Enhancing the Ability in Detecting Defects Occurred in Covered Pipe by using Matching Pursuit and Smooth Empirical Mode Decomposition

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ABSTRACT

Pipes that carry gas into residential buildings are one of the most important infrastructures in cities. These pipes are prone to corrosion after a period of time because of different environmental factors. In order to avoid any pipe rupture that may cause explosion, the integrity of such pipes must be checked on a regular basis. Ultrasonic guided wave is an effective method for structural health monitoring of plate like structures and pipes. However, the signals that are obtained from guided waves can be very difficult to interpret due to mode conversion, overlapped modes and dispersion effect. In order to extract meaningful information of guided wave signals, using advanced signal processing methods are inevitable. The problem of dispersion effect is taken care by the method called matching pursuit. The separation of overlapped modes is contributed by another method called smooth empirical mode decomposition. Dispersion means that the velocity of the propagating wave is a function of its frequency. As in most guided wave applications in pipe inspection, narrowband tone-burst excitation signal is commonly used, dispersion causes guided wave signal to spread in time axis as it travels and changes its shape. Matching pursuit is a greedy algorithm that can be used to approximate signals. This method iteratively approximates a signal by its predefined dictionary. The waveforms predicted by matching pursuit have the maximum resemblance with real GW signals. Hence, the true defect related signals can be identified even after the consideration of mode dispersion. The smooth empirical mode decomposition combines the methods of empirical mode decomposition and wavelet transform. It is used to expose a natural corrosion hidden in highly overlapped and the contaminated signals generated from the propagating guided waves in a concrete covered pipe. The validation of the above proposed methods had been verified by both simulation and experimental results that were tested on real concrete-covered pipes.

1 Introduction

Guided wave (GW) is an effective method for nondestructive testing of pipes, plates, beams and cables. GW based inspection has some challenges when it is applied to real applications. Dispersion is a common problem associated when using GW\textsuperscript{[1–3]}. Dispersion deteriorates signal resolution and complicates signal interpretations in experimental data. In order to deal with signal complexities and extract physical meaning of its features, using an advanced signal processing techniques is inevitable. While methods based on time-frequency representations are valuable tools for analyzing the guided wave signals, they cannot separate the overlapped wave-packets within the same frequency range. Moreover, most algorithms developed for GW based inspection have neglected the effect of dispersion in occurred during the propagation of GW along a pipe. Addressing this problem, a method called matching pursuit (MP) was used to deal with such situation. MP can be used to approximate the signals by selecting basic waveforms from a dictionary D. For a successful decomposition and approximation of a GW signal with MP, the design of an appropriate dictionary is of vital importance. This design must be based on prior information about the propagation of

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GW in a pipe. For the dispersion and overlapped GW modes, finite element method (FEM) was used to predict the form of wave packets propagating along the inspected pipe. The accuracy of prediction was improved by adding a single atom to the solution set at each loop. Each atom contributed a set of GW waveform. The atom selection criterion of MP utilizes the time localization of GW’s reflections that causes a portion of dispersive wave-packets to be composed mainly of a single echo. Hence, MP maximizes the matching of waveforms between the atoms and the real GW signals. With the help from FEM, many atoms were formed as a dictionary. Those atoms with frequency inconsistency with the excitation signal were discarded, whilst, those atoms have the maximum resemblance with real GW signals were retained. Finally, the atoms that contain true GW reflected signals with dispersion effect were displayed and the sources of reflection could be identified.

In real application of detecting natural corrosion in pipes that are passing through concrete walls from the external wall to an internal unit of a residential building, many reflected signals will be overlapped to each other due to mode conversion and reflections from concrete. To separate the overlapped signals, the smooth empirical mode decomposition (SEMD) was designed. It is based on the use of conventional empirical mode decomposition (EMD) and tone-burst wavelet, which was adopted in the sifting stage to improve the final outcome in SEMD. The process of selecting a proper mother wavelet that suits best for decomposing the overlapped signal plays an important role. The common practice is the use of Morlet wavelet as the mother wavelet. Since in GW inspection, the incident wave is usually a, the use of the tone-burst waveform as the mother wavelet is more appropriate than the Morlet wavelet as the shape of reflected GW will be more similar to the tone-burst signal. During the sifting stage, wavelet de-noising was applied to eliminate unwanted frequency components from each Intrinsic Mode Function (IMF). The results show that SEMD can extract fault features even when the signal is highly contaminated. In the experiments conducted for inspecting corrosion occurred in the portion of the pipe that was covered by a concrete wall, SEMD proves that it can successfully determine the location and severity of defects. It not only could separate the reflected GW signals that were entering and exiting the concrete wall section from the temporal waveform of the reflected GW, but also could reveal the natural corrosion with complex geometry that was hidden and located inside the concrete wall section of the inspected pipes.

2 Matching Pursuit

Matching Pursuit (MP) is a greedy algorithm that iteratively approximates a signal \( x(t) \) by selecting the atom \( a(t) \) from a redundant dictionary \( D \) that best matches the signal\[4\]. The dictionary is a matrix whose columns are well-known elementary signals with the same sampling frequency as the signal \( x(t) \). The best match in the iteration is the one that produces the maximum inner product with the signal. From a mathematical point of view, MP approximates a signal as a linear combination of some atoms \( y_n(t) \) plus a residue \( r_n(t) \) after \( n \) iteration:

\[
x(t) = y_n(t) + r_n(t) = \sum_{i=1}^{n} c_i a_i(t) + r_n(t)
\]

\[
= \sum_{i=1}^{n} \langle x(t), a_i(t) \rangle a_i(t) + r_n(t),
\]

\[
\|a_i(t)\| = 1
\]

In Eq. (1), \( c_i \) is the corresponding coefficient of atom \( a_i(t) \) that determines its amplitude and is a real number. The iteration in MP continues until the second-order norm of the \( r(t) \) for optimum approximation becomes minimum [5]:

\[
\|r_n(t)\|_2 = \|x(t) - y_n(t)\|_2 < \varepsilon
\]
in which $\varepsilon$ is a pre-defined value depending on the noise level in the signal (usually unknown and must be set by trial and error). Assuming the signal has been approximated by $n - 1 \geq 0$ atoms, for further approximation by $n$ atoms the MP algorithm in consecutive steps is as follows:

1. Calculate the inner product between the residue $r_{n-1}(t)$ and all atoms in $D$ excluding the ones that were already selected in the previous iterations.

   $\langle r_{n-1}, a_n \rangle \geq \rho \sup \langle r_{n-1}, a \rangle, a \in D$  \hspace{1cm} (3)

   where $0 < \rho \leq 1$ is some number independent of $n$.

2. Choose an atom $a$ that generates the maximum inner product with $r_{n-1}(t)$:

   $11, \sup , n, n, n, n, r, a, a, a, D, \rho, \leq, 0$  \hspace{1cm} (4)

3. Calculate the new residue:

   $r_n(t) = r_{n-1}(t) - \langle r_{n-1}(t), a_n(t) \rangle a_n(t)$  \hspace{1cm} (5)

4. The new approximation of the signal $x(t)$ with $n$ atoms can be represented as:

   $x(t) = \sum_{i=1}^{n} \langle x(t), a_i(t) \rangle a_i(t) + r_n(t)$  \hspace{1cm} (6)

5. The approximation in each iteration can be improved by compromising between reducing the energy of the resulting residue $r(t)$ and is defined as:

   $\|r_n(t)\|_q = \sum_{i=1}^{N} |r_n(t_i)|^q, 0 < q < 1$  \hspace{1cm} (7)

6. At each iteration $k$, the correlation coefficients between the residue $r_{k-1}$ and the dictionary $D$ excluding its previously selected atoms are calculated. All atoms whose absolute correlation coefficients are above a predefined threshold $T_h$ are selected. Choosing an atom from this set ensures a significant reduction in $||r(t)||_2$. A chosen atom at each iteration must minimize by:

   $\arg \min \|r_n(t)\|_q = \arg \min \left\{ \sum_{i=1}^{N} |r_n(t_i)|^q \right\}$  \hspace{1cm} (8)

3 **Smooth Empirical Mode Decomposition (SEMD)**

One of the major problems of Empirical Mode Decomposition (EMD) is frequent appearances of mode mixing. Mode mixing means that an IMF consists of signals of widely disparate scales or signals of a similar scales residing in different IMF components. Ensemble Empirical Mode Decomposition (EEMD) provide improvement for mode mixing when the analysed signal contains high-frequency intermittent oscillations. Meanwhile, EMD experiences end effects problems and redundant IMFs that in some cases might affect the final results. In order to reduce this effect, in SEMD the wavelet transform is applied on IMFs during the sifting process by the following equation:

$W_{j,k} = \int_{-\infty}^{+\infty} IMF_i(t) \psi_{j,k}(t) dt$  \hspace{1cm} (9)

where $W_{j,k}$ is the $k^{th}$ wavelet coefficient at the $j^{th}$ level, $j, k \in Z$. And $\psi_{j,k}(t)$ is the mother wavelet. Threshold denoising is then utilized to eliminate unwanted components in every IMF. After de-noising, new wavelet coefficients are estimated and subsequently, a new IMF is reconstructed. After, that, unlike conventional EMD, this time, the new purified IMF’s is subtracted from the original signal:

$r_i(t) = x(t) - IMF_i(t)$  \hspace{1cm} (10)

The aforementioned process is repeated in every sifting stage so that a new set of IMF’s are extracted from the signal. As it was previously mentioned, for guided wave signals, incident waves are well known and consequently, it can be inferred that the signals consists of a combination of the incident waves plus unwanted reverberations. The same assumptions can be made for IMF’s that consequently shape the original signal. Therefore, for guided wave signal in which the tone-burst signal is selected for the
excitation. This assumption can be made when the dispersion characteristics of guided waves is neglected. As a result, instead of using standard well-known mother wavelets, in SEMD tailored tone-burst function was used as a mother wavelet which best matches the ultrasonic guided wave signal. The steps for implementing SEMD and finding $IMF_i$ are as follows:

1) Compute $IMF_i$ of the recorded responses.
2) Calculate the wavelet coefficients according to the following equation,

$$W_{j,k} = \frac{1}{\sqrt{s}} \int_{-\infty}^{+\infty} IMF(t) \psi\left(\frac{t-l}{s}\right) dt.$$  \hspace{1cm} (10)

3) Estimate de-noised new wavelet coefficients by the predefined positive value of thresholds $T$,

$$d(W_{j,k}) = sgn(W_{j,k})(|W_{j,k}| - T)_+$$ \hspace{1cm} (11)

4) Reconstruct $IMF_i$ from the de-noised coefficients through the inverse wavelet transform

5) Subtract $IMF_i$ from $x(t)$ and obtain the residue $r_i(t)$

6) Replace $x(t)$ with the residue and return to step 1; repeat the iteration process and continue until the residue $r_n(t)$ becomes too small or a monotonic function from which no more $IMF$ can be extracted.

Two main points are focussed here. First of all, the location of concrete on both signals must be identified. In another word, the signals reflecting the existence of concrete and its position in the signals must be determined. The second point which is the most important is whether there is corrosion in the pipe and at what location. The prerequisite for such goals is to identify the group velocity value by which time of flights for relevant wave packages are calculated. The group velocity ($v_g$) can be pinpointed on the dispersion curves. As an alternative, group velocity can be calculated by measuring the time of flights on a signal that belongs to a normal pipe:

$$v_g = \frac{L}{A}$$ \hspace{1cm} (12)

In which $L$ is the twice length of the normal pipe prior covering it with concrete in pulse echo-mode and $A$ is the time shift between the near and far end signals. The reason for selecting a normal pipe without concrete cover for the calculation is the simplicity of guided wave signals without any overlapping modes. Parameter $A$ can be manually measured but in order to accurately determine $A$, the cross correlation function (CCF) of the two signals of pipe ends is computed. The time shift between the two signals corresponds to the maximum value of their CCF as shown below,

$$A = \max \left( \frac{1}{T} \int_0^T x(t)y(t + \tau) \, dt \right)$$ \hspace{1cm} (13)

where $T$ is observation time, and $x$ and $y$ are near and far end signals, respectively.

### 4 Experimental Results using Matching Pursuit algorithm

The experiment was conducted on an 80 cm long steel pipe. It was a standard pipe that is commonly used to deliver natural gas to each household unit of any residential building. The pipe has a diameter of 33 mm and 4 mm wall thickness. To protect the pipes from corrosion, such standard pipes have thin and multilayer coatings which include zinc, epoxy and acrylic. A crack representing a defect was artificially made on the pipe. In the experiment, a magnetostrictive sensor (MsS) was used to excite $L(0,2)$ GW mode and then receive the reflected GW in a pulse-echo mode. The MsS sensor consists of a flexible printed coil \cite{6} and a smart material which is made from highly ferromagnetic patch \cite{7}. The $L(0,2)$ mode was excited at a particular frequency with five cycles and acted as a tone-burst signal modulated by Hamming window. The excited tone-burst signal was also simulated according to Equation (14).

$$X(t)_{\text{excitation}} = \sin(\omega t + \theta) \left( 0.08 + 0.46 \left( 1 - \cos \left( \frac{\omega t}{5} \right) \right) \right)$$ \hspace{1cm} (14)

When conducting the experiments, the tone-burst signal was excited through an arbitrary signal generator and amplified by RITEC 4000 pulser and receiver. Fig. 1 shows the schematic diagram of the experimental setup.
In Figure 2a the measured signal from the abovementioned experimental setup is illustrated. The signal is contaminated with some unwanted components. Despite having a contaminated signal, matching pursuit had recovered the signals in their true identify. The first wave packet to be approximated as a first atom is the incident signal as shown in Fig. 2b. The second and third atoms are representing the reflections from the end and the crack as shown in Fig. 2c and Fig. 2d respectively.

In the second experiment, capability of MP with dispersive dictionary in separating overlapped modes is verified. We conducted an experiment on the same pipe with some alteration. We added another crack on the same pipe that had a 22 mm distance in the axial direction from the initial crack. The two cracks together with MsS sensor on the pipe are shown in Fig 3.
Figure 3. The real gas pipe with two closely located cracks.

Since the distance between the two cracks is close, the two wave packets reflecting from them are overlapped as shown in Fig. 4a. The algorithm of MP was applied to analyze this signal and expecting the reflections generated by the two cracks could be separated. Similar to the case with one crack, the first approximated atom refers to the incident signal as it has the highest energy at the location of the sensor (Figure 4b). The second atom indicates the reflection from the pipe end (Fig. 4c). The third and the forth atoms represent the reflections generated by the first crack and the second crack as shown in Fig. 4d and Fig. 4e respectively. Hence, the algorithm of MP proved to have the ability to separate two closely located cracks that have their reflected signals overlapped to each other as shown in the original raw signal of Fig. 4a.
Figure 4. The experimentally measured signal in a pipe with two cracks and its approximation by MP: (a) the originally measured signal; (b) atom 1—the incident signal; (c) atom 2—the reflection from the pipe end; (d) atom 3—the reflection from the first crack; and (e) atom 4—the reflection from the second crack.

4 Experimental Results using Smooth Empirical Mode Decomposition

In order to verify the applicability of the proposed method experiments were carried out. In stage 1, the experiment was conducted on two 80 cm long steel pipes. They were standard pipes delivering natural gas to residential buildings with the diameter of 33 mm and 4 mm wall thickness. One of them was pristine while the other had a corrosion extended over 17 cm along the pipe as shown in Fig. 5. The corrosions were naturally formed and the pipes were provided by the sole gas supplier in Hong Kong. Both pipes were partially covered by the concrete to simulate real concrete walls at residential buildings.

Figure 5. Steel pipe with natural corrosion

For the corroded pipe, the defective part was placed inside the 20 cm long concrete wall (Fig. 6). Figure 7 illustrates a schematic diagram of the experimental setup. For the corroded pipe the concrete wall is located 48 cm away from one end which is 8 cm different from the normal pipe. An array of PZT strips was bonded at one end of the pipes to transmit and receive guided waves in pulse echo mode. The strips are axisymmetrically distributed, so that longitudinal modes excitation is guaranteed and flexural modes are suppressed. L(0,2) mode in 160 KHz was preferred over the guided wave modes because of its straightforward excitation and its less attenuation in comparison with the torsional mode T(0,1). In this frequency, it is nondispersive with the highest group velocity as depicted in the dispersion curve in Fig 8.

Figure 6. (a) The concrete-covered pipe and (b) the locations of the concrete covered section.

Figure 7. Schematic diagram of experimental setup of concrete covered pipes.
For the excitation $L(0,2)$ mode, it was selected at 160 kHz (Fig. 8) with 5-cycle tone burst signal modulated by hamming window. Fig. 9a shows the raw signal measured from a normal pipe that was partially covered by a concrete wall and its frequency spectrum in Fig. 9b. After applying the Tone-burst wavelet, then the reconstructed signals are shown in Fig. 9c. Note that the reflections caused by the concrete wall and the end of the pipe have been separated and easily to be identified. Fig. 9d shows its FFT spectrum with a shaper frequency bandwidth. The highlighted first and second wave packets in Fig.9c are the guided waves reflected when entering and leaving the concrete covered section. By comparing this temporal waveform with that of Fig.9a, one can see that it is impossible to detect the concrete section only by raw signal.

Figure 9. (a) Raw signal measured from a normal pipe that was partially covered by a concrete wall with (b) its spectrum (c) the reconstructed signals by the Tone-burst wavelet and (d) its FFT.

In stage 2, the experiment on a real pipe that was used to carry gas to a residential building was repeated. Similar to the experiment conducted in stage 1, a MsS was mounted on a pipe that was passing through a concrete wall. For the pipe with corrosion, the rusty portion was started at the entry of the concrete wall.
and extended all the way to the portion of the pipe that was covered by the concrete wall. However, there were two areas in which the corrosion was severe: the entry of the concrete wall and an area right before the end of the concrete wall. Table 1 lists the different time of flights that indicate critical positions in the concrete covered pipes. In other word, it is expected to see those positions at the calculated time of flights according to Table 1. The time of flights are calculated with a group velocity of 5100 m/sec. With the help of Tone-burst wavelet, the TOF of the start and the end of the concrete covered section can be identified.

Table 1. Calculated time of flights for critical positions in the concrete covered pipes

<table>
<thead>
<tr>
<th></th>
<th>Time of flight (ms)</th>
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<tbody>
<tr>
<td></td>
<td>$t_1$ (start of concrete wall)</td>
</tr>
<tr>
<td>Group velocity 5100 m/sec</td>
<td>0.15</td>
</tr>
<tr>
<td>Normal pipe</td>
<td>0.18</td>
</tr>
<tr>
<td>Pipe with corrosion</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Figs. 10a and 10c depicts the measured signals acquired from a similar type of pipe with a real corrosion located inside the concrete covered section. As can be seen in Fig. 10a, the temporal raw signals have multiple overlapped wave packets. They were generated by numerous reflections from the concrete, the corroded area, the end of the pipe. The overlapped wave packet were further contaminated by the noise and other undesired modes. After applying the tone burst wavelet to filter the raw signals, the reflected signals generated by the start and the end of the concrete covered section, the corroded area and the end of the pipe can be identified in Fig. 10c. Fig. 10d is the corresponding frequency spectrum of the filtered temporal signal. The centre frequency of the excited tone-burst signal can be identified at around 160 KHz.

Figure 10. (a) Raw signals measured from a corroded pipe that was partially covered by a concrete wall (b) with its spectrum (c) the reconstructed signals by the Tone-burst wavelet (d) its FFT

Furthermore, in order to overcome the shortcomings of conventional EMD, the SEMD was utilized. SEMD used the excited tone burst wavelet as the mother wavelet. The main point is that not only GW signals may contain a lot of contaminations; each IMF may include some unwanted components. Thus, with the aid of
wavelet transform on IMFs in sifting process, unwanted reverberations can be discarded from their wavelet coefficients. Fig. 11 demonstrates the signals obtained from the normal pipe and the corroded pipe with their IMFs. SEMD only used the first four IMFs to reconstruct the reflected GW signals. The rest of the IMFs have very low energy in comparison with the raw signal.

![Figure 11. Decomposition of signals into their IMFs by SEMD for (a) the normal pipe and (b) the pipe with a natural corrosion](image)

The locations of concrete wall plus the pipe end in time axis can be easily verified according to Table. 1. Since the reflection of the guided wave from the end has much higher energy, it can observed in IMF2 as well. In IMF1 between the start and end of the concrete wall, the signal is very clear and there is no implication of any defect. It should be noted that the first wave packet in IMF1 which can also be seen in the original signal, is the reflection of the position of MsS that had initially been installed there to measure the group velocity in pitch catch mode. In addition, the first wave packet in IMF2 is the reflection of the guided wave from the near end (close to the MsS in Fig. 11). Moreover, Fig. 11 demonstrates the signal for the corroded pipe in conjunction with its IMF. Similar to the first IMF for pristine pipe, the location of the concrete wall and pipe end are evident in the IMF1 and can be verified again according to Table. 1. As
aforementioned, the corrosion was placed inside the concrete wall. Therefore, seeing such wave packets inside the wall is not unexpected. In addition, unlike the IMF2 for the normal pipe, the reflection from the pipe end does not appear in the second IMF. This because much of the signal energy was already reflected back towards the MsS as a result of the GW hitting the corrosion. The higher order IMFs for both the normal pipe and the corroded pipe do not have meaningful information as the signal energy becomes very low and their absolute cross correlation is close to zero as shown in Fig 12.

5 Conclusion

This paper presents a new approach of GW inspection for identifying defects occurred in concrete covered pipes that commonly used to deliver gas and water to each household unit of modern buildings. The reflected GW signals are very difficult to interpret due to mode conversion, overlapped modes and dispersion effect. In order to extract meaningful information of GW signals, the signal processing methods, MP and SEMD, were designed and used. The problem of dispersion effect was taking care by MP. The separation of overlapped modes was solved by SEMD. The signal processing methods, MP and SEMD, were used for exposing critical information from signals from the concrete covered pipes. With the help of FEM, many atoms were formed as a MP’s dictionary. Those atoms with frequency inconsistency with the excitation signal were discarded, whilst, those atoms have the maximum resemblance with real GW signals were retained. Experimental results prove that even the GW reflected signals were distorted by dispersion effect, the source of each GW reflection had been identified. SEMD method was developed by EMD and tone-burst wavelet transform. The tone-burst wavelet was used to purify the IMFs in the sifting process. With the aid from SEMD, the overlapped signals had been separated. By applying both MP and SEMD on real gas pipes that were partially covered by concrete wall, the undesired dispersion effect and overlapped wave modes have been minimized. Hence, the positions of the concrete wall, the pipe end and the location of defect occurred in the covered section of pipe can be clearly identified.

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