THE EXTRACTION METHOD FOR DISPERSION CURVES FROM SPECTROGRAMS USING HOUGH TRANSFORM

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Abstract

A Hough transform-based method is developed for the extraction of dispersion curves from spectrograms. This method has been successfully tested using experimental data from both an acoustic emission (AE) signal simulator, and actual AE sources. The method determines the distance to the signal source with an accuracy from 1 to 10% even when the signal arrives only to one sensor.

Keywords: Dispersion curves, spectrogram, extraction, Lamb waves, source location

Introduction

The main purpose of new research in the field of acoustic emission (AE) is development of techniques based on intelligent processing of waveforms, rather than on analysis of a limited set of AE parameters. Typically AE testing is performed on thin-walled metal structures with the wall thickness of 3 to 50 mm, AE signals are emitted by cracks as wideband impulses with the length of order of 1 µs, working frequencies of AE sensors are within the range of 20-1000 kHz, and the distances between AE sources and sensors are much larger than the wall thickness. In this situation the signals arrive to sensors in the form of Lamb waves [1]; in most cases, in the form of combination of fundamental modes, namely, S₀ and A₀. The main feature of this type of waves is dispersion, the frequency dependence of the propagation velocity, resulting in arrival of the different frequency components of the impulse to an AE sensor with a spread of tens and hundreds µs (Fig. 1). This substantially impairs an accuracy of conventional AE source location, based on the calculation of arrival time differences and affected by the level of threshold and the average value of velocity measured in several times at the tested structures with the use of AE signal simulators.

The promising method for analyzing AE signals propagating as Lamb waves is application of spectrograms, which give a signal energy distribution in the time-frequency plane \( \{t, f\} \) [2-5]. Hence, on the spectrogram \( W(t,f) \) of the AE signal emitted by the source as a wideband impulse at the time point \( t₀ \), which propagates along the infinite plate of \( h \) thickness in the form of combination of S₀ and A₀ Lamb waves, and received by the AE sensor being at \( L \) distance from the source, there are distinctive portions of two curves, which are specified by equations,

\[
t(f) = \begin{cases} 
  t₀ + L/V_{S₀}(f, h, V_L, V_T) \\
  t₀ + L/V_{A₀}(f, h, V_L, V_T)
\end{cases}
\]  

(1)

Here, \( V_{S₀} \) and \( V_{A₀} \) are group velocities of S₀ and A₀ waves, \( V_L \) and \( V_T \) are velocities of bulk longitudinal and transverse waves in the material. The intensity of dispersion curves portions pertaining to different frequencies varies due to signal attenuation in the structure and non-uniformity of the sensor frequency characteristics.
As a rule, during the AE testing, the values of $V_L$, $V_T$ and $h$ are known. Thus, knowing the distance to source $L$ and the source operation time $t_0$, it is possible to characterize the AE signal spectrogram; alternatively, the signal spectrogram contains information about $L$ and $t_0$. Use of such information substantially increases the reliability and the accuracy of AE source location in comparison with the traditional threshold crossing method. Thus, the problem of developing an algorithm of dispersion curves extraction from the AE signal spectrogram is urgent.

Fig. 1. The relationship between the group velocities and arrival times of different components of the AE signal.

**Extraction Method**

In addition to the parameters specified above, the AE waveform and signal spectrogram are influenced by crack type, radiation direction, signal attenuation, frequency characteristic of AE sensor, noise, and edge reflections. These significantly complicate the AE signal spectrogram with the result that the extraction of dispersion curves is more complex and not always resolvable problem [6].

We selected to use the generalized Hough transform method of extraction [7], offered in paper [8] for the case of arbitrary curves. As is evident from equation (1), any pair of plots of the dispersion curves of fundamental Lamb modes on the spectrogram is specified by two parameters previously unknown, namely, source operation time and distance of propagation. Thus, a number of the dispersion curves constitute a two-parameter family. Let us associate the two-dimensional parameter space $\{L, t_0\}$ with this family. Each point in the parameter space corre-
Corresponds to a pair of dispersion curves of S<sub>0</sub> and A<sub>0</sub> modes in the time-frequency plane \{t, f\} (Fig. 2).

The problem of extraction reduces to search a set of parameters \{L_{Hough}, t_{Hough}\}, such that the dispersion curve plots (1) superimposed on the AE signal spectrogram in the widest frequency range falls on regions, where absolute values of the spectrogram coefficients exceed some threshold. As a threshold we have used the maximum absolute value of the spectrogram coefficients, which is multiplied by some factor \(\varepsilon\) to be selected as required by the noise level.

![Diagram](image_url)

Fig. 2. An example of three points in parameter space \{L, t_0\} and three corresponding pairs of dispersion curves in the time-frequency plane \{t, f\}.
Because a waveform recorded by a digital AE system is a one-dimensional array, whose elements are signal values at the sensor input at the discrete set of time points, the spectrogram calculated on its basis is a two-dimensional array, whose elements correspond to combinations of time and frequency values, pertaining to some discrete sets. To search parameters \( L_{Hough} \) and \( t_{Hough} \), it was decided to organize two discrete sets of \( L \) and \( t_0 \) values. The values \( L \) were searched within the range from 0 to the value \( L_{max} \). \( L_{max} \) is equal to the distance between the neighboring sensors or to the size of the tested structure. The values \( t_0 \) were searched within the range from the \( t_{min} \) \( < t_{min} = 0, t_{max} = t_{pretrig} \) to the pre-triggering value \( t_{max} = t_{pretrig} \). Here, \( t_{min} \) is the lowest operating frequency of sensor rounded to the nearest frequency on the spectrogram, and \( t = 0 \) corresponds to the beginning of the waveform. The quantity of elements in the array of distance values \( L \) was based on the required accuracy of distance measurement, the time values \( t_0 \), as a rule, were searched with a step equal to the reciprocal of the sampling frequency.

The so-called accumulator two-dimensional array was organized so that each element should correspond to the quantity of spectrogram elements being on the \( S_0 \) and \( A_0 \) dispersion curves at corresponding combination of \( L \) and \( t_0 \) values from the discrete arrays described above and having values, exceeding the threshold in absolute value. To calculate values of the accumulator array elements, all combinations of variables \( L \), \( t_0 \) and \( f \) from three appropriate arrays were searched. For each combination of the variables the value \( t(f) \) was calculated by equation (1), and this value was rounded to a multiple to the reciprocal sampling frequency. The absolute value of spectrogram element corresponding to \( f \) and \( t(f) \) was compared with the threshold, and in case of threshold-crossing a unity was added to the corresponding element of the accumulator array. Comparison of the accumulator array elements values permits to find the desired pair of \( S_0 \) and \( A_0 \) dispersion curves containing the greatest quantity of spectrogram points with absolute values above the threshold.

In a shorter form the algorithm used may be described as follows: parameters \( \{L_{Hough}, t_{Hough}\} \) are searched such that

\[
H\left(L_{Hough}, t_{Hough}\right) = \max_{i=I_{1}, j=J_{1}, J_{2}} H\left(L_{i}, t_{j}\right),
\]

where

\[
H\left(L_{i}, t_{j}\right) = \sum_{k=K}^{L_{max}} \left\{ \theta \left( W\left(t_{j} + \frac{L_{i}}{V_{A_{k}}(f_{k}, h, V_{L}, V_{T})}, f_{k}\right) - \varepsilon \max \left| W \right| \right) + \theta \left( W\left(t_{j} + \frac{L_{i}}{V_{S_{k}}(f_{k}, h, V_{L}, V_{T})}, f_{k}\right) - \varepsilon \max \left| W \right| \right) \right\}.
\]

\( \theta(x) = \begin{cases} 
1, & x \geq 0 \\
0, & x < 0 
\end{cases} \) — Heaviside step function, \( \max \left| W \right| = \max_{n=I_{1}, m=J_{1}, J_{2}} \left(W(t_{n}, f_{m})\right) \),

\( L_{i} = L_{max} \), \( I \) is user-defined quantity of elements in the array of distance values \( L \),

\( J_{1} = \left[t_{min}, f_{s} \right], J_{2} = \left[t_{max}, f_{s} \right], f_{s} = \) sampling frequency, \( \lfloor x \rfloor \) is integer part of \( x \),

\( |x| \) is absolute value of \( x \), \( f_{k} = \frac{k}{K} F \), \( K_{1} = \left[\frac{f_{min}}{F} K\right], K_{2} = \left[\frac{f_{max}}{F} K\right] \),

\( K \) is number of indexes on the frequency axis in the treated spectrogram,
\( F \) is the highest frequency on the treated spectrogram, \( f_{\text{max}} \) is the highest operating frequency of sensor,
\[
t_j = j / f_c, \quad J = \lceil T \cdot f_c \rceil, \quad T \text{ is duration of the waveform.}
\]

The following major disadvantages of Hough transform-based method should be mentioned. First, the result depends on the threshold that should frequently be corrected manually on the basis of the noise level. Second, for any input signal, including a purely noise signal, this method gives some result, and no criteria for eliminating such results, frequently senseless, are involved in the Hough transform-based method.

**Experimental Verification of the Present Technique**

To evaluate the validity of the present technique, a series of experiments using a Hsu-Nielsen pencil-lead break and an electronic simulators of AE signals were applied on pipelines and cut portions of pipes having a wall of 8–17 mm thickness and 530–1220 mm diameter with and without insulation, liquid-filled and empty (Fig. 3). The distances between the signal source and the sensor were up to 56 m. Three types of AE sensors with the operating frequency ranges equal to 3-60, 40-100 and 130-200 kHz were used. Sampling frequency varied from 1 to 2 MHz.

![Fig. 3. An experiment using an electronic simulator of AE signals.](image)

It has been found that the spectrograms based on Wigner-Ville [9] and Choi-Williams [4] transforms are the most suitable for the experimental data analysis. The spectrograms on the basis of continuous wavelet-transform allowed for revealing dispersive curves of Lamb waves with worse resolution [4] that had an adverse effect on the accuracy of measurement of the distance to the signal source.

The accuracy of distance measurement was typically within the range from 1 to 10% (Table 1) depending on what frequency portions and what Lamb modes were observed on the spectrogram (Fig. 4). The best results in steel structures were obtained when the spectrogram exhibited the \( S_0 \) dispersion curve portions corresponding to the range of frequency from 1.5 to 4 MHz-mm/h. In this range, derivative of \( S_0 \) group velocity with respect to frequency is large.
Fig. 4. An experiment on a pipeline without insulation. Hsu-Nielsen source is located at different distances from the AE sensor. Spectrograms based on Wigner-Ville transform, the results of dispersion curves extraction ($\epsilon = 0.05, f_{\text{min}} = 30 \text{ kHz}, f_{\text{max}} = 200 \text{ kHz}$) and corresponding dispersion curves.
enough in absolute value. The portions of the dispersion curve of the \( A_0 \) mode corresponding to 0 to 1 MHz-mm/h range possess the similar property, but did not yield high accuracy of distance measurement, since the ratio of the width of the dispersion curve observed on the spectrogram to the corresponding frequency was substantially higher than in case of the \( S_0 \) mode.

Table 1. An experiment on pipeline without insulation. The actual values of the distance between the Hsu-Nielsen source and the AE sensor vs. the results of dispersion curves extraction at different values of the threshold. \( f_{\text{min}} = 30 \text{ kHz}, f_{\text{max}} = 200 \text{ kHz} \).

<table>
<thead>
<tr>
<th>Actual values of the distance, m</th>
<th>Results of extraction at ( \varepsilon =0.01, \text{ m} )</th>
<th>Results of extraction at ( \varepsilon =0.02, \text{ m} )</th>
<th>Results of extraction at ( \varepsilon =0.05, \text{ m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.52</td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td>1.0</td>
<td>0.94</td>
<td>0.92</td>
<td>0.97</td>
</tr>
<tr>
<td>1.5</td>
<td>1.44</td>
<td>1.41</td>
<td>1.45</td>
</tr>
<tr>
<td>2.0</td>
<td>1.99</td>
<td>2.10</td>
<td>2.01</td>
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<tr>
<td>2.5</td>
<td>2.32</td>
<td>2.51</td>
<td>2.51</td>
</tr>
<tr>
<td>3.0</td>
<td>2.72</td>
<td>2.97</td>
<td>2.97</td>
</tr>
<tr>
<td>4.0</td>
<td>3.55</td>
<td>3.52</td>
<td>3.96</td>
</tr>
<tr>
<td>5.0</td>
<td>4.74</td>
<td>4.74</td>
<td>4.89</td>
</tr>
<tr>
<td>8.0</td>
<td>0.98</td>
<td>9.51</td>
<td>6.52</td>
</tr>
<tr>
<td>10.0</td>
<td>0.95</td>
<td>0.92</td>
<td>10.10</td>
</tr>
</tbody>
</table>

It has been revealed, that the present method is inoperative when the distances between AE sources and sensors are less than 0.5–1 m, because in this case the different portions of dispersing curves are insufficiently separated from each other along the time axis (Fig. 5). At the same time, this method has appeared to be efficient at the distances at least up to 56 m.

Fig. 5. A spectrogram of a signal from AE simulator, located at 0.15 m from AE sensor.
The coefficient \( \varepsilon \) specifying the threshold level, as a rule, was selected within the range from 0.001 to 0.05, depending on the noise level. No universal threshold level suitable for analyzing any AE signals was found. Therefore, as a rule, when going from one test piece to another, the threshold should be selected anew, since at the arbitrarily selected threshold level the method frequently produced evidently incorrect results (Fig. 6).

Fig. 6. The influence of the threshold level factor \( \varepsilon \) on the results of the dispersion curves extraction. Spectrogram of AE signal, incorrect results of dispersion curves extraction at \( \varepsilon = 0.02 \), correct results of dispersion curves extraction at \( \varepsilon = 0.05 \) and corresponding dispersion curves.

It was found, that the pipe curvature had no significant effect on the values of group velocity and this made it possible to use the Lamb wave model instead of the more complicated Pochhammer-Chree model [10, 11]. However, when analyzing the spectrograms, the substantial problem was in signals arriving not by the shortest routes, but by helixes, once or several times rounding the pipe. Existence of such signals resulted in occurrence of one or several additional curves on the spectrogram, which in contrast to electromagnetic interferences or other noises, are indistinguishable in their shape from the true dispersion curves. As a result, there could be a situation when at the threshold level selected incorrectly, the Hough transform method of extraction produces the value of distance between the AE signal source and the sensor, measured not along the shortest route, but along one of the helixes (Fig. 7).
Next, this technique was used during testing of a buried gas pipeline with the distance between pits of about 40 m. In inspecting the pipeline, a number of AE signals arrived only to one of the mounted AE sensors. The lack of data for the time of arrival to the second AE sensor gave no way of measuring the source coordinates, which in turn did not allow for classifying AE sources. The location executed by the present method showed that the sources were separated from the AE sensor by 1.0 to 3.5 m (Fig. 8), and it was possible to classify the AE sources as the “noncritical active sources”.

Fig. 7. A spectrogram of AE signal propagating by the helixes, incorrect results of dispersion curves extraction and corresponding incorrect dispersion curves.

Fig. 8. A spectrogram of AE signal from a buried gas pipeline with the large distance between pits, results of dispersion curves extraction and corresponding dispersion curves.
With the successful results of the experimental check, the Hough transform method of extraction was added (Fig. 9) to the software complex of AE systems "A-Line" [5, 12].

![Fig. 9. “A-Line OSC Processing” software.](image-url)

**Conclusions**

1. The Hough transform-based method is developed for automatic dispersion curve extraction from spectrogram with evaluation of their parameters, namely, the distance to the AE source and the source operation time.
2. The technique has been successfully tested using experimental data from both the AE signal simulator, and the actual AE sources.

3. The developed technique allows for calculating the distance to the signal source with an accuracy from 1 to 10% even when the signal arrives only to one sensor, giving the chance to perform the AE testing both in case of buried pipelines with the large distance between pits, and in case of one-sided access to a particular extended test piece.

References