A method for the direct, real-time recording of ground displacements during earthquakes
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ABSTRACT

This paper presents the development of an integration circuit which can be used in conjunction with existing accelerometers to directly record ground motion acceleration, velocity, and displacement time histories in real-time. Because this circuit can compute the time histories on-line, this improves the current off-line processing required to obtain the ground motion time histories. The real-time acceleration processing (RAP) circuit consists of two integrators which can process the ground acceleration data in real-time to obtain velocity and displacement. Results verifying the accuracy of the displacements generated by the RAP circuit, when used with an accelerometer, are compared to the output from a linear variable differential transformer (LVDT).

INTRODUCTION

The design of a structure for seismic excitation requires accurate and complete characterization of the ground motion expected at the site. Effects on structures may be caused by ground motion shaking (vibratory effects) or by ground displacement (ground failure). Ground motion shaking is typically characterized in terms of peak amplitudes (acceleration, velocity, and displacement), duration, response spectra, or time histories. Ground displacement, or ground failure, a secondary effect of ground shaking, may be triggered by liquefaction or other soil weakening effects including massive flow failure, lateral spread, ground settlement, and loss of bearing strength (Page, et. al. [1]). The reports of recent national and international workshops authored by Iwan [2], Marshall [3], CERF [4] and Page, et. al., [1] have identified the need for more complete and accurate descriptions of ground motion shaking and ground failure to assess ground motion and structural response during earthquakes.
The accuracy of ground motion characterization depends on the number and type of appropriate instrumentation array(s) at a potential site to characterize the earthquake source mechanism and the factors affecting the propagation of waves from the source to site, accuracy of the instrumentation, and the data processing mechanism used. Traditionally, the ground motion parameter recorded during an earthquake is acceleration. Accelerometers are widely used because they are initially inexpensive, require little maintenance, are relatively compact, and have functioned adequately during earthquakes. Currently available analog recording systems used to record strong ground motion and structural response include, for example, the widely used Kinemetrics SMA-1 accelerograph (Diehl [5]). The basic transducer is an analog device which records the data on photographic recorder with recording initiated at the time that a predetermined threshold of motion is exceeded. The recorded analog acceleration data is digitized and then analytically processed off-line to compute corrected acceleration, velocity, and displacement time histories, Fourier and response spectra, and other ground motion quantities of interest (Trifunac and Lee [6]). Digital systems, on the other hand, directly record the data in a digital format. Digital technology is rapidly developing but has not been widely adopted for field use due to its current high cost and required maintenance. It is anticipated that eventually all accelerometers will record digitally due to their potential for low cost with small size, low power requirements, and large dynamic range.

Current practice is to retrieve the analog recorded acceleration time history from the instrument and then off-line use a computer program to correct, integrate, and filter the acceleration to derive velocity and displacement time histories. Various analytical techniques have been used to process the raw acceleration record which incorporate low-pass filtering, transducer adjustments, and baseline correction for linear trends. The processing technique used can affect the accuracy of the resulting velocity and displacement time histories. The purpose of the standard processing method derived by Trifunac and Lee [6] is to correct the uncorrected, digitized accelerogram for error introduced in the signal during recording (instrument errors), during photographic processing and enlargements of the raw accelerogram, and during digitization of the record. The resulting errors (or noise) are primarily concentrated at the low and high frequency ends of the signal and therefore affect the reliability of the original signal at these ends. During processing, the integration of the accelerograms to derive velocity and displacement time histories requires a minimization of the low frequency (long period) errors. Low frequency distortions, such as baseline errors, present in the signal can greatly affect the area under the acceleration curve, and hence the accuracy of the integration would be affected by such distortions. Trifunac, Udwadia, and Brady [7] and Hudson [8] give a comprehensive analysis of the variable sources, magnitudes, and significance of the errors in digitized signals and discuss the correction procedures to reduce or eliminate these errors.
Because the amplitudes of ground displacements computed from doubly integrated corrected accelerations are sensitive to low frequency errors, the selection of appropriate values for the high pass filter used in standard processing has been investigated. Trifunac, Udwadia, and Brady [7], Hanks [9] and [10], Trifunac and Lee [11], Basili and Brady [12], Hart, Rojahn, and Yao [13], Pauschke [14], and Shakal and Ragsdale [15] investigated the accuracy of ground displacements computed by various processing schemes. These studies showed that reliable estimates of the ground displacements can be computed from the doubly integrated corrected accelerations given careful selection of the low frequency cutoff limit. To improve accuracy, various authors such as Sunder and Connor [16], Converse, Brady, and Joyner [17], Erdik and Kubin [18], and Lee [19] have proposed alternative analytical methods for processing digitized analog strong motion accelerograms.

To date, however, no one standard processing technique has been adopted by the earthquake engineering profession. Therefore, the reliability of the computed ground motion time histories is a function of the processing scheme used. In addition, the current processing schemes cannot provide ground motion data in real-time. Hence, there is a time delay between the occurrence of the seismic event and the obtainment of data needed to assess the ground motion and structural response.

REAL-TIME ACCELERATION PROCESSING CIRCUIT

To eliminate the problems associated with off-line processing to compute corrected acceleration, velocity, and displacement time histories, the real-time acceleration processing (RAP) circuit was developed as a simple and accurate way of obtaining these time histories directly in real-time (Lang, Pauschke, and Ryan, [20]). Because accelerometers are widely used to record strong ground motion and structural response, the RAP circuit was devised to be used in conjunction with existing accelerometer technology.

The RAP circuit consists of two integrators which process the acceleration signal to obtain velocity and displacement time histories. The determination of displacement from an accelerometer set stringent requirements on the RAP circuit design. To be useful for seismic applications, the double integration required to obtain accurate displacements must meet several critical design goals. First, the circuit DC offset drift must be minimized to minimize circuit induced displacement error, i.e., low frequency error. Second, the design must allow for easy access to the data at all levels of the process. Third, the design must have compatibility with existing in-place accelerometer instrumentation. Finally, the circuit response must be linear and have a high degree of accuracy over a wide dynamic range for low frequency stimuli.

Analog circuitry was selected mainly because of the initial conditions issue in integration. With digital circuitry, pre-event initial conditions
occurring prior to the start of data acquisition must be incorporated into the
digital integration approximation method. The RAP circuit design is a
continuously running integrator and therefore inherently incorporates the initial
conditions into the process once the circuit has been calibrated.

The long term integration requirement precluded the use of standard
operational amplifier based integration circuits. A unique approach to
integration was required to accommodate the requirements of long-term
operation and minimal long-term drift. To meet the design goals, the voltage-
to-frequency converter (VFC) based circuit was developed as an improved
integration circuit. The block diagram for one half of the RAP circuit (i.e.,
one integrator) is shown in Figure 1. The full RAP circuit cascades two of the
circuits shown in Figure 1 in order to perform double integration. The RAP
circuit can be used in conjunction with commercially available strong motion
accelerometers to obtain ground acceleration, velocity, and displacement data
in real-time.

RAP CIRCUIT OPERATION

The basis of the RAP circuit is the voltage-to-frequency conversion and the
counting operation. Since counting is the basis for integration, an Analog
Devices AD652 VFC was utilized to convert the input voltage signal into a
stream of pulses with the pulse rate being proportional to the input voltage.
The integration is completed by feeding the output of the VFC into the clock
input of a standard TTL up/down counter. The Analog Devices AD652 VFC
was chosen for its range, linearity, and versatility.

Signal conditioning circuitry was required at the input of the VFC to
amplify the signal for maximum dynamic range and to accommodate positive
and negative acceleration signals. In addition, a zero voltage signal input must
be converted to zero frequency to prevent counting with no input. To handle
this and to maximize the dynamic range, the RAP circuit was configured for
bipolar voltage input. In this configuration, zero frequency corresponds to -5
V and full scale frequency corresponds to +5 V. Consequently, in bipolar
operation both positive and negative signals will be converted to the same
frequency span. This is essentially an absolute value operation and was
achieved by using a full wave rectifier. To retain information on the signal
polarity, a zero crossing detector was employed. The zero crossing detector
is input to the up/down select pin on the counters. This configures the
counters to count up for a positive voltage and down for a negative voltage.
To observe the output, a standard bipolar D/A conversion circuit is used on the
outputs from the counters. The circuit consists of an Analog Devices
AD7541A D/A and a Motorola TL072 dual op amp chip configured to
condition the D/A output signal. This circuitry allows the user to view the
output of the first stage of integration and also serves as the input to the
second stage of integration to complete the double integration process.
In summary, the general operation of a single stage of integration is as follows. The input signal is amplified, rectified, shifted, and input into the VFC. The VFC converts the signal into equivalent frequencies which are summed by the counters. The D/A converter then provides a voltage between ±5 V that corresponds to the integral of the input signal. The signal from the D/A converter can then be viewed on an oscilloscope, stored, or used as an input to the next integration.

VERIFICATION OF RAP CIRCUIT ACCURACY

The RAP circuit was used in conjunction with a piezoresistive accelerometer to verify the accuracy of the displacements determined directly in real-time from the acceleration signal. A test set-up was devised to provide simple steady-state sinusoidal inputs to the RAP system circuit. A standard function generator was used to drive a Brüel & Kjaer 4809 vibration exciter (shaker). The shaker was driven with sinusoidal signals of different frequencies and test results were collected at steady state. The shaker is capable of a maximum peak to peak displacement of 8 mm. An IC Sensors Model 3145 silicon micromachined piezoresistive accelerometer was attached to the shaker table to transduce the acceleration. The output of the accelerometer was coupled to the circuit through a two pole active low pass filter with a 30 Hz cutoff frequency. In ground motion studies, accelerometers with frequency response down to 0 Hz (DC) are used since the range of ground motion frequencies are low (0 to 33 Hz).

The displacements computed by the RAP circuit were compared to a direct displacement measurement device, i.e., a linear variable differential transformer (LVDT). The device outputs a voltage which is proportional to the length of core within the coils of wire. In this experiment, the case of the LVDT was fixed with respect to the shaker. The core was attached to the surface of the shaker and allowed to move freely in and out of the case. A Schaevitz model 500 DC-E LVDT was used to transduce the displacement. This LVDT has a sensitivity of 0.8 V/mm and a linearity of 0.25% full scale with a nominal linear range of ±12.5 mm.

Several test runs were made at 11 and 30 Hz. Two different amplitude excitation signals were used for the 11 Hz sine wave and one amplitude was used for the 30 Hz signal. This paper presents the results from one of the 11 Hz sine wave tests in Figure 2. The results show that the RAP circuit and LVDT outputs are closely matched. The displacement error, computed as the difference between the RAP circuit and LVDT outputs, is shown in Figure 3. The high frequency modulation in Figure 3 is coupling noise from external sources. This noise can be greatly reduced by appropriate shielding and printed circuit board construction. The residual low frequency, 11 Hz modulation is an artifact of the propagation delay through the RAP circuit. The LVDT signal has no delay, and therefore there is a phase shift between
the two signals. The measured DC offset representing constant displacement error is less than one micrometer. The results demonstrate the ability of the RAP circuit to perform accurate double integration for time-history displacement studies.

FUTURE IMPROVEMENTS FOR THE RAP CIRCUIT

While initial testing showed that the RAP circuit performed well, a number of improvements can be made to reduce noise and enhance sensitivity and accuracy. As mentioned above, once the circuit design is finalized, the circuit should be built on a printed circuit board using low-noise layout rules. Also, low-noise amplifiers which exhibit very low drift are available at a higher cost. The potential improvement in terms of sensitivity and overall performance most likely would justify the additional cost.

The testing to date has been limited to small scale laboratory vibration tests. Once the circuit design has been finalized, additional laboratory and field testing should be performed. Ideally, testing should include applications to recorded structural response, i.e., the RAP circuit could also be readily used in conjunction with commercially available accelerometers to record structural response.

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REFERENCES


Figure 1. Block diagram of one real-time acceleration processing (RAP) integration circuit to perform single integration. Two circuits are cascaded to perform double integration. Input shown can be an accelerometer.

Figure 2. Comparison of the displacement time histories computed from double integration by the RAP circuit and those recorded by the LVDT due to shaker excitation at 11 Hz.
Figure 3. The displacement error of the time histories shown in Figure 2, i.e., the difference between the displacements computed by the RAP circuit and those recorded by the LVDT.