Remote Sensing of Impacts With Non-Gaussian Distributions

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***Abstract*—In this paper, a method of remotely detecting (sensing) sudden impacts is presented. The detector is designed for Poisson-, Erlang-, or lognormal-distributed signals while discriminating against Gaussian-distributed, uniformly-distributed, and impulsive noise and signals. The method uses the energy content of the impact signal by using an entropy-based estimator. The method is especially useful for detecting impacts on pipelines caused by falling rocks, construction projects, seismic activity, etc.**

***Index Terms*—pulse detector, pipe strike, robust, noise discrimination, noise rejection.**

I. Introduction

The structural integrity of pipelines and other structures is often inferred by remotely sensing impacts or movement of the structures. These structures, whether above or below ground, are vulnerable to damage from many sources. Typically, sensors (usually acoustic) are placed on the structures and monitored remotely. Impacts can occur due to falling rocks, right-of-way encroachment by construction crews, or seismic activity. When these impacts occur, the remote sensing system alerts operators or generates an alarm. Because these structures are generally in a remote area, false alarms are obviously a problem. Discrimination against non-impact signals is desired and needed.

Continuous monitoring of remote structures for seismic events, impacts occurring during excavation in proximity to the structure, or falling objects, such as falling rocks and landslides, is not a simple task. Detection of impact signals is typically performed with acoustic sensors, such as geophones or accelerometers. Acoustic detection is susceptible to background and sensor noise. The wanted impact signal can be masked, either partially or completely, by these noises. By necessity, the sensitivity of the acoustic sensors is very high. This high sensitivity, in combination with noise, can result in a significant number of false detections. Low-level ground movement, and thunder are particularly troublesome. By making use of the energy characteristics of the signal generated by the impact, detection systems can distinguish the impact signal from the unwanted noise.

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II. Algorithm Description

The algorithm makes an estimate of the signal envelope, performs an integration of the envelope, and compares the ratio of these parameters in determining if an impact has occurred. Specifically, an energy-based envelope of the impact signal, $x(k)$, is estimated. A ratio is then formed using this envelope and an integrated version of the envelope over an integration period, m. This ratio is compared to a threshold, β. If the threshold is exceeded, a flag, $f(m)$, representing the present integration period is set if $f(m\text{-}1)$, representing the result of the ratio/threshold comparison for the previous integration period, is not set. Detection of an impact is declared if $f(m)$ is set, and $f(m\text{-}2)$ is not set.

The impact signal envelope is derived from the energy in the signal, rather than the signal amplitude. The envelope is an entropy-based envelope using

$$w(m) = \sqrt{\frac{2\log(n)}{n}}\sigma_{\mathbf{x}}^2 \quad (1)$$

where n is the time interval over which the integration is performed, and $\sigma_{\mathbf{x}}^2$ is the variance of the signal vector of dimension equal to the integration interval. This entropy-based envelope estimation is the based on that used by Donoho for wavelet coefficient shrinkage [1].

The integrator is implemented as an exponential integrator using the form

$$v(m) = \sum_{j=1}^{n}\left[(1-\alpha)\,y(j-1) + \alpha\, w(m)\right] \quad (2)$$

The integrator output is calculated for each input sample over the integration interval with $y(j)$ being the present integrator output, $y(j\text{-}1)$ the previous integrator output with $y(0) = 0$, $w(m)$ the present entropy-based envelop value (a constant value over the integration period), and α the control variable.

The threshold, β, is a function of the maximum of the entropy-based envelope and the envelope/integrator ratio. For Poisson, Erlang, and lognormal distributions, the control variable is set so that over a single integration period, the integrator output is between 1/3 and 2/3 the envelope maximum. The optimum threshold, β, was found to be 6 times this ratio, or a value between 2 and 4.

The algorithm is then listed as:

$$
\begin{aligned}
f(0) &= 1 \\
y(0) &= 0 \\
\mathbf{x}(k) &= \left[x(k), x(k-1), \cdots x(k-n-1)\right] \\
w(m) &= \sqrt{\frac{2\log(n)}{n}\sigma_{\mathbf{x}}^2} \\
r(m) &= \frac{w(m)}{\sum_{j=1}^{n}\left[(1-\alpha)y(j-1)+\alpha\, w(m)\right]} \\
f(n) &= \begin{cases} 1 & r(n) > \beta, f(m-1) = 0 \\ 0 & otherwise \end{cases}
\end{aligned}
\tag{3}
$$

$\mathbf{x}(k)$ is a n-dimensional vector of the present and $(n - 1)$ input samples from the impact sensor, with $\sigma_{\mathbf{x}}^2$ equal to the variance of $\mathbf{x}(k)$. An impact is declared if $s(m) = 1$ according to

$$
s(m) = \begin{cases} 1 & r(n) > \beta, f(m-2) = 0 \\ 0 & otherwise \end{cases}
$$

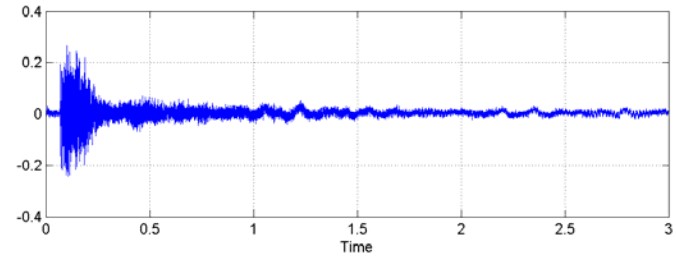
III. Testing

Underground pipelines are used to move fluids (e.g., oil, natural gas, water) from place to place. These underground systems are subject to damage from naturally-occurring and man-made sources. Additionally, pipeline movement, over time, can cause cracks, leaks, and other problems. Consequently, underground pipelines are a prime subject for remote impact sensing.

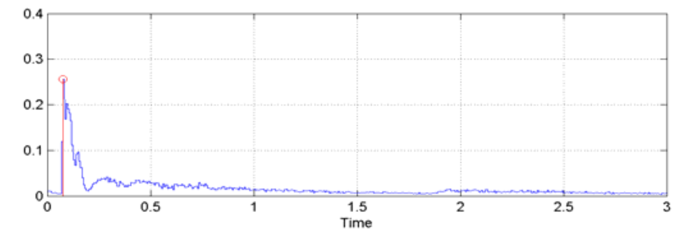
The algorithm was tested on pipelines in service on the east coast. An obvious impact pulse and the entropy-based envelope of the impact signal is shown in Figure 1. The vertical line is added to show where the algorithm declared an impact detection. Figure 2 gives a typical noisy acoustic sensor output. The algorithm correctly detected the pipeline impact and ignored the extraneous noises. A test was also conducted with bursts of large background noises and low-level impact signals. One test result is given in Figure 3. Again, the algorithm correctly identified the impact to the pipe.

IV. Conclusion

When acoustic sensors are used to detect impacts on pipelines, a noisy pulse signal is generated due to high sensor sensitivity and the long distances the signal travels. Typical pulse detectors have generally experienced high false detection rates because of the noise contamination. We have presented a unique algorithm that is robust to the typical noise associated with these sensor outputs. The algorithm is successful in discriminating against Gaussian, wideband, and impulsive noise. Tests with actual pipeline strikes show the algorithm is also sensitive and can detect very-low-level signals.

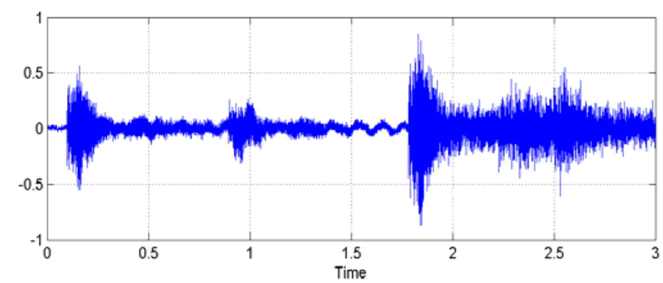


(a)

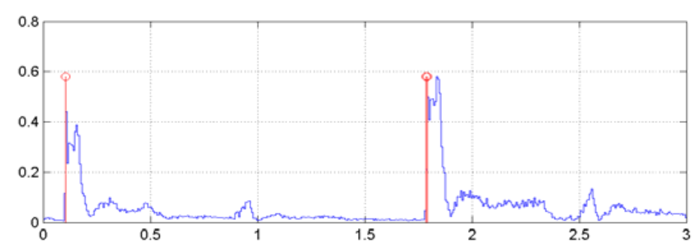


(b)

Figure 1. (a) Acoustic Sensor Signal. (b) Entropy-Based Envelope and Strike Detection Indication.



(a)



(b)

Figure 2. (a) Acoustic Sensor Signal. (b) Entropy-Based Envelope and Strike Detection Indication.

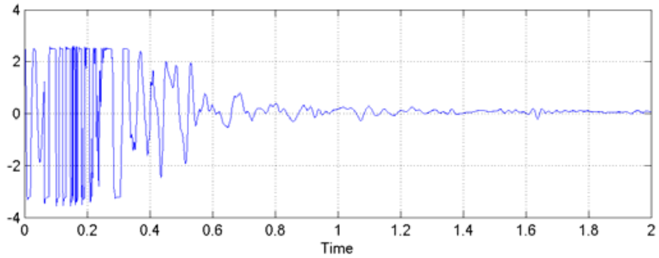


Figure 3a. Acoustic Sensor Signal.

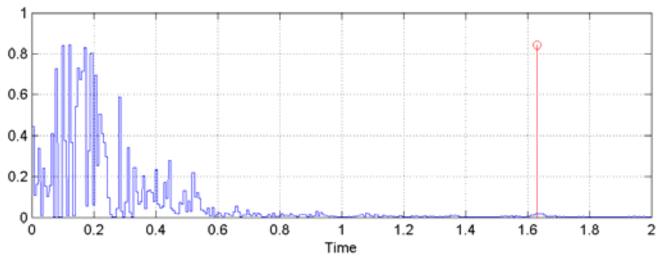


Figure 3b. Entropy-Based Envelope and Strike Detection Indication.

REFERENCES

[1] David L. Donoho, "Nonlinear Wavelet Methods for Recovery of Signals, Densities, and Spectra from Indirect and Noisy Data, *Proceedings of Symposia in Applied Mathematic*s, American Mathematical Society, p 173-205, 1993.