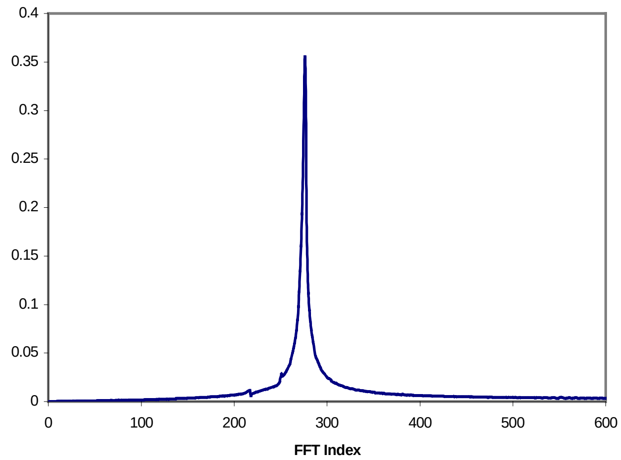

Chart 2, FFTTF Magnitude Response

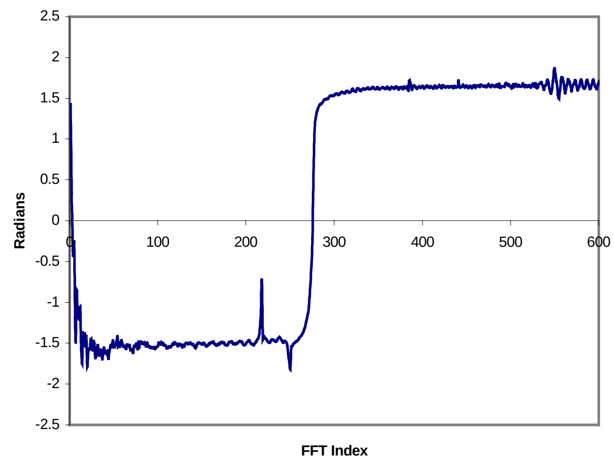

Chart 3, FFTTF Phase Response

Ideally, the phase response of the FFTTF is a smooth curve with a 180-degree transition at the resonant frequency (Chart 3). The slope of the transition is proportional to the Q (damping) of the system. It would seem that the magnitude signal of Chart 2 is not really needed, as the phase data should contain everything needed to calculate the resonant frequency. However, phase wrap errors and wild phase oscillations occur when the response is calculated using low-level signals [3]. These oscillations cause phase data to swing from plus pi to minus pi when the pickup coil (input) signal is low (as occurs far from resonance).

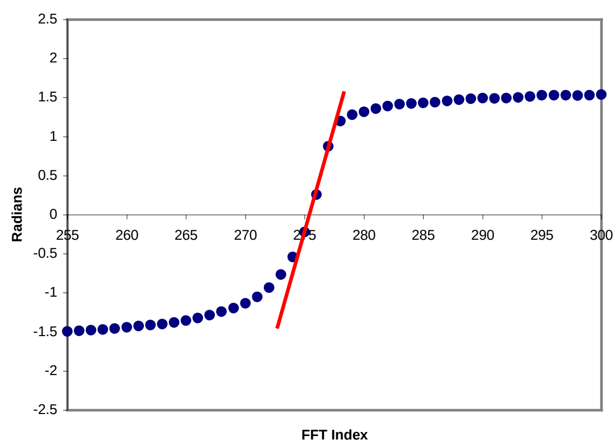

Chart 4, FFTTF Phase Response Curve Fit

The magnitude data provides a clear indication of the resonant frequency general proximity. Once a starting place is found using the magnitude data, the index into the FFTTF is held and the phase data is examined in the same region. The zero crossing in the phase data is found and an equation is fit to the data points around the zero crossing. From this equation, an exact frequency value at the zero crossing can be determined, giving a more accurate measure of the true resonance (Chart 4). Note that this method essentially ignores the corrupted phase data far from resonance.

It should be mentioned that in an ideal piston motion system there is only one resonance (other than harmonics). This system is far from ideal, and while other resonances are sometimes observed, the highest magnitude peak is treated as the true resonance (or closest to the true resonance) [4].

Frequency to Mass Conversion

At this point the algorithm has made an accurate measure of the resonant frequency. The only task remaining is the convert the frequency value to mass based on the relation

$$m = \frac{k}{\omega^2}, \tag{4}$$

where k is the spring constant and ω is the resonant frequency. The spring constant k is difficult to measure (accurately) mechanically, but it can be determined using known weights and a calibration procedure. To find k, ω is determined for several known weights (m), and a data set of (m, ω^2) is built. k is defined as the slope value that fits the observed data.

HARDWARE

The hardware for mass detection algorithm is based on a Texas Instruments DSP. DSPs are optimized for intensive iterative operations, and are therefore ideal for FFT calculation and other signal processing applications.

Signal Generation

Signal generation is accomplished with a 16-bit digital to analog converter (DAC). The signal is multiplexed to allow up to eight weight pads to be controlled. The signal is then amplified with a voltage to current amplifier.

Signal Recording

The pickup signal is buffered through a differential amplifier to remove common mode noise. It is then digitized with a 16-bit analog to digital converter (ADC). As previously discussed, no anti-aliasing filtering is used because of phase information distortion. The pickup signal is also multiplexed to allow one of eight channels to be selected.

Requirements for Operation

The resonant weight pad controller is capable of stand-alone operation. Code is self-contained on board via electronically programmable read only memory (EPROM). A simple system requires only a computer with an RS-232 serial port (standard PC COM port), dedicated software, one controller board and up to eight resonant weight pads.

The controller also works well with a networked system of sensors, using RS-232 communications protocol. Power requirements are +5V at 20mA, +12V at 10mA and –12V at 10mA, for a total of 340 mW.

EXPERIMENTAL RESULTS

Accuracy is not as important as repeatability in this case, which serves the design well because accurate calibration has proved difficult to do. The nature of the weight pad makes it sensitive to container placement [4]. This makes accurate calibration difficult because the same item may get two different weight results based on where it was placed on the weight pad.

Repeatability variance changes proportionally with the amount of mass measured. Best case repeatability is 0.04% variation of measured mass (when measuring 0.5kg). Average repeatability over the mass range is roughly 0.25% of measured mass. Long-term testing is necessary to provide more accurate data.

FUTURE WORK

It is anticipated that mass detection time can be decreased. Further study of the ideal chirp based function may lead to advances that help decrease the detection time. It may also be possible to optimize the existing chirp to reduce the detection time as much as 30-40%.

The practical weight detection range is a function of the cantilever springs in the weight pad. Stiffening or softening these springs can optimize the pad for different weight ranges. However, the amount of current needed for adequate excitation will increase or decrease proportionally to the spring rate. Since the controller is designed for the current spring rate, it may not be able to deliver sufficient current for weight ranges requiring stiffer springs. Future designs will be capable of sourcing more current, ensuring that the controller is suited to a wide mass range.

ACKNOWLEDGMENTS

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Reference:

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