DETECTION AND DIAGNOSIS OF STRUCTURAL MODIFICATIONS—THEIR RELATED PROBLEM OF SENSOR POSITIONING

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ABSTRACT

The problems of structure monitoring become more and more important. Adapted techniques, based on modal analysis, are currently studied and developed. The building of a good monitoring passes through a lot of choices concerning the identification method, the diagnosis phase, the strategy of sensor positioning. These different problems are analysed and illustrated in this paper by the specific application of offshore structures monitoring.

1. INTRODUCTION

A mechanical structure monitoring project, based on the dynamic behaviour follow-up, has to face problems which are of several types. Some of them are very specific to the kind of structure, but, nevertheless, we can outline a general scheme.
We analyse, in this paper, the different possible choices of methods and interactions between them, which have been investigated in a specific case: the monitoring of offshore structures behaviour.

In this application, we shall see that, the structural model is a linear Finite Elements model with, as input forces, a natural excitation, the swell. (The case of natural excitation is often encountered in the monitoring problems). This model will guide us to adapted identification modal parameters technique, the efficiency of which has been compared to effects of simulated structural modifications through a sensitivity analysis.

Starting from these two choices, the model and the identification methods, the diagnosis, detection and sensor positioning techniques have been investigated. We describe this process in the following sections.

2. OFFSHORE STRUCTURE VIBRATION MONITORING

In the case of vibration monitoring applied to the offshore structures, we have to face some severe experimental requirements:

* **Ambiant excitation**: Second alternative to the modal analysis performed with controlled input, the measurement of structure behaviour generated by natural excitation gives some interesting advantages:
- The cost of a monitoring campaign is much lower.

- Since the only limitations come from mass memory manipulations, it allows for the possibility of a permanent monitoring.

- The energy, "free" supplied, has been shown to provide satisfactory excitation levels on one hand, and, on the other hand, it leads to monitor precisely the modes which are actually powerful all through the structure life, i.e. those which involve the structural strength actually needed by the structure to withstand the environmental forces.

The choice of this method, nevertheless, does not go without drawbacks:

- The unmeasured excitation (here mainly the swell), is nonstationary process, both in energy and in direction.

- Its spectral content is not as close to a white noise one as it should be for optimal detection capacity. However, it has been proven to be a flat spectrum in the relevant modal frequency band.

* Physical changes: The structural modifications, the detection of which is wished, can be of several types, mass or stiffness changes, local or global, and can be caused by environmental conditions (tide, swell direction, significative height) which lightly modify the modal parameters. Among them we can quote:

<table>
<thead>
<tr>
<th>Local modifications</th>
<th>Mass</th>
<th>Stiffness</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Member flooding, deck operation</td>
<td>Crack, soil modification</td>
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</table>

<table>
<thead>
<tr>
<th>Global modifications</th>
<th>Mass</th>
<th>Stiffness</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Fouling</td>
<td>General node crack</td>
</tr>
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</table>

* Sensor location: Up to now, the very high costs of installation and maintenance, due to the severe oceano-meteo conditions in North sea, have limited the number of observed degrees of freedom and prohibited the use of movable instrumentation. If this last point has been partially solved, thanks to novel measurement techniques[1], the three problems of modal identification under natural excitation, physical changes diagnosis and sensor location optimization have to find efficient solutions.

2.1 Identification method

Two types of basic assumptions are used in the present project:

* Hypothesis on the behaviour of the structure: We suppose that the dynamic behaviour of the structure can be described by a stationary, infinite order, linear dynamical system.
Hypothesis on the input: In the frequency range we are interested in, the input forces of the dynamic equation can be considered like a non-stationary white noise (i.e. with time varying covariance matrix). In fact the inputs we have to consider are the second derivatives of forces, the measurements being accelerations.

The behaviour of the structure can be broken up into an infinite number of unimodal vibrations. By the combination of the interesting frequency range, the geometry of the input forces, the layout and finite number of the observation points, only few of these unimodal vibrations are sufficiently powerful to be detected.

Under the previous hypotheses, we can describe the behaviour of the structure by the system:

\[
(M_p^2 + C_p + K)Z_s = E_s
\]

\[
Y_s = L_z Z_s
\]

with \( p \) the derivative operator and \( s \) the continuous time

\( M, C, K \) the mass, damping and stiffness matrices

\( Z_s, Y_s \) the state and observation vectors

\( E_s \) the non-stationary white noise with time-varying covariance matrix

We take here a short cut in the reasoning, and claim that, starting from Eq. (1), we demonstrate that the discrete observation vector process can be modelised by a multidimensional ARMA process (Auto Regressive Moving Average):

\[
Y_t = \sum_{i=1}^{n} A_i Y_{t-i} = V_t - \sum_{j=1}^{n-1} B_j V_{t-j}
\]

where \( t \) is the discrete time

For more details see [2], [3] and [Prevosto & al in this seminar]

The searched modal informations are given by the solution of a kernel problem:

\[
(I - \sum_{i=1}^{n} A_i Z_k ) \omega_k = \theta
\]

\[
(\omega_k + j\omega_k) \delta t
\]

where \( Z_k = e^{j\omega_k \delta t} \)

\( \omega / 2\pi = \) modal frequency

\( \delta t = \) sampling period

\( \varepsilon = \omega / (\omega^2 + \omega^2)^{\gamma} = \) modal damping

\( \omega_k \) the observed part of the modal shape
It follows that the developed identification method includes three steps:

* Computation of the matrix covariance function of $Y_t$

* Identification of AR part of Eq. (2), i.e. the $A_s$ matrices

* Resolution of the kernel problem, Eq. (3)

2.2 The feasibility study:
Identification accuracy and physical change sensitivity comparison

The identification method, above described, thus, has been studied and developed rather than Fourier techniques, due to its robustness to a non-stationary excitation and to its better precision on modal parameters.

Nevertheless, an important step of a monitoring project is to compare the precision of the identification method with the deviations due to some typical physical changes. This step enables a quantified evaluation of the capability of such a method to contribute to the detection and (or) diagnosis of a variety of classes of defects.

To do so, an analysis of the short term variability has been estimated experimentally, based on the study of a jacket behaviour. (P-data instrumentation included two bi-axial horizontal accelerometers at mudline level and two at deck level). The precisions on the frequencies and relative modal deflection (mudline/deck) of the first three modes are listed in table 1.

<table>
<thead>
<tr>
<th>Relative Standard Deviation</th>
<th>Mode 1 First E-W Bending mode</th>
<th>Mode 2 First N-S Bending mode</th>
<th>Mode 3 First Torsion mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Modal Shape (mudlevel/decklevel)</td>
<td>1%</td>
<td>1.5%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

Table 1: Relative Standard Deviations

Simultaneously, based on the dynamic model of this jacket fitted on the first three modes measured on the platform, a large variety of physical damages has been simulated. On the first order modes, effects of different types of bracing removals, changes of soil stiffness, deck masses modifications, water fillings of bracings have been computed with the Finite Element code STRUDL. It has given relative maximum variations on the modal shapes, always reaching 6% (resp. 10%), with observation points limited to the jacket instrumentation (resp. all legs and levels), whereas in some cases, frequency changes were below 0.3%.
These two studies have demonstrated that, with the complete information, frequency plus modal shape, we are able to detect realistic physical changes on this type of structure.

Because of the wide range of possible physical and environmental changes not related to critical damages, global detection techniques are not sufficient. (Global here means, detection of: "some change in a very large subset of physical modifications "), they must be replaced or completed by diagnosis techniques, diagnosis equivalent to detection of: "one change in a very large subset of physical modifications".

Several methods, which are able to solve such a very difficult problem have been studied and developed. They are briefly described in the following section.

2.3. Detection, diagnosis and sensor positioning

Monitoring techniques have to face two types of problem.

* Are relevant variations larger than parameter identification precision?

* How to link, identified parameters variations and physical modifications (their types or their locations)?

Global detection techniques can succeed if the first problem is solved, the diagnosis techniques must answer to the second one. The sensor positioning strategy methods aim to improve the performances of these two techniques under some technical or operational constraints.

2.3.1 Diagnosis

We describe, hereunder, three types of diagnosis techniques which have been investigated. For each of them we will describe the three important characteristics of this type of method, that is to say:

* The reference information

* The diagnosis step itself

* The type of diagnosis that can be made

2.3.1.1 Model Fitting

The first of them is the well known model fitting technique.

The reference information is a F.E. model which has been very well fitted starting from a previous modal parameters subset. This model can be a reduced one, from a design model.

The diagnosis consists in adjusting the reference model with an updated modal parameters subset. This technique, already successfully tested, uses for convergence criterion the modal frequency deviations. The results on the simulated frequency changes, sometimes very low,
indicate that this choice may not be the best one, and that a criterion on the modal shapes can greatly improve the technique.

With such a method, we diagnose and localise physical changes. The geometric precision of these informations, obviously, depends upon the initial model reduction level. For extensive results see [5].

2.3.1.2 Modal Shape Monitoring

The second method, that we call Modal Shape Monitoring, is a more direct observation of identified parameters. Here, modal frequencies are not used, but flexibility parameters are computed from modal vectors (very close to the principle employed in [6]). In fact we have studied three types of modal flexibility vectors. (see fig. 1).

The reference, for this method, is a subset of modal vectors and more precisely, one or all of its associated modal flexibility vectors.

The diagnosis is made by the comparison with an updated subset of flexibility vectors.

The advantage of these flexibility vectors is that they localise a defect, which is not the case with modal shapes. The diagnosis of the physical nature of the modification diagnosis does not seem possible. Nevertheless, we notice, here, that the authors of [6] claim that the flexibility parameter is insensitive to a deck mass change.

Tests have been led on 21 modifications cases simulated during the feasibility study. Starting from this theoretic information, identification noise has been added, to simulate a more realistic situation. Among all these cases, 10 modifications have been located, 5 only detected and 6 have been left undetected. An exemple of output result is given in fig. 2.

2.3.1.3 Detection technique

This last diagnosis method, is quite different of the previous ones.

Here the reference is a dictionary of representative directions of parameter changes \( \theta_4 \), which has been obtained from a F.E. model, but not necessarily well fitted (for exemple a design model).

The diagnosis is made by a statistic hypotheses test, between \( H_0 \) (no change), and \( H_{a1} \) (change in the \( \theta_4 \) direction). The value of test \( T_{a1} \) gives the decision parameter.

As the number of possible mass and stiffness changes is very large, a preprocessing classification must be realised in order to extract representative directions of changes families. The proximity measure used in this classification is:

\[
d_{4j} = \frac{(T_{a1}/c_{a1})}{(T_{a1}/c_{a1})}
\]
with $T_{0m/0_1}$ standing for the value of the test: "change in
$\theta_m$ direction, knowing there is a change in $\theta_1$ direction". The
coherence of these families in term of physical changes is important to
give a good diagnosis. (for example, family of deck mass changes, of
first level stiffness changes, ...).

Some tests have been made on a small lumped-mass model which are
promising. For more details, see [4], [7].

2.3.1.4 Advantages and drawbacks

Advantages and drawbacks of these three techniques are resumed
hereunder.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Drawbacks</th>
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<tbody>
<tr>
<td>Model fitting</td>
<td>-Probably, the most</td>
</tr>
<tr>
<td></td>
<td>-Very well fitted reference model.</td>
</tr>
<tr>
<td></td>
<td>-For the moment, $\delta f=0$</td>
</tr>
<tr>
<td></td>
<td>blocks the method.</td>
</tr>
<tr>
<td>Modal shape monitoring</td>
<td>-No reference structural model.</td>
</tr>
<tr>
<td></td>
<td>-Possible localisation, very</td>
</tr>
<tr>
<td></td>
<td>difficult diagnosis</td>
</tr>
<tr>
<td>Detection technique</td>
<td>-Reference FE model has not to be</td>
</tr>
<tr>
<td></td>
<td>very well fitted.</td>
</tr>
<tr>
<td></td>
<td>-Building of coherent families.</td>
</tr>
<tr>
<td></td>
<td>-It can be an in-line technique.No</td>
</tr>
<tr>
<td></td>
<td>updated identification needed.</td>
</tr>
</tbody>
</table>

2.3.2 Detection

In the previous section, we dealt with a change detection method.
As the aim was the diagnosis, the direction of change was a vector. In
fact, the same technique can be used to detect a change in a subspace or
a subset of parameters. This provides a more global detection which can
be used to build an alarm approach.

This set of parameters can be:

- the coefficients of the AR part of the identified model (see §2.1).
  For our application, a subset of it has no physical meaning. In fact,
  as the damping ratios are highly dependent of the excitation, so are
  the AR coefficients. Then, this global detection is not an appropriate
  one.

- the modal parameters. Here, we can eliminate from the parameters
  set, the damping coefficients and work, only, on the subset of the
  modal frequencies and vectors.
An important remark, is that all these techniques of detection are insensitive to a change in the excitation (energy, direction), at least as long as the observed parameters are independent of it. And, we recall here that the developed detection algorithms works directly on the measurements, without updated identification.

2.3.3 Sensor positioning

The problem of sensor positioning has often found its solution from practical considerations: Location on the antinode (problem of energy), at deck level (problem of cost), at mudlevel (monitoring of soil modification); but it has never received rigorous solution (a first empirical solution has been used by TECNOMARE, only based on energetic notions [8]).

Indeed, when we have more than one mode and, above all, more than one sensor, the problem is very difficult and the idea of an absolute optimum sensor location is an utopic idea.

The problem has to be defined as follows,

Given:

- some operational and technical constraints giving us costs related to each instrumented point.
- severity weights on each possible structural modification (risk analysis)

Find:

- the cost-risk tradeoff associated to all the possible sensor layouts.

In this aim, we have developed a computation tool of the detection test power described before. [9]

The output information of such a procedure can be simplified along the following scheme:

\[ C_0 \rightarrow IP_0 \rightarrow \{ L_1 \}_0 \rightarrow \]

\[ \{ R_j = \min f(P(D_j, L_1), S(D_j)) \} \rightarrow \max R_j \]

with \( C \) financial cost, \( IP \) instrumentation project, \( L \) sensor layout, \( D \) damage, \( S \) damage severity, \( R \) risk factor, \( P \) detection power of a given damage with a given sensor layout, \( f \) risk function.

This optimization technique can be used, either to define the characteristic of a fixed or movable instrumentation, or in the case of a movable one, to determine the agenda of a campaign and (or) the best inter-campaign fixed configuration of the instruments lay-out.
3. CONCLUSION

If some of the choices explained in this paper are specific to the case of offshore structures, we have wanted to point out, by an example, the different problem of a modal monitoring project. So, we have shown, the variety of diagnosis techniques which can be employed and we have warned against the idea of an all cases optimal sensor layout.

REFERENCES


1. **Bending Flexibility**

\[
Fl_k = \frac{\sqrt{(X_{k}-X_{k-1})^2 + (Y_{k}-Y_{k-1})^2}}{\sqrt{(X_{k}-X_{\phi})^2 + (Y_{k}-Y_{\phi})^2}}
\]

2. **Bending Flexibility Angle**

\[
AFl_k = \tan^{-1} \frac{1}{\sqrt{(X_{k-1}-X_{k})^2 + (Y_{k-1}-Y_{k})^2}} - \tan^{-1} \frac{1}{\sqrt{(X_{k}-X_{k-1})^2 + (Y_{k}-Y_{k-1})^2}}
\]

3. **Torsion Flexibility Angle**

\[
ATO_k = \tan^{-1} \frac{V_{k-1}-V_{k}}{X_{k-1}-X_{k}} - \tan^{-1} \frac{V_{k}-V_{k-1}}{X_{k}-X_{k-1}}
\]

X, Y horizontal axes, Z vertical axis

In bold line, a leg deflexion

**Figure 1: Flexibility parameters**
Case 1: Diagonal Removal

Case 2: Horizontal Removal

In dashed line, the removed bracing.

The size of the arrows indicates the values of the deviation at each structural node.

Figure 2: Deviations between reference and updated flexibility parameters on torsion mode.