Cost effective structural monitoring -

An acoustic method, phase II

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RESEARCH REPORT 325
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This report looks at the active acoustic monitoring of offshore jacket structures. The principle behind the method is that changes in a structure can be detected via changes in acoustic transfer functions measured between appropriate points on the structure.

In this report we describe the results of numerical simulations and of physical experiments on a scale model. The construction of the scale model (a 1/100 scale plastic model of the Claymore jacket) was described in an earlier report. Numerical simulations indicate that the method is sound in principle. Experimental results show that it is also effective in practice, with damage location being accurate to within the length of a structural member.

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1 SUMMARY

This report is a deliverable on contract no. 3935, a project to look at the active acoustic monitoring of offshore jacket structures. The principle behind the method is that changes in a structure can be detected via changes in acoustic transfer functions measured between appropriate points on the structure.

In this report we describe the results of numerical simulations and of physical experiments on a scale model. The construction of the scale model (a 1/100 scale plastic model of the Claymore jacket) was described in an earlier report. Numerical simulations indicate that the method is sound in principle. Experimental results show that it is also effective in practice, with damage location being accurate to within the length of a structural member.

In the experiments carried out to date we have used a set of acoustic sources at the top of the structure to transmit signals to a set of receivers at the bottom. This is analogous to medical tomography, in which a cross-sectional image of the body is obtained by sending and receiving signals (x-rays in the medical case) through the body. However, feedback from the industry indicates that it would be better to have both transmitters and receivers at the top of the structure for practical reasons. We have carried out numerical simulations of this arrangement and it leads to results that are better than the “tomographic” method. As part of an extension to work on this project we plan to verify this by experiments on the scale model rig.

2 NUMERICAL MODELLING

We needed to be able to model the received waveforms for two reasons. Firstly, if we are to be able to deduce from the recorded signals where the damage is, we need to understand the process of transfer of acoustic energy through the structure: the paths it takes and the minimum travel times between any two points. Secondly, in order to develop our damage location algorithms we needed noise-free data on which to test them.

Our numerical model is based on the same structure used for the physical scale model: the Claymore jacket (see Plate 1). It assumes that the jacket consists essentially of beam-like members joined at nodes. It models waves travelling along members with one velocity only, and models the division of energy at a node as a simple equipartition among the joined members.

Thus our model ignores wave types other than longitudinal waves. There are several reasons for this simplified approach. Our damage location algorithms use only the earliest arrival of energy at a sensor from a point of damage, and this will almost always have travelled through the structure at the longitudinal-wave velocity. Other wave types (torsion waves, bending waves, Lamb waves) will travel at lower velocities and can be left out of the modelling.

To some extent we are making a virtue of a necessity, since the resources of the project would not be sufficient to allow the creation of a more detailed numerical model of the acoustics of the structure. Nor would it be possible to run such a model in a reasonable time on a desktop PC running MS Windows. However it is also true to say that a more detailed model would be of questionable value: it would be unlikely to represent the properties of the physical structure sufficiently accurately, and adjusting it to fit observations on the structure would be a complex and difficult task. The virtue of a single-wave-type model is that it is relatively easy to bring it into agreement with the physical model, as we shall see.
The modelling algorithm uses a modified time-stepping approach that propagates an acoustic impulse arriving at any node to its immediate neighbours (i.e. to nodes directly connected to it by members). An acoustic impulse is introduced at the transmitter location on the structure, at time step zero. Its energy is divided equally between the members connected to the transmitter location. The precise arrival time of the impulse at the node at the far end of each member is then calculated, and the amplitude of the impulse is entered into the time-record for that node at the time step nearest to the precise arrival time. The event is “tagged” with the difference between the time of the step and the precise arrival time. The size of the time step is kept smaller than the travel time along the shortest structural member.

The algorithm then proceeds to the next time step for which (given the known transit times along the various members) it is possible that an event may have arrived. If there are any events associated with any node of the structure, these are first examined to see if any of the events at any one node coincide precisely in time (i.e. if their time-difference tags are equal). If so, the events are amalgamated in such a way as to conserve acoustic energy. All events at each node are then propagated forward in time to its immediate neighbours, taking their time-difference tags into account. Again, they are propagated to the nearest time step, and tagged with the difference between the time of the step and the precise arrival time. This process is then repeated until the required number of time steps has been covered. This is set to be at least equal to the maximum acoustic transit time across the structure, and usually longer.

This approach is better than simple time stepping because it enables transit times to be modelled accurately without having to use a very short time step, while still ensuring that all possible acoustic propagation paths are included in the model. This results in a computationally efficient algorithm that can model propagation between many transmitters and receivers through a highly complex structure in a few tens of minutes on a PC.

Note that in our current implementation of this model we have chosen to identify model “nodes” with physical nodes of the structure. We are free to include more nodes in the model if we wish: for example we could place several “nodes” along each member. This would increase the resolution with which the damage location algorithms (which derive their knowledge of the structure from the forward-modelling algorithms) could locate damage when the damage does not occur at a structural node.

The numerical model leads to predicted transfer functions between each transmitter-receiver pair. The propagation algorithm yields a list of events with their times and amplitudes at each receiver, for each transmitter. These are converted to sampled time series data by using standard sinc-interpolation to add each event to the time series. An example appears in Figure 1 below. In this figure, the transfer function before damage is shown in red; that after damage is shown in green; and the difference between the two is shown in blue. It gives some indication of the complexity of the process of acoustic transmission: near the onset of the trace, individual events (representing reflections from nodes) can be distinguished. However these rapidly decline in amplitude while becoming more closely spaced in time, so that the difference trace soon becomes a seemingly random continuum.

Note that no bandwidth limitation has been applied to this trace, so that each event appears as a sinc-function, that is to say a positive-going pulse accompanied by low-level “ripples”. We have made no attempt to model absorption, which would cause the signal to decrease rapidly with time.
Figure 1: Example of a modelled transmitter/receiver transfer function

3 CALIBRATING THE NUMERICAL MODEL AGAINST THE PHYSICAL MODEL

As in any situation where one is trying to match the behaviour of a real structure with a numerical model, the agreement between the two can be improved by comparing predictions with measurement. Figure 2 below shows a scatter plot of predicted first arrival times versus measurements for a set of six transmitters at the top of the structure and eight at the bottom.

Figure 2. Predicted vs. observed travel times
Note that the numerical model times have been calculated using the measured longitudinal-wave velocity in the plastic. This plot suggests that there is an additional propagation delay that is larger, the further the transmitter is from the receiver. Furthermore this delay increases faster than linearly with traveltime.

This delay is probably mainly due to delays in propagation through nodes, which are likely to have quite complicated dynamics which it is beyond the scope of this project to model. To get around this problem we simply applied a correction to the model travel times based using a best-fit quadratic expression calculated from the transmitter/receiver offsets in x, y and z directions. The errors in predicted arrival times after applying this correction appear in figure 3 below. The errors are significantly reduced.

![Error in arrival time vs corrected modelled arrival time](image)

Figure 3: Errors after correcting model predictions

4 CASE STUDY 1: “TOMOGRAPHIC” GEOMETRY

Before moving on to describe our damage location algorithms, we shall give an example of the results from numerical and physical scale-model versions of an experiment in which one of the main legs of the structure was damaged. The layout of the transmitters and receivers was the “tomographic” arrangement: transmitters at top, receivers at bottom.

4.1 NUMERICAL MODEL RESULTS

The experiments used six transmitters at the top of the structure and eight receivers at the bottom. Their positions are indicated in the wire-frame diagram of the structure shown in Figure 4 below. One of the main vertical legs was severed. The small red sphere shows the
damage location. It is immediately below the node at the right-hand rear, one down from the top.

Figure 5 shows the modelled signal transmitted down the vertical leg on which the damage is located, from the transmitter at the top (shown by a red “1”) to the receiver at the bottom (red “A”). Note that the signal was only calculated up to 330 time steps. The difference (blue) signal shows the effect of the damage. It produces a large effect, which starts at the onset of the signal: because the damage lies on the direct transmission path from transmitter to receiver, the effect of the damage is evident in the first arrival. This is of great significance when inverting these data to locate the damage.

Figure 6 shows the signal that is obtained by transmitting from the node to the left (red “2” in Figure 1) to receiver “A”. The difference in signals still starts at the signal onset, because the damage lies on the shortest path from transmitter to receiver. However it is much smaller, because the shortest path is no longer unique. There are in fact five paths of equal length that are shorter than any others, and only one of these passes through the damage point. Hence most of the energy in the direct arrival is unaffected.

Figure 7 shows the signal that is obtained by transmitting from node “2” to receiver “B”. The damaged node no longer lies on the direct path, and consequently the difference caused by the damage occurs later than the first arrival. Whereas the first arrival is at time step 93, the difference first appears at step 144. The difference signal is small.

Figure 4. Wire frame diagram of scale model jacket. Transmitters are shown as stellated spheres, receivers as wire cage spheres
Figure 5. Numerically-modelled time signal of transmission down damaged leg, before (red) & after (green) damage and difference (blue) signal

Figure 6. Numerically-modelled time signal of transmission from transmitter “2” to receiver “A”, before (red) & after (green) damage and difference (blue) signal

Figure 7. Numerically-modelled time signal of transmission from transmitter “2” to receiver “B”, before (red) & after (green) damage and difference (blue) signal
4.2 SCALE MODEL RESULTS

We ran into significant difficulties with signal stability, for three reasons. Firstly, the adhesive used to join the polycarbonate members did not set solid but remained in a visco-elastic phase when set. It turned out to be highly temperature dependent in its properties, and we could only obtain consistent results by maintaining the rig at a constant temperature to within 0.1°C. We achieved this by wrapping individual members and nodes in insulating material, and containing the entire structure in an insulating “tent”. The room outside was then maintained at a constant 20°C using normal thermostatic heating controls, and this proved to be acceptable, although drift has always remained evident in the results.

The second difficulty was that the sampling frequency of the recording system turned out not to be stable enough. It was of order one part in five hundred or better; in practice we need a stability five times as good as this. It would not be difficult to achieve this level of stability now that its importance is evident. Again, however, results are degraded.

Lastly the sampling was not synchronised with the transmission, which caused timing “jitter”.

Figure 8 shows the measured signal transmitted down the vertical leg on which the damage is located, from the transmitter at the top (shown by a red “1”) to the receiver at the bottom (red “A”). The difference (blue) signal shows the effect of the damage. As in the numerical model results, the damage produces a large effect, starting at the onset of the signal.

Note that the visual appearance is very different from the modelled data: the data here are band limited and have as many negative-going as positive-going excursions. Absorption is also causing higher frequencies to be attenuated preferentially at later times.

![Figure 8. Scale model results: transmission from transmitter “1” to receiver “A”, before (red) & after (green) damage and difference (blue) signal](image)

Figure 9 shows the signal obtained by transmitting from transmitter “2” to receiver “A”. The difference in signals still starts at the signal onset, because the damage lies on the shortest path from transmitter to receiver. As in the numerically modelled results, it is smaller. It is interesting to note that it is not as small: evidently the route via the damage point is preferred to others (i.e. carries relatively more energy) in the scale model (not surprising since its cross section is larger).
Finally, figure 10 shows the signal from transmitter “2” to receiver “B”. The onset of the difference is later than the onset of the trace, and the difference signal is smaller in relation to the pre-damage signal.

Figure 9. Scale model results: transmission from transmitter “2” to receiver “A”, before (red) & after (green) damage and difference (blue) signal

Figure 10. Scale model results: transmission from transmitter “2” to receiver “B”, before (red) & after (green) damage and difference (blue) signal
5 DAMAGE LOCATION ALGORITHMS

We have developed two different algorithms. Both depend on the arrival times of “difference events” being identified on the recorded traces. This requires arrival times of major differences to be picked out of the recorded time signals. So far we have carried out this process manually. We have looked at automated means of picking, some of which appear promising, but further development will be required before they are sufficiently reliable.

The first of our two algorithms accepts not only the earliest-arriving difference events but also subsequent events as well. For each identified event on each trace, it calculates all possible paths by which the signal can have travelled from transmitter to receiver. All nodes that lie on each of these possible paths are possible damage sites, and the algorithm collects the possible sites associated with each event on each trace into a set. The algorithm calculates a similar set of such possible damage sites for each signal and each event; it then takes the intersection of these sets (i.e. chooses the node or nodes which belong to all of them) as its final indication of possible damage site(s).

We have tested this algorithm on model data and obtained good results. However its computation times can be extremely long (later events can be associated with millions of possible paths). The ability to handle multiple events on one signal has turned out not to be an advantage in practice, since on real data it becomes hard to distinguish genuine events from background noise after the arrival of the first event.

For these reasons we have concentrated our efforts on a simpler and more robust algorithm. This algorithm works only with the earliest-arriving damage event on each trace. This is in line with the philosophy underlying our approach to modelling, which is to calculate shortest-path travel times using longitudinal wave speeds (i.e. it is likely to get earliest arrival times right but likely to estimate later arrival times less accurately).

This algorithm works by considering each node of the model in turn to be a possible damage site. It works out the expected earliest damage event arrival time for each transmitter/receiver combination and compares this with the arrival time of the first difference event picked on the recorded data. The time difference is squared and taken as a measure of error in the assumption that the selected node is the site of the damage. The squared error is summed over all transmitter/receiver pairs and divided by the number of contributing pairs to produce a mean-squared timing error for that node.

The exercise is repeated for each node of the structure. The result is a “map” of mean-squared error over the structure. The node at which it is least is considered to be the damaged node. The confidence of identification can be measured by the relative size of the error at that node compared to others. We shall refer to this as the “least mean-square” (LMS) imaging method.
One elaboration of this method that occasionally improves the imaging of noisy data is to preferentially weight the results in favour of transmitter/receiver signals for which the difference event arrives soon after the first arrival. Thus later events, whose timing is usually more difficult to pick accurately, are given less weight in the imaging process. This is achieved by weighting the square error for a given signal by the factor

$$\frac{1}{1 + \left(\frac{\tau_d - \tau_1}{\tau_0}\right)^n}$$

in which:

- $\tau_1$ is the first arrival time;
- $\tau_d$ is the arrival time of the damage event;
- $\tau_0$ is a scale time such that damage events occurring later $\tau_0$ after $\tau_1$ are weighted less heavily;
- $n$ is the weighting exponent: later events are weighted less strongly if $n$ is higher.

Common values used for imaging our scale model data are $n=4$ and $\tau_0 = 1m\text{sec}$. 
6 RESULTS OF IMAGING

The results of applying the LMS imaging method to the numerically modelled data in section 3 are shown in Figure 9 below. Errors at each node are coded via both the colour and the size of a sphere centred at that node. The actual damage site was the first node below the top of the rightmost vertical. The error is indeed smallest at this node, where it is zero (since the numerically modelled data is error-free), but it is also very small on neighbouring nodes as the figure shows. The position discrimination is not very strong, and a small amount of error in the data could result in the wrong node being identified.

The error is largest on the far side of the rig from the damage site.

If we now apply the same imaging method to real data recorded in the same way, we obtain the error distribution shown in Figure 12.

![Figure 11. Numerically modelled data](image)

Map of LMS error over nodes of structure. Damage site was first node below the top of the rear rightmost vertical.
Figure 12. Scale model data

Map of LMS error over nodes of structure. Damage site was first node below the top of the rear rightmost vertical.

Figure 10 shows that the damage has in fact been located not at the actual damaged node, but at the one above it: the top, rear rightmost node. It is typical of the “tomographic” arrangement of transducers (transmitters at top, receivers at bottom) that results lack vertical resolution: the vertical position of the damage makes little difference to the time of arrival of the first damage event for transducers close to the vertical leg on which the damage lies, so the LMS algorithm cannot discriminate very well.

1 RESULTS OF A “REFLECTION” GEOMETRY NUMERICAL EXPERIMENT

We expect that if we use the “Reflection-mode” layout, with both transmitters and receivers at the top of the structure, the LMS algorithm should be able to locate the damage more definitely. To test this we carried out a numerical experiment, with the damage in the same place but with the receivers moved from bottom to top. The results of applying the LMS algorithm to the data are shown in Figure 13.
Figure 13. Numerically modelled data: “Reflection” mode experiment

Map of LMS error over nodes of structure. Damage site was first node below the top of the rear rightmost vertical.

The vertical discrimination of the damage position is clearly much better than it was in the model tomographic experiment. Lateral discrimination is just as good. This leads us to believe that reflection mode measurements are likely to lead to better results than the tomographic arrangement.
8 CASE STUDY 2: TOMOGRAPHIC AND REFLECTION RESULTS FROM CUTTING A DIAGONAL

A diagonal strut was cut through at the point indicated by the red marker in Figure 14 below.

Numerical and physical experiments were carried out. LMS imaging results for numerical-model data using the tomographic geometry are shown in Figure 15. Like the first case study, the results show a lack of discrimination of vertical position.

To confirm that this was not merely a result of noise on the data, figure 16 shows the LMS results obtained using numerically modelled data. Again, although the errors are (not surprisingly) larger, there is a vertical “smearing” which limits the confidence with which the damage can be located. Minimum LMS error occurs at the node at the bottom of the diagonal strut rather than the top.
Figure 17 shows the image obtained from reflection-mode numerically modelled data. The vertical location is much improved; lateral location is as good as the tomographic image. This supports our belief that reflection mode experiments produce clearer images that the tomographic geometry. We intend to carry out physical model experiments to confirm this.
Error spheres for each node position on structure

Transmitters at 8, 8, 1, 1, 1, 8, 1, 3, 1, 8, 1, 3, 5, 8, 1, 5, 1, 8, 1, 5, 5

Receivers at 8, 8, 4, 1, 1, 8, 4, 1, 5, 8, 4, 2, 1, 8, 4, 2, 5, 8, 4, 4, 1, 8, 4, 4, 5, 8, 4, 5, 1, 8, 4, 5, 5

Attenuation delay time = 1 ms
Attenuation power = 6
Minimum LMS error of 7.4277 occurs at node 8, 4, 5, 1
Maximum LMS error of 104.073 occurs at node 8, 1, 5, 5

Figure 16. Case study 2: Physical model data. LMS image of damage location: tomographic geometry
9 CONCLUSIONS

We have carried out experiments on the acoustic-transmission method for locating damage in a structure. These have been both numerical simulations and physical experiments on a plastic scale model in the laboratory.

We have used two different geometries for the numerical experiments: a “tomographic” geometry in which transmitters are at the top of the structure and receivers are at the bottom (so that signals pass through the damaged section), and a “reflection” geometry in which both transmitters and receivers are at the top (and signals are reflected from the damage).

Both numerical and scale model experiments show the damage being located to within one strut when the tomographic geometry is used – i.e. it may not be located to the right end of the strut. Simulation suggests that the reflection method does better, locating the damage at the correct node. We need to confirm this by physical experiment.
Plate 1 the 1/100 scale plastic model of the upper half of the Claymore jacket.