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Acoustic monitoring of the hulls of Floating Production Storage and Offloading facilities (FPSOs) for corrosion and damage

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Acoustic monitoring of the hulls of Floating Production Storage and Offloading facilities (FPSOs) for corrosion and damage

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This work explored possible means of monitoring the structural health of Floating Production, Storage and Offloading facilities (FPSOs) using structural acoustics.

After wide consultation, it was concluded that there are only two technologies that stand a reaslistic chance of reaching practical application: acoustic emission monitoring and sparse-array monitoring using guided waves (Lamb waves). The former will be applicable to monitoring crack growth; the latter to crack detection and corrosion monitoring.

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2 EXECUTIVE SUMMARY

We have carried out a series of interviews with experts involved in the design, build, operation, maintenance and inspection of FPSOs (Floating Production, Storage & Offloading facilities). Based on these, and on the open literature on the subject, we have arrived at a view of the industry s need for structural monitoring on FPSOs and what approaches are likely to be acceptable. The most pressing requirements appear to be for monitoring for active crack growth in the splash zone of the outer hull, and for growth of corrosion pits in tank floors and walls.

We have also conducted an extensive review of the technical literature on acoustic methods of structural monitoring. We have examined available methods for their suitability for monitoring FPSOs of the general design currently in use within the UKCS (UK Continental Shelf) area. The review found three methods that might be feasible on structures of this size: monitoring of the frequencies of localised structural modes; acoustic emission; and sparse-array monitoring using lamb wave excitation.

Closer consideration of application to FPSOs showed the first of these (monitoring localised modes) to be too insensitive to be useful.

Acoustic emission is a well-known technique and would be applicable to crack monitoring in the outer hull, although large numbers of transducers are likely to be required. Although monitoring corrosion in onshore storage tanks is also an established technique, it would be more difficult to apply on an FPSO because the emission levels are very low and other noise sources are likely to interfere. Emissions from adjoining tanks are another complication.

Sparse-array lamb-wave monitoring would locate cracks or corrosion patches by injecting travelling ultrasonic waves into tank wall plates and detecting their reflections from damage sites up to several metres away. Progressive damage would be distinguished by the increase in signal reflection strength over time. This technique is still at the development stage, but is likely to become available within a few years and is certainly the most promising technique for corrosion monitoring.

We recommend carrying out trials of acoustic emission and of sparse-array lamb wave monitoring when it becomes available. Acoustic emission should be applied to crack detection in the splash zone of the outer hull, preferably on a vessel regularly exposed to severe sea states. Sparse-array monitoring should be applied to corrosion detection. The slop tanks appear to be a suitable test area because corrosion is more likely than in ballast or cargo tanks.

3 INDUSTRY CONSULTATION

Our objective was to gather opinions and information from around the industry on structural integrity monitoring of the hull, ballast tanks and cargo tanks of FPSOs, having regard principally to corrosion but also to fatigue damage. We consulted a classification society, an inspection organisation, a marine research institute, a marine design consultancy and two FPSO operators, all of whom have an active interest in the subject.

3.1 INTRODUCTION

A recent study into UKCS FPSO inspection, repair & maintenance conducted by Lloyd s Register found structural defects in every one of the FPSOs featured [1]. Almost all of these had not been detected by the conventional scheduled-inspection process:

> The UKCS FPSO fleet is relatively young. An important conclusion of the study therefore was that most of the failures discussed occurred in the early operating years, before any inspection plan could have detected signs of deterioration and before any maintenance plan could realistically be expected to anticipate the failure. Despite all attempts to establish a linkage, inspection and maintenance did not feature large in the history of failures. Design and construction however was a dominant factor in the overwhelming majority.

In other words, inspecting the existing vessels at five year intervals is not a sufficient safeguard against structural failures arising from imperfect design and build. While experience gained by the industry over the years will no doubt lead to a decline in the number of failures arising from design, this will not necessarily be true of construction-related defects. It is clear that, at the most general level, monitoring as opposed to inspection has a part to play in FPSO maintenance. By picking up defects as they occur, a monitoring system could potentially yield a large reduction in risk.

We interviewed experts involved in FPSO design, build, operation and maintenance. The interviews gave a mixed impression, principally because different organisations have very different interests. For example a classification society will obviously be keen to see monitoring and inspection schemes made as effective as possible, while operators feel under pressure to maintain production with minimum downtime for inspection and repair. The following is a summary of our impressions. Records of the interviews and documents on which it is based are either reproduced in the Appendixes or included in the references section.

Operators appear confident that their vessels are well designed and, provided the build is not defective, will last at least ten, probably fifteen, years before significant signs of deterioration appear. Nevertheless there appears to be a lively interest in the possibility of automated monitoring. This apparent contradiction arises because of the number of incidents in which defects have been seen to arise from inadequate design[1] or defective construction (notably poorly-applied coatings). Thus while operators are confident that experience is leading to improved designs, they cannot guarantee that further experience will not turn up new problems; neither can they be sure that a particular vessel will not have unforeseen defects of construction. Since most FPSOs have their tanks inspected on a five-year rolling program, either type of defect could cause a serious problem before the first inspection picks it up.

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[1] *The inadequacy appears to lie in a failure to foresee the degree of structural stress, rather than in poor design. Some interviewees have suggested to us that the accepted methods of forecasting structural loading from sea state statistics leads to underestimation of the loads actually experienced by FPSOs in the North Sea.*

Views differ as to whether it is corrosion or fatigue damage (cracks and failed welds) that should be monitored, with the two operators we spoke to actually holding diametrically opposing views. We present the views on corrosion and cracking below.

3.2 CORROSION

Protection against corrosion of the hull and of seawater ballast tanks is provided by coatings and in some areas by sacrificial anodes.

For tankers, according to a Lloyd s principal surveyor, quoted by an expert in the field:

> Effective corrosion control in segregated water ballast spaces is probably the single most important feature, next to the integrity of the initial design, in determining the ship s effective life span and structural reliability .

In FPSOs, seawater ballast tanks (BTs) lie between the inner and outer hulls in a double-hulled vessel, or between the hull sidewalls and the cargo tanks in a single-hulled vessel. The BTs are normally completely lined with an epoxy-based coating. This used often to be black coal tar epoxy, which is cheap, flexible and highly water-resistant [2], but is being replaced by modified epoxies which are more resistant to chemical attack and can be given a light colour, making inspection easier (see Appendix A). In addition the BTs are normally provided with sacrificial anodes. As well as providing protection against corrosion, inspecting the rate of erosion of these anodes gives a guide to the electrochemical currents flowing and hence to the effectiveness of the coating in the vicinity of each anode: if the coating is breached, the current will increase greatly and the surrounding anodes will erode more quickly. Exactly how effective anodic protection is in FPSO BTs is unclear[2].

In FPSOs, cargo tanks (CTs) will only hold crude oil. In the UKCS, the crude is not sour , and sulphate-producing bacteria and sulphurous acid corrosion are not likely to be found. CTs tend to have their floors coated, and up to 2m of the wall above the floor, but the remainder of the walls is usually left bare. This is because the produced water (PW) content, usually small, will tend to fall to the floor. PW can contain large amounts of dissolved salts and may be acidic, and the tank floor needs protection. With no conductive fluid in contact with the side walls however, there should be no need for a coating in this area. CT roofs are sometimes coated as a precautionary measure, in case PW evaporation products condense and produce corrosion (Appendices C, E).

The effectiveness of coatings is highly dependent on how carefully they are applied [3]. The surface must obviously be clean and dry (although coal tar epoxies do tolerate some oil and grease), and the coating thickness is very important. If it is too thin, corrosion will occur before the design life is reached; too thick, and the coating will crack, exposing the steel to corrosion. This is particularly likely in corners and angles ([3];Appendix D).

The most likely form of corrosion is pitting corrosion in tank floors where the coating has failed. This is likely to be most severe near the boundaries of the horizontal plate [4]. Pitting corrosion forms a narrow conical penetration into the plate. It grows quickly once initiated and can result in complete penetration and hence a loss of cargo containment.

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[2] *For anodic protection to be effective the anodes and the surfaces to be protected must be immersed in a continuous volume of seawater. According to reference [4] they need to be immersed for at least 5 days to become fully effective. The ballast tanks on an FPSO are frequently filled and emptied as cargo is loaded and unloaded; this suggests that for at least some of the time (depending on how often they are emptied) the BTs will not have the full benefit of cathodic protection.*

In addition, the floor of a BT will probably remain wet while the tank is nominally empty, leaving it exposed to corrosion without cathodic protection during this time.

Welds are particularly vulnerable to corrosion if not protected [4]. The reason is believed to be galvanic action between the weld material (anodic) and the steel of the surrounding plate (cathodic).

Interviewees views on corrosion varied enormously. Operator 1 saw pitting corrosion as the obvious thing to monitor: produced water (PW) tends to collect at the floor of cargo tanks (CTs), attacking the coating and then corroding the steel behind it. Operator 2 had complete faith in his lines of defence against corrosion: monitoring the state of sacrificial anodes in the ballast tanks (BTs), and inspecting coatings in all tanks every five years, would pick up coating failures in good time, allowing repairs to be scheduled well before the structure suffers significant damage. He therefore saw no need for a corrosion monitoring system. A naval architect working for an independent marine consultancy took the opposite view, agreeing with operator 1 that pitting corrosion in tank floors would be worth monitoring. However a test and measurement specialist working for a national marine research institute maintained that some companies were better than others at ensuring that the coatings of their FPSOs tanks were fully effective, so that each of these two views was true for some FPSOs.

None of those interviewed laid any stress on monitoring the hull externally. Hulls are protected externally by coatings and by sacrificial anodes; using the impressed-current technique [3] allows the extent of coating deterioration to be monitored[3]. Divers and ROVs are used to inspect the submerged hull, but direct inspection is used sparingly because of the rough sea conditions to which FPSOs are typically exposed. The general view appears to be that the external surface is sufficiently well protected not to require frequent inspection. However, we note from Lloyd s report [1] that in one out of six UK FPSOs surveyed the external hull treatments had failed severely enough to require repair.

Deck heads normally suffer only distributed corrosion which proceeds very slowly, typically at less than 0.1mm/year. While it can be unsightly it is not normally a threat to vessel integrity.

3.3 CRACKING

No one we interviewed disputed that cracking is common in FPSO structures. Several of our interviewees commented that, like the tankers on which their designs are closely based, FPSOs are designed to have a high degree of structural redundancy. They are built from low-grade steel using fairly basic standards of welding, with large numbers of stiffening ribs, decks and frames added to the hull, tank and bulkhead plates (to cope both with sea loading and with hydrostatic loads as tanks are filled and emptied). They can tolerate a high level of fatigue damage without undue degradation of structural strength. However there are limits. In one purpose-designed vessel, insufficient stiffening of the hull frames allowed a degree of flexure that produced widespread and significant cracking that has necessitated a programme of reinforcement of the frames.

Nevertheless we found no general agreement on the usefulness of monitoring fatigue damage. One operator was particularly interested in monitoring side-shell condition in the splash zone in order to predict fatigue life more accurately; the other believed that, because hulls have very few external attachments that might act as crack initiation points, the normal five-yearly inspection schedule was adequate. The test & measurement specialist thought that, with ever larger structures planned for the future (particularly for LNG storage and transport), fatigue would become a major problem and monitoring would be highly desirable.

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[3] *If the protective coating becomes very thin or ruptures, the impressed current automatically increases to protect the hull. Monitoring the current allows the overall state of the coating in the region of the anode to be assessed, but does not identify the precise location of coating defects.*

3.4 CONCLUSIONS FROM CONSULTATIONS

3.4.1 General

There appear to be two different aspects to the potential role of structural condition monitoring on FPSOs. Firstly, monitoring would be the logical way to allow for the shortcomings in design and construction that have led to the appearance of defects in at least a significant proportion of the UKCS FPSO fleet[4]. As noted in Lloyd s report [1], on a normal class-based inspection schedule these would not be picked up within five years, and on a typical risk-based strategy, seven years.

Secondly a monitoring system would have an obvious role to play on FPSOs as they grow older. After fifteen years, any FPSO will be required to undergo frequent inspections. A monitoring system could allow less frequent inspections with consequent savings in cost and production capacity.

The attitude of the industry to new monitoring technologies seems likely to be governed by cost. If a system demonstrably saves more in terms of inspection costs and lost production than it costs to install and run, it will find favour with operators. If it does not there is unlikely to be much enthusiasm for it.

Any new system will also have to gain the backing of the class societies, who must be prepared to allow less frequent inspections on a vessel fitted with it. The argument that a monitoring system can pick up defects resulting from design and build errors is likely to carry some weight with the societies; however they will have to be convinced that a proposed system is effective in doing this. The only system so far put forward acoustic emission monitoring has not yet found acceptance on FPSOs in this sense. Identifying a system which is both technically effective and acceptable to both classification societies and operators will occupy the remainder of this project.

3.4.2 Areas of Application

3.4.2.1 Corrosion monitoring

Possible applications include the floors of tanks where pitting corrosion is a potential problem. In the crude oil tanks, pitting could produce loss of containment leading to pollution. Other sites at risk include the ballast tank walls and floors, the hull exterior and the deck head (where distributed corrosion can occur). The slop tanks would be an ideal site for trials of prospective monitoring systems because the corrosive mixtures of fluids they often contain means that they are more likely to suffer significant corrosion, but since they are small and readily repaired it is unlikely that permanent monitoring could be justified.

3.4.2.2 Fatigue monitoring

Monitoring should be considered in areas where a single failure would lead to unacceptable consequences. These include the splash zone of the external hull and the walls of the cargo tanks (i.e. the internal bulkheads). Elsewhere, structural redundancy makes failure of an individual

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[4] All FPSOs discussed in the interviews recorded in Appendices A-F had such defects. All six FPSOs considered in reference [1] also had such defects.

member less important, and a sensible strategy would be to monitor a few selected areas. For example, a single hull frame could be selected and monitored.

3.4.2.3 Matrix of risk

The following table summarises the perception of risks to different parts of the structure gained from industry consultation.

Table 1 Risk Matrix for structural zones versus corrosion and cracking

Zone	*Protection*	*Effectiveness*	*Current inspection*	*Corrosion risk*	*Cracking risk*	*Monitoring relevant*
CT floor	Coating	Good	Visual, 5 year cycle	Moderate	-	yes
CT wall	None	-	Visual, 5 year cycle	Low	Low	
CT ceiling	Coating	Good	Visual, 5 year cycle	Low (UKCS)	-	
BT interior	Coating, cathodic	Very good	Visual, 5 year cycle	Moderate	-	yes
Hull frames	Coatings	Good	Visual, 5 year cycle	Low	High	yes
Exterior hull	Coating, cathodic	Very good	Impressed current monitoring Visual, 5-7 year period	Moderate	Low	yes
Deck	None	-	?	Low	-	

4 INFORMATION SEARCH ON ACOUSTIC TECHNIQUES

We carried out searches using databases of European and US patents; using the Compendex search engine to search the academic literature; manual searches of selected professional and academic journals; and web searches of commercial and academic websites. In a few instances we have held initial discussions with technology holders.

There are a few general reviews of Structural Health Monitoring (SHM) in the literature, for example [6], with disappointingly few references to recent work on marine structures. There is interesting work being done on wireless sensor networks, which unfortunately is unlikely to be feasible inside storage tanks because of intrinsic safety issues, and would not be feasible in seawater tanks because the RF signals would not propagate far enough.

Most of the useful results found can be classified under the following headings proposed at the initial project meeting:

1. *Monitoring global structural modes*;
2. *Monitoring Local structural modes*;
3. *Acoustic Emission; and*
4. *Transfer function methods*.

We did not find any references to the fifth category which we had suggested, namely the use of *Statistical Energy Analysis (SEA)* to monitor structural condition. We have included a short section on the method for reference nonetheless.

There is also a class of techniques which can be appropriately classified under a separate heading, *point testing techniques.* Although we regard these as less likely to be useful they are included for completeness.

In the following sections we have divided up the various methods discussed in the literature under these headings.

4.1 METHODS BASED ON MONITORING GLOBAL STRUCTURAL MODES OF VIBRATION

If a structure changes, its modes of vibration will also change. They may change in frequency, damping, and shape. In principle therefore, by monitoring various attributes of the modes of vibration of a structure one may detect changes in the structure. Methods using measurement of modal strain energies can detect and locate damage [8]. Alternatively, by measuring frequency response functions at a few points, damage can be detected with relatively few sensors [9]. Distributed corrosion may cause a reduction in flexural stiffness and thus reduce modal frequencies [14]; fatigue may produce an accelerating reduction in modal frequencies as failure approaches [21]. Sophisticated methods for estimating modal parameters can improve detection thresholds, [10], [11], [21]. If one has a sufficiently accurate and detailed knowledge of the dynamics of the structure, it should be possible to deduce the exact nature and location of the change [19], [24].

Using the sound made by a tapped object as a guide to its condition has of course been known in one form or another for a very long time. On the Victorian railways for example, wheel-tappers [5] used long-handled hammers to tap the wheels of carriages and locomotives: a cracked wheel would not ring true . A cracked church bell is readily detected by its spoilt sound.

Both of these examples illustrate the strengths and weaknesses of the technique. It can be extremely simple to use, and in principle at least requires only a single monitoring point. The structure under test need not even be excited if there is sufficient mechanical excitation arising in normal use [16]. However the damage to the structure needs to be significant before it becomes easily detectable by this means.

There have been repeated attempts to extend the method by making it more sensitive to less severe damage such as pre-critical cracks or corrosion. There have been many theoretical and laboratory studies of the change in modal response of cracked beams and plates, looking for attributes which will aid detection [22], [23], [24]. An example closer to the subject of the present study is the monitoring of the swaying modes of offshore jacket structures under sea loading [12], [13]. Monitoring jacket structures requires the monitoring of very low frequency modes (periods of order 1 sec and longer) with extreme precision. This requires monitoring jacket motion for long periods of time in the presence of quasi-periodic forcing and background noise from production operations. In addition there is the problem of varying topsides mass and mass distribution. The method is regarded as being limited to detecting the failure of major structural members; where there is structural redundancy, failure of an individual member is unlikely to be detected.

The method has been applied to buildings with apparent success [37]. Another application is the monitoring of the vibration of bridges to detect damage [20]. Methods divide into those using ambient vibration and those using forced vibration. Halling et al [15] showed that damage to a freeway bridge could be detected by monitoring mode shapes and frequencies under artificial excitation. Mazurek et al [16] used vehicular excitation of a road bridge to measure structural mode frequencies and damping. Toksoy & Atkan [17] detected damage in a three-span reinforced concrete bridge by monitoring modal flexibility. Pandey and Biswas [18] showed that modal flexibility could be estimated from simple low frequency measurements

In all of these areas it has become apparent that a great deal of effort is required to make the technique sensitive. In beam applications, typically a crack must occlude at least 20% of the area before its effect is discernible even under ideal conditions; 50% is a more practical target. In complicated structures, complete severance of a member may be required. If the structure includes redundancy, detection of damage at a single point can become practically impossible.

The application of this approach to detecting corrosion and fatigue cracking on an FPSO would be highly problematic. An FPSO is designed with a high degree of structural redundancy, and its modal response to sea loading will be very insensitive to damage which is, in structural terms, minor. It would be necessary to monitor the structural response very carefully over a long period of time, during which the loads on the structure must be kept unchanged. Given the constantly-changing levels of fluid in various tanks, this condition is most unlikely to be met.

This approach might thus be suitable for the detection of major structural deterioration, but is unlikely to be useful for monitoring less extreme levels of corrosion or fatigue.

4.2 METHODS BASED ON MONITORING LOCAL STRUCTURAL MODES OF VIBRATION

This is the same approach as the previous section, applied to part of a structure which is dynamically independent (or semi-independent) of the rest of the structure. A good example would be a panel fixed to stiff ribs at its edges [38]. The panel can vibrate out of plane essentially as if it were fixed at its edges. Then one can excite its normal modes by tapping the panel, and for example a change in the distribution of stiffness produced by a patch of corrosion would be detectable via its effect on mode shapes and frequencies. As in the previous section, different approaches can use either artificial excitation or background noise as an excitation source.

The method works in essentially the same way as global modal monitoring, but has the advantage that it is insensitive to changes in the rest of the structure. Small changes in the member under test can thus be more readily detected. Nevertheless it remains true that significant damage must occur before the change in modal response becomes large enough to be detected in non-ideal conditions.

On FPSOs the most obvious application would be to panel-like members such as bulkheads and tank floors, as suggested for example in [24]. These are very large units tens of metres across, heavily reinforced by stiffening ribs, frames etc typically spaced 1 2m apart. Depending on the wave modes one chooses to excite, these could behave either as single substructures with identifiable modes, or modes could be localised by the effect of the stiffening ribs. Unfortunately it is unlikely that things will be that simple: the ribs will affect any travelling waves and will tend to convert their energy into other wave types; localised modes will not be entirely confined by the ribs but will leak out into the surrounding structure. It is more likely that there will be some modes (probably lower-frequency ones) that will be suitable for monitoring an entire bulkhead, while others will be too rapidly attenuated by interaction with ribs[5].

For localised monitoring, the bulkhead would preferably be monitored when there was no fluid on either side, since otherwise wave energy could be lost to the fluid, increasing its apparent damping and reducing the sensitivity to corrosion or fatigue[6]. This method would require each local area (i.e. the area to which modes are confined the area between a pair of stiffeners) to be instrumented separately. The density of instrumentation would depend on the desired accuracy of location of defects: if they are merely to be located within the local area, very few sensors might be required (perhaps only one per local area).

In-plane waves will be less sensitive to the presence of fluid. Unfortunately they will also be less sensitive to corrosion and cracking, which have a stronger effect on the effective moment of area of the plate than on its effective area[7].

Overall, the most localised modes offer the best prospect for structural monitoring. Out-of-plane waves are likely to be most promising. Surveys would preferably be carried out when the plate area is not in contact with fluid (i.e. when both neighbouring tanks are empty). We suspect that this condition may not occur very often.

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[5] *The regular spacing of the reinforcing ribs makes it very likely that there will be a clear separation in frequency between modes localised by stiffening ribs and modes which extend across the entire bulkhead. It is well-known that ribbed structures exhibit a passband-stopband structure, with waves in some frequency bands propagating easily while others do not propagate (see e.g. [40] chap V sec 5). The pass bands will correspond to bands in which modes of the entire bulkhead can exist, while only localised modes will exist in the stopbands.*

[6] *According to [25] the effect of a crack on the modal response of a submerged plate is detectable, the main effect being to increase the apparent mass of the plate. However the author was working on an isolated plate at low frequencies. At high frequencies (above the so-called coincidence frequency at which plate bending wave velocity matches acoustic velocity in the fluid), losses to the fluid will be high. For a plate built into a structure, there will be some radiation losses even at low frequencies due to edge wave radiation.*

[7] *Cracks and corrosion grow from the surfaces of a plate. They therefore affect its bending stiffness more than its compressive stiffness. Hence out-of-plane waves, which involve strong bending, are more affected than in-plane waves. See for example [23].*

4.3 ACOUSTIC EMISSION

The use of acoustic emission (AE) for monitoring crack growth is very well established and is comprehensively reviewed in [26]. There is little doubt that it could be applied to monitoring fatigue crack growth in frames, even in the presence of significant background noise: acoustic emission has already been successfully applied to offshore platforms for crack growth monitoring [27]. However, this application required a high density of sensors attached within a metre or so of the cracks being monitored. In order to be a practical means of large-scale structural monitoring, AE would have to be able to cover much larger areas of the structure with a small number of sensors, and do it reliably.

The pitting-corrosion process is known to produce acoustic emission from metal, with most attention paid to stress corrosion cracking in stainless steel [28], [29]. AE is also observed in mild steel [30], [32]. It occurs at least partly because of hydrogen production within the corrosion pit and probably also because corrosion causes the material to expand, and broadband acoustic emission results when the corrosion products break away from the parent metal. Several approaches to measuring and classifying corrosion using AE have been proposed [29], [30], [31], and it appears to be possible to identify the stage, rate of progression and extent of corrosion from AE signal characteristics.

The most relevant application of AE to date has been its application to the detection of active corrosion in the floors of large liquid-hydrocarbon storage tanks at refineries and storage depots [32], [33]. A few sensors are attached to the vertical outer wall of the tank. The sound emitted by corrosion is transmitted through the fluid in the tank to the tank wall and is detected by the sensors. By triangulating using the arrival times of individual events at different sensors, an indication of the location of the corrosion can be obtained. Taken together with the rate of occurrence of AE events, this gives a guide to how widespread the corrosion is, and how rapidly it is advancing. A user-group study has confirmed its effectiveness as a survey tool for storage tanks [34].

Whether or not this method is practical for FPSOs will depend crucially on whether the levels of sound produced by the corrosion process are high enough to be detectable against background noise. There are two potential difficulties. Firstly, fatigue cracking will probably be progressing at the same time as corrosion. The only reference to relative levels of AE from cracking and corrosion that we have found in the open literature [32] suggests that the levels of AE produced from the corrosion of steel are very substantially below those produced by crack growth. The authors state that the detection system must be more than forty times as sensitive as those used for AE detection in pressure vessel testing. Thus the emission from corrosion may be masked by crack growth, unless enough sensors are used to achieve effective separation of the two on the basis of their location: i.e. if quietly-growing corrosion in a tank floor can be separated from much louder cracking in hull frames.

Secondly there is the problem of noise generated by normal operations on board the FPSO. Corrosion monitoring has been shown to work only in isolated storage tanks which have no other noise sources operating; an in-service FPSO, with valved flow of fluids and gases at very high pressure in addition to noise from power plant, may have significant levels of structure-borne and fluid-borne noise. However Williams [35] states in Chapter 6 that on offshore production platforms, background noise in the frequency range 60-180kHz is undetectable or only just detectable. If noise levels on FPSOs are comparable then background noise may not be a problem.

4.4 STATISTICAL ENERGY ANALYSIS

This is now a well-known technique described in many textbooks [39], [40], [41]. It is used principally for predicting noise and vibration levels either within or radiated from built-up structures. It is based on drawing an analogy between heat diffusion and the flow of acoustic energy in structures and the surrounding fluids. It deals essentially with statistical properties of the acoustics of structural subsystems, such as modal density, rms velocity, and average modal damping. It offers a way of analysing or estimating vibration levels at frequencies that are too high for finite element modelling to be practical. In the case of a bulkhead in an FPSO, this is likely to mean all frequencies of order 10Hz and above.

The SEA approach can be used to estimate subsystem parameters and to detect significant changes in them. These parameters could include average thickness of a plate; average bending stiffness; and strength of dynamic coupling between different structural elements such as frames and bulkheads. These are estimated from the levels of broadband vibration measured on the different elements, either as a result of artificial excitation or of background noise. Thus for example the method could be used to estimate the loss of metal from distributed corrosion; reduction in stiffness as a result of cracking or corrosion; or corrosion along a weld seam where a bulkhead meets the hull for example.

There are however many questions to be answered before this technique could be considered worthy of further investigation. How many sensors would be required per structural element? What sort of bandwidths would be required? How will fluid loading of the structure affect results? What accuracy can be expected?

We have not been able to find any published work on the use of SEA for structural condition monitoring, which in itself is not promising. The more general literature on the use of SEA for dynamic analysis tends to talk of levels of accuracy in terms of a few dB [41], and this has certainly been the experience of the author in applying SEA to analysing noise transmission from wind turbines. Fahey in the same reference goes so far as to state that no rigorous method of quantifying the uncertainty in SEA-derived parameter estimates has yet been demonstrated These levels would not be good enough for the detection of early-stage cracking or corrosion, where changes in response of less than one percent would have to be quantified.

4.5 TRANSFER FUNCTION METHODS

This is a generic term for methods in which the structure, or a part of it, is excited at one or more points, and its response to each excitation is measured at one or more points elsewhere on the structure. Inspection-oriented techniques will typically look for features arising in the received signal that not would not be present if there were no defects in the structure [42]; a monitoring-oriented technique will look for changes in the received signal(s) over time that indicate a deterioration in the structure [43].

Generally speaking the sensitivity of these methods increases with the number of transducers deployed and with the bandwidth of the signals used. As a rule, a higher bandwidth requires transducers to be placed closer together and hence, taking the two factors together, sensitivity increases rapidly with bandwidth. However, so does cost and the complexity of the system.

We are aware of two types of method. An acoustic-band method recently researched for the HSE [43], [44] is intended for monitoring. It aims to provide a relatively cheap medium-sensitivity method for detecting major cracks, failure or flooding of individual members in an offshore jacket structure. Using point excitation approaches familiar from dynamic structural testing, the method injects signals with a bandwidth of around 10kHz at a small number of points in the structure. Signals are detected at a similar number of receivers. Some or all of the received signals change if damage occurs. Given a very simple model of acoustic propagation through the structure, the damage can be located for subsequent closer investigation. The method relies on structural waves that propagate throughout the structure. Its resolution is limited, partly because of the limited signal bandwidth, but also because of the enormous complexity of the resulting signals. Only a fraction of the information contained in them can be usefully recovered. The method has so far been demonstrated in the laboratory on a scale model; as far as we know it has not been demonstrated on a full-scale structure. It uses standard structural-acoustic source technology and can work with standard sensors. We shall refer to this as the sparse array method.

The second type of method uses guided waves for structural inspection: the excitation of particular wave modes (lamb waves) travelling in particular directions [45], [46]. This method has usually to be tailored to the particular type of structural member being inspected; one commercial system is designed to find corrosion or cracking in the wall of steel pipes in process plant [42], while systems aimed at plates have been a research area for some years [47], [48]. The transducers are highly specialised, with specific transducers being developed for specific applications [45], [46]. Generally speaking these methods use tone burst signals to avoid the effects of dispersion; frequencies are usually in the low ultrasonic range (20kHz 200kHz). The range of these techniques is usually measured in metres, although recent experiments using guided waves to inspect continuous welded rail have achieved ranges of a few tens of metres [50].

Neither of these types of method is likely to be directly applicable to FPSOs as it stands. The first type lacks the sensitivity to detect individual corrosion pits or fatigue cracks. The second type would be far too labour intensive, requiring transducers to be moved around the structure to perform thousands of individual inspections.

However we believe that a hybrid method could be developed that would be very well suited to FPSO monitoring. This would essentially consist of adopting the response monitoring approach of the first type, and combining it with the use of particular wave modes typical of the second. Structural elements such as bulkheads would then be monitored using a sparse array of transmitter/receivers. Rather than guide the waves in a particular direction, they would be allowed to propagate throughout the substructure: the transmission from each transducer would be received by all. As in the sparse array method, changes in the signals over time would be used to diagnose changes in the substructure, and the changes would be located using the time of arrival of the change signals at different transducers. For a simple structure such as a plate, the location procedure would essentially consist of triangulation. An interesting early step in this direction is reported in [49].

4.6 POINT TESTING METHODS

Standard ultrasonic methods are too familiar to require description here, and are available from a large range of suppliers. An ultrasonic probe is held against a metal plate or rib, and reflections reveal the remaining thickness of the member, and the presence of corrosion or cracking.

This is usually a manual operation, but magnetic robotic crawlers are available that can inspect a ship s hull remotely [51]. There would of course be the problems of getting them in and out of tanks, and of their negotiating stiffeners, strakes, frames etc. A miniature ROV equipped with a phased ultrasonic array might be easier to use, but stability of positioning could be a problem. There is a second, very widely used method of point testing, traditionally known as the coin-tap method. The surface to be tested is simply tapped with a small metal object, and the acoustic response gives information on the state of the surface. The method is rendered more quantitative by using a conical hammer tip instrumented with a force transducer to make a measurement of point impedance [52]. The author has successfully used the same method for testing composite blades of wind turbine generators for internal delaminations. This would be easier to interpret than ultrasonic data but would only detect corrosion.

This is really an inspection method rather than a monitoring tool: an operator would be required to run the inspection device. Having an extra person on board an operating FPSO might well present problems of its own: we understand that FPSOs are run as very tight ships, with facilities and accommodation at a premium.

FPSO Operators we spoke to expressed extreme reluctance to allow remotely-operated devices inside the tanks of an FPSO (Appendix C): any robotic device would need to be rendered intrinsically safe, and guaranteed not to drop any components that could block or damage a pipe or pump.

5 CONCLUSIONS FROM INFORMATION SEARCH

5.1 GLOBAL MODES

We do not believe that the monitoring of global modes of an FPSO presents a viable method of monitoring. This is principally because it would not be sensitive enough to pick up levels of cracking and corrosion low enough to offer an advantage over existing inspection strategies. It is in any case likely that changing conditions on board (which tanks are full/empty, etc) would have a much greater effect on global response than would pre-critical cracks or corrosion pitting.

5.2 LOCAL MODES

It is just possible that local-mode monitoring may be a feasible method for ribbed plates such as bulkheads and tank walls which are sometimes fluid-free. It may be less effective for plates which are never fluid-free, such as hull plates. It will be important to select modes which are well-localised and sensitive to changes in plate mass and stiffness distribution. It would require relatively few sensors.

However, although the method may be less vulnerable than global mode monitoring to changing shipboard conditions, ultimately it shares the latter s limited sensitivity. We have not found convincing evidence that cross-section reductions of less than 20% could be detected.

Although there is a large literature on theoretical and laboratory investigations, we have not found references to any industrial applications of the technique.

5.3 ACOUSTIC EMISSION

AE methods exist for the detection of both crack growth and active corrosion. On an FPSO AE sensors would have to be deployed as they are for corrosion detection and location in oil storage tanks: in arrays on the tank walls. However it cannot be said whether AE would work in an FPSO until figures are available on the relative levels of sound radiated from cracks, normal on-board operations, and corrosion.

5.4 STATISTICAL ENERGY ANALYSIS

The current literature does not suggest that SEA has advanced sufficiently to provide accurate measurements of properties such as average area mass density of a plate (i.e. remaining thickness of metal), or change in intrinsic damping (which might betray cracking). Its accuracy is of the order of 30-40% at best. As such we cannot recommend it.

5.5 TRANSFER FUNCTION METHODS

Although no one method which would fit the bill exists at present, a marriage of two existing techniques (sparse array acoustic monitoring and guided-wave inspection) holds promise. A joint research programme has been proposed to the EPSRC by Imperial College and Bristol University, in which Mecon will participate if the proposal is successful.

5.6 POINT TESTING METHODS

These would be feasible if they could be delivered by a crawler robot adapted to cope with reinforcing ribs or an ROV with very good positioning capabilities. However the industry does not appear to be receptive to the idea of robotic devices operating inside tanks.

5.7 OVERALL CONCLUSIONS

Our discussions with the industry suggest that, while cracking and corrosion are not spoken of as being major problems for FPSOs in general, there is sufficient interest to generate support for trials of promising methods. Trials of crack monitoring could be carried out on hull plates in the splash zone; corrosion monitoring could be tried out in slop tanks, where the presence of aggressive fluids makes it more likely to occur.

There are three methods which appear to be both technically feasible and potentially acceptable to the industry. These are:

1. Acoustic emission;
2. Transfer function measurement based on a sparse array of lamb-wave transducers;
3. Monitoring of localised modes of structural vibration.

The transducers to implement all three of these methods are available, at least in laboratory prototype form. None however has yet been applied to a problem equivalent to an FPSO outside the laboratory.

6 APPLICATION TO FPSOS: THEORETICAL CONSIDERATIONS

In this section we consider what the scale and complexity of a monitoring system based on each of our three chosen technologies is likely to be, and the fundamental limits to its effectiveness.

We have done this with two possible monitoring strategies in mind. The first, and theoretically preferred, option is to monitor all tanks equally. Because this may not be attractive in practice (owing to cost, complexity, reliability etc) we have also considered the theoretical implications of monitoring a selected subset of tanks for the complexity and effectiveness of the monitoring system. Note that we do not mean by this the probabilistic implications of monitoring a subset, which we take to be fairly obvious (i.e. if you monitor only say half the tanks then you run a finite risk that significant corrosion will occur in the unmonitored tanks even though you see none in the monitored ones). Rather we are addressing the impact on the monitoring of one tank of whether or not its neighbour is also monitored: since the tanks share bulkheads they are not independent structures, and as we shall, see their monitoring systems may not be independent either.

6.1 ACOUSTIC EMISSION

6.1.1 Monitoring Fatigue Cracking

As we have seen, industry is most likely to be interested in AE monitoring for fatigue cracking in the splash zone of the hull. Crack monitoring is the area in which acoustic emission as a technique has been most thoroughly investigated, and it should in theory be effective. The considerations are therefore mainly practical and are discussed in section 6.

6.1.2 Monitoring Corrosion

As discussed in section 3, corrosion in the floor of onshore storage tanks is monitored using AE sensors mounted on the outer wall of the tank. The main differences in the present application will be:

1. the level of general background noise will be much higher;
2. operations such as fluid pumping may be going on in the tank;
3. there may well be active fatigue cracking going on in the vicinity;
4. there may be fluid on both sides of the bulkheads on which the transducers could be mounted.

The effect of there being unwanted sources of noise (1-3) is difficult to predict. According to Physical Acoustics Ltd, it takes about an hour to make the measurements with their TankPac system for detecting corrosion in storage tanks. If it is possible to find quiet periods in which the competing noise sources are not operating then they need not affect the design or performance of the AE sensor array. This is discussed further in section 6.

If it is not possible to find quiet periods then the impact is likely to be considerable. If we ignore issues of spatial resolution (which we probably can because the signal bandwidths are of order 100kHz, giving a potential resolution of order 1cm) then discriminating corrosion from other, much louder sources of noise could potentially require a very large number of transducers. In the most general case, if there is no limit to the possible number of emitting sources (pumps and other machinery, fluid flowing through valves, cracks, and corrosion patches), then the number of transducers required will be of the order of the ratio of the power emitted by the loudest source to that emitted by the quietest (this is discussed in more detail in Appendix H); that is the square of the ratio of their amplitudes. For example, if fatigue cracking is forty times louder than the corrosion as stated in [32], then 1,600 sensors will be required to discriminate fatigue cracking from corrosion. Louder sources such as high pressure fluid flow may make the situation even worse.

However if we can put a limit on the number of sources that the sensor array is likely to have to resolve then its size can be reduced very substantially. Again speaking in general terms, if there will always be less than N sources then an array size of order a few times N sensors should be sufficient to discriminate them (Appendix H). The issue of what N should be assumed to be will be addressed in Section 6, but any reasonable finite number is clearly going to bring AE back within the bounds of possibility.

The AE transducers will most likely be deployed on the walls of crude oil tanks, below the normal surface level of the fluid. Point 4 in the list above arises because these bulkheads will divide the tank being monitored either from another crude oil tank or from a seawater ballast tank, either of which may well contain its own sources of acoustic emission, or provide an alternative propagation path for background noise. These sources will therefore also excite the wall-mounted sensors. This means that the adjoining tanks will themselves require arrays of AE sensors to discriminate these additional potential sources, and the arrays in the different tanks will need to share information on source positions and intensities. In effect, one very large array of sensors will be required to cover the entire set of tanks. Thus if there are M adjoining tanks being monitored for corrosion, an array of a few times M×N transducers will be required, resulting in a large and complex system.

One consequence of this is to make it much more difficult to apply AE to a few selected tanks. For each selected tank, extra transducers will have to be provided to discriminate sources of noise in adjoining tanks. The number of additional transducers is likely to be quite large: in for example a tank which has four adjoining tanks which may contain additional noise sources will require four times as many transducers (i.e. 4×N) to discriminate the potential extra noise sources.

6.1.3 Summary

From the theoretical perspective, there is no reason why AE should not be used to monitor splash-zone fatigue cracking of hull plates. It could also monitor progression of pitting corrosion in tank floors provided quiet periods of at least an hour can be found in which there are no competing noise sources. However, the total number of transducers needed for corrosion detection will be at least several times that used for a land based tank survey because adjoining tanks share bulkheads. If all tanks are monitored then the number of transducers <u>per tank</u> need not be greater. If however the operator cannot count on quiet periods, in which neither normal shipboard operations nor the effect of sea state on the structure are producing noise, then many more transducers will be required to discriminate these additional sources of noise.

6.2 SPARSE LAMB-WAVE TRANSDUCER ARRAYS

This technique relies on detecting small changes in structural-acoustic signals exchanged between a sparse array of transducers. The transducers are attached to the structural member (e.g. a tank floor) which is being monitored. As we have already seen, the technique would be a combination of existing techniques of guided-wave inspection with sparse-array monitoring.

The signals exchanged between the transducers may be tone-burst signals or broadband pulses. Tone-burst signals have the advantage of not suffering from the effects of dispersion (change of propagation velocity with frequency): they do not change shape as they propagate through the structure. Broadband pulses can convey more information but can suffer from dispersion depending on the frequency band they occupy. Dispersion makes interpretation more difficult, although it can also convey information on the distance that a pulse has travelled through the plate.

The choice of centre frequency of the signal will be a trade-off between a number of requirements. Higher frequency signals will have shorter structural wavelengths, and will be more strongly scattered by small areas of pitting corrosion or by pre-critical cracks, giving greater sensitivity to corrosion and cracking. On the other hand higher frequency signals may also be more strongly scattered by the stiffening ribs attached to the bulkheads and hull plates, and will attenuate more rapidly. In addition, the higher the frequency of the signal, the higher the number of Lamb wave modes that can propagate, each with a different velocity. This makes the location of any defects more complicated. A possible compromise would be to choose a signal with a wavelength equal to the typical size of the defect being monitored for. In the case of pitting corrosion, this sets a wavelength of around 8mm[8], which is less than the typical plate thickness of around 20mm. In the case of crack detection, a crack depth of 20% of plate thickness should be detectable, giving much the same wavelength.

Several different wave modes can propagate in plate-like structures at these wavelengths, and this allows some flexibility in the design of the transducer system. Longitudinal, quasi-plane waves (which are in phase across the plate thickness: so-called S0 waves) are non-dispersive over a wide range of frequencies, travel faster than other wave types, and are relatively easy to generate at low frequencies. Bending waves (A0) are also relatively easy to generate at low frequencies and also become non-dispersive at higher frequencies. So-called bouncing shear waves[9] are very good for crack detection and may also work for corrosion pits. However if fluid is in contact with one or both sides of the plate then all three of these modes will be attenuated by radiation into the fluid (intrinsic absorption by the steel itself will be relatively low: according to [53], attenuation is of the order of $50 \times \left(\frac{grain\,size}{wavelength} \right)^3$ dB/m, which for a wavelength of order 80 times the grain size gives negligible attenuation). There may also be a certain amount of energy absorption by the anti-corrosion coatings applied to the plates.

All of these modes will radiate energy into the surrounding fluid if the tank is full, but their attenuation rates will differ. Thus the choice of wave mode, and therefore transducer design, will also depend partly on whether monitoring can take place when there is no fluid on either side of the plate. If not, the radiation efficiency of different modes will also have to be taken into account.

Another important factor will be the presence of attachments to the plate. As we understand it, tank walls plates are typically stiffened by parallel ribs welded on at intervals of order 1m. Inevitably, waves propagating through the plate will be partially reflected by these ribs, and some of their energy will also be converted into other wave types. If the ribs are of the same order of thickness as the plate, this will lead to a significant loss of amplitude of the wave as it

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[8] *A corrosion pit is conical. The surface apparently reaches a diameter of about twice the plate thickness when it has penetrated the plate thickness. On this basis its diameter will reach 8mm when its depth is 20% of plate thickness. On the basis of the authors own experience with corrosion detection in metal, it rapidly becomes very difficult to detect defects shallower than this, and we suggest this as a realistic target for detection.*

[9] *Bouncing shear waves are easily generated and propagate by bouncing obliquely between the faces of the plate. They are strongly affected by near-face features such as part-thickness cracks. They are used by British Gas for cast iron pipe wall inspection and have been used by the author for water pipe inspection.*

passes the rib [54]. Some attenuation is unavoidable: although some wave modes may be less attenuated by ribs, they are likely to be higher-order modes that are not only more difficult to generate and detect but also less sensitive to cracks and corrosion.

It is obviously desirable to make transducer spacing as large as possible to minimise the total number. The factors discussed above place limitations on transducer spacing which it is difficult to quantify without knowing more about operational conditions. However it is likely that in the cross-rib direction (normal to the ribs), high signal attenuation will limit the spacing to a few times the rib spacing. In the along-rib direction the spacing may be much greater, depending on the factors already discussed. Insufficient information is available at present to make any firm decisions on spacing, but we suggest that an appropriate target to aim for would be a spacing of 2m in the cross-rib direction and 5m along-rib. For a typical tank floor this would require around 40 transducers.

For the system to show a high sensitivity to cracks or corrosion, it will need to detect small changes over time in the signals exchanged between the transducers. These will have to be discriminated from changes in signals caused by other factors. From the author s experience of sparse-array condition monitoring [43], [44], temperature variation is likely to be a significant factor, since it causes slight changes in the velocity of sound in steel (about 1% change for 55°C). Changes in static stress may also cause slight changes in sound velocity. The most obvious means of correcting for variations is to use the travel times between transducers (i.e. the time of the first arrival) to measure the sound speed. Other possible sources of change include changes in the condition of the coating (which it may however be desirable to detect).

6.3 LOCALISED MODES

Localised modes of tank walls and floors could mean either modes of the entire wall or floor, or more local modes defined by the spacing of the stiffening ribs, frames and stringers attached to the bulkheads and tank floors. Whole-wall modes are likely to be extremely insensitive to the development of individual cracks or corrosion pits and we will concentrate on the more localised modes of areas of plate between stiffening members. We will consider modes involving out-of-plane rather than in-plane vibrations, since as we saw in section 3.4 they are likely to be more sensitive to damage. Typically, ribs will be spaced about a metre apart; stiffening frames or stringers will be spaced around 4metres apart, and hull plates will be around 20mm thick. This implies modes with frequencies from around a hundred hertz upwards.

We will assume that the method would be implemented using background noise to excite the local modes, rather than using artificial excitation. This is feasible given the low modal frequency range: background noise in built-up systems is typically highest at low frequency. To provide exciters for each local area would require a very large increase in cost as well as a doubling the complexity of the system.

For a typical tank there will be of the order of a hundred such areas per wall (or floor). Thus even if the method can be made to operate with only one transducer per local area, the number of sensors required to monitor a single tank floor fully will be large.

To keep the number of sensors down to one per working area, the method will have to work by detecting shifts in modal frequency rather than changes in mode shape. As we saw in section 3.4 these shifts are typically very small for the levels of damage that a monitoring system would be expected to detect (i.e. well short of levels at which failure of a member, or loss of tank containment, would occur). Reference [25] reports a change of only 3.5% in the frequency of the fundamental mode of a submerged plate when a crack area reached 33% of the cross sectional area of the plate. Changes only become significant when the crack approaches full-width and the plate is about to fail.

To test the effect of pitting corrosion, we constructed a simple finite element model of a plate section using the FEMdesigner code. The plate was modelled as mild steel with a face area of 1m×4m and a thickness of 20mm, with its edges fixed in six degrees of freedom. 20,000 elements were used. The first 15 modes of vibration were analysed. The plate was then modified by altering a patch 100mm square, offset from the centre of the plate to avoid high-order symmetry effects. The patch had its stiffness reduced tenfold and its density reduced to 200 to represent a patch of corrosion product.

While we do not claim that this model accurately reflects the detailed dynamics of a corroded plate, we are confident that it is a good indicator of the scale of effect to be expected. Table 2 below compares the modal frequencies with and without the corrosion patch. The mode index is the numbers of antinodes along the long and short axes of the plate.

Table 2 Modal Frequency Shifts from Modelled Corrosion Pit

Mode no.	*Index*	*Freq(Hz)*	*After damage*	*% change*
1	1,1	136.91	137	0.07
2	2,1	143.54	143.65	0.08
3	3,1	156.1	156.06	-0.03
4	4,1	176.03	175.96	-0.04
5	5,1	204.35	204.19	-0.08
6	6,1	241.45	241.26	-0.08
7	7,1	287.33	287.12	-0.07
8	8,1	341.77	341.26	-0.15
9	1,2	373.18	372.8	-0.10
10	2,2	380.46	380.01	-0.12
11	3,2	393.06	392.97	-0.02
12	9,1	404.49	404.01	-0.12
13	4,2	411.58	411.35	-0.06
14	5,2	436.68	436.21	-0.11
15	6,2	468.98	468.71	-0.06

The changes in frequency are extremely small. In practice we believe that they would be impossible to detect, for two reasons. Firstly the background noise providing the excitation will not be white, but will be strongly coloured by the other areas of the structure through which it has passed to reach the subsystem being monitored. This coloration will change slightly with the state of the rest of the structure: changes in machinery operating condition; in static loading; in temperature, and in fluid content of tanks. These could cause apparent changes in the response spectrum that far exceed those actually due to corrosion.

Secondly the temperature and static loading of the subsystem itself will change with time. Temperature changes change the velocity of sound. In steel, this velocity change is approximately 1% per 55° C. Produced fluids may be at significantly higher temperatures than surface ambient temperature, and fluctuations exceeding 10°C are to be expected. These would produce shifts in resonant frequencies far greater than those shown in the table.

Thus we do not believe that local modes will provide a realistic means of detecting corrosion in tank walls and floors. They may however be capable of detecting cracking once it has occluded a significant proportion of the cross section of the plate (say around 20%),

7 APPLICATION TO FPSOS: PRACTICAL CONSIDERATIONS

7.1 ACOUSTIC EMISSION

7.1.1 Cracking

In section 5 we saw that AE could be used to monitor cracking in the splash zone of the hull. This could be done with transducers of conventional design, except that they would have to be waterproof because they would have to be mounted on the inside of the hull, which is typically a ballast tank. It should not be necessary to remove the anticorrosion coatings before attaching the sensors.

The main problem with monitoring large areas of the hull will be the number of transducers this requires. If say four transducers are deployed per square metre of hull plate, then monitoring a band say 5m high running the length of a single 20m tank would require 400 transducers; running 400 cables to a control room would obviously be problematic.

A possible answer to this problem in the longer term is fibre-optic strain sensors [55]. Many sensors may be incorporated into a single optical fibre, requiring only a single connection. There is no theoretical limit to the number of sensors on a single fibre other than the bandwidth that the fibre can carry, and this technology might well make the AE approach more practical for this application. However, although optical fibre strain measurement is well established and equipment is available for measuring strains at the micro-strain level, measuring the much smaller levels required for AE is still at the R&D stage.

7.1.2 Corrosion

The practical problems here include those for crack detection, but with the addition that the transducers must be intrinsically safe. We saw in section 6 that if AE monitoring can be carried out during periods when the structure is otherwise quiet (i.e. no sea-state loading producing AE as a result of hull stresses; no machinery or processing noise), then the number of sensors needed to instrument a tank need not be larger than the number required for an onshore tank (we understand this is around 30 sensors). However, neighbouring tanks will also need to be instrumented because sensors mounted on a tank wall will receive AE signals from the tank on either side of it. Furthermore if the quiet-working condition cannot be met then the number of sensors in each tank may have to be increased significantly.

Again, fibre-optic sensors are a possible future solution to the problem of fitting and connecting large numbers of sensors. However the performance demands would be more stringent: the signals from corrosion are much smaller than those from cracking. As far as we know this level of performance is not yet available.

7.2 SPARSE LAMB-WAVE ARRAY

The main practical problem, as with AE, is likely to be attaching the transducers to the plating and routing cables to the control centre.

The transducers can probably be attached to existing coatings. It is likely that the devices will be piezoelectric, operating below a megahertz, so that a 1mm covering of epoxy over a 20mm steel plate will have very little effect. This would also reduce the risk of coating damage.

Unlike AE, optical cable sensors are not an option because the transducers must transmit acoustic signals as well as detect them. The number of cables could nevertheless be radically reduced by using a bus system in which many transducers are fed via one cable. This would require transducers to have some local intelligence and storage. Transducers would need to be addressable so that each could be programmed individually. A monitoring cycle would then consist of a sequence of firing cycles: during each firing cycle, one transducer is addressed and set to transmit , while other transducers in its vicinity are set to receive . A go command is then issued; the chosen transducer transmits, and all selected transducers (including the transmitter) record the signals they receive in response. Each transducer is then addressed in turn and its data transferred to the control centre. This firing cycle is repeated for each transducer in turn until the monitoring cycle is complete.

Building this sort of capability into a small transducer is no longer difficult. Mecon Ltd has for example built a complete sensing, processing, storage, power supply and download system into a miniature hand-arm vibration dosimeter that fits between a workman s fingers inside his work glove without causing any discomfort or obstruction. The required miniaturised, low voltage, ultra-low power electronics is readily available and is now very cheap. For sparse array transducers, all that would be required would be a microcontroller, a small amount of RAM and possibly a small rechargeable battery. It can be made intrinsically safe.

7.3 LOCAL MODES

As with both AE and sparse arrays, the number of transducers is likely to be large: perhaps 100 transducers for a typical crude oil tank floor. As with AE, these could eventually be optical fibre strain sensors, attached to the floor to measure the strain associated with vibration, possibly requiring just a single optical cable running out of the tank. Alternatively the scheme put forward for sparse arrays (section 7.2), with many electromechanical sensors attached to a single bus cable, could be used.

In contrast to the AE approach for corrosion, the technique would need to be used when there is a high level of background noise. It would preferably be activated when the tank is empty. Neither of these conditions is likely to cause a problem to operators.

8 APPLICATION TO FPSOS: CONCLUSIONS

Despite its attractive simplicity, we cannot recommend pursuing the method of monitoring localised mode frequencies because of its insensitivity to low levels of damage. While it could certainly detect high levels of fatigue damage, the structure would by then be so close to an unacceptable structural failure that the method would be of little use. It would be incapable of picking up an individual corrosion pit in a tank floor.

Acoustic emission (AE) appears to offer a viable means of monitoring fatigue damage. However in order to cover significant areas of the hull, present techniques would require large numbers of transducers and large amounts of cabling. Operators are unlikely to find this attractive. Future developments may make it possible to integrate large numbers of transducers into a single optical fibre, requiring only one (non-electrical) connection, which would largely overcome this problem. Such a development could well help the technique to overcome its image in the offshore industry of being expensive to deploy.

AE is less attractive for detecting corrosion in FPSO tanks. The tanks share walls, which means that for complete effectiveness the tank system would have to be monitored as a whole, leading to a very large and complex system. Monitoring could only take place in conditions of complete quiet: sea state zero, no machinery operating, and no movement of fluids taking place. While this can no doubt be arranged, it will interfere with normal operations and would thus count against the technique. It is unlikely that fibre optic sensors could be used because of the low level of the signals.

Sparse array monitoring would be effective for both cracks and corrosion, but it would require about forty transducers per tank floor. However there appears to be no reason why the number of electrical connections could not be kept small by attaching the transducers to a single bus cable. The system could be retrofitted and once in place could be entirely automatic. However, application of the sparse array technique to structural monitoring is still a research area and is probably a few years away from deployment offshore.

9 OVERALL CONCLUSIONS

Our consultations strongly suggest that the industry owners, operators, insurers and inspectors would support the development of monitoring systems for cracking and corrosion. These systems would serve to give warning of early deterioration due to defects in design or build within the first few years in service, which are fairly common in current designs of FPSO in the UKCS, as well as supporting the maximisation of service life.

The monitoring methods that appear from the literature to be the best candidates for this application are:

- acoustic emission ;
- sparse array lamb wave monitoring ;
- local mode monitoring.

Further investigation of theoretical and practical considerations shows that the third of these methods is insensitive to pitting corrosion and pre-critical cracking and hence will not be very useful.

Acoustic emission should be effective for detecting fatigue cracking in hull plates. It will however require large numbers of transducers. It would be much cheaper and easier to apply if optical fibre sensors were used in place of the present piezoelectric transducers, but this appears to be some way off. It is likely to be much more difficult to apply to corrosion detection.

The sparse-array monitoring method could be applied to either cracking or pitting corrosion. Although the basic technologies for this technique are available, it is still very much a development area. Like acoustic emission it will require large numbers of transducers. Although optical fibre transducers could not be used, large numbers of transducers can probably be attached to a single bus cable, so that only a single connecting cable need be run into a tank.

10 RECOMMENDATIONS

We recommend that a trial of acoustic emission should be carried out, aimed at detecting fatigue cracking in hull plates in the splash zone. The trial should be targeted at an area thought to be at maximum risk from fatigue loading. It will be necessary to develop immersible sensors, since they will be attached to the inside of the hull plates in what is normally a seawater ballast tank. In the longer term, fibre optic sensors may offer a route to a reduction in the cost of the transducer fit, and a radical reduction in the number of connections required.

For corrosion detection we recommend developing a sparse lamb wave array, in which transducers are attached to a tank wall or floor at intervals of several metres. Using a bus system to connect the transducers would allow a trial system to be established on a single cable. A slop tank might provide a good test site for such a system: slop tanks frequently suffer from corrosion, they are less critical to FPSO performance than the main cargo tanks, and they are more easily accessible.

11 APPENDIX A

FPSO Corrosion Monitoring
Interview with a Class Society s Inspector

15th July 2004

The class society inspector was happy to provide the author with a thumbnail sketch of his Society s view of the position with respect to inspection of FPSOs in the UKCS area. However, given the complexity of the subject, he did not regard this as suitable for publication. His view was that a more thorough consultation would be needed in order to achieve a coherent, publishable account.

12 APPENDIX B

FPSO Corrosion Monitoring
Interview with a Class Society Technical Specialist

15th July 2004

The specialist emphasised the class society s interest in the area of AE. It can be used for monitoring fatigue and stress corrosion cracking (SCC), which is hard to spot by other means. The dominant acoustic emission needs to be from active crack growth to ensure detectability. AE signals can be correlated with the extent and rate of crack growth.

The class society saw AE as a long-term global monitoring tool for safety-critical locations rather than for inspection or spot checks. The duration of the monitoring period required to detect crack growth can be predicted from a physical model of the acoustic emission process but the monitoring period would normally be at least a month for SCC or fatigue. Acoustic emission does provide a reliable means of detecting crack growth where the crack is actively growing and as such could be used to detect fatigue crack growth in FPSO hulls.

The specialist was not sure how effective AE would be for single overload tests (e.g. detecting flaws in pressure vessels during pressure a overload test). Because of the Kaiser effect[10] AE levels would not be very high unless loading significantly exceeded levels previously experienced by the structure. It is also uncertain whether a single overload would result in the crack growth required to ensure detection, using over pressurisations of 10%. Moreover the issue of silent cracks means that in practice flaws may be present but remain undetectable during a single overload test. This is less of an issue for long term monitoring.

The specialist was also dubious about using AE for the detection and location of corrosion on an FPSO (e.g. using Physical Acoustics tank-monitoring system TankPAC), because of the high levels of background noise. However he referred to a BRITE-EURAM project which had claimed success in localising corrosion damage on shore based tank systems (with presumably lower levels of background noise)..

[10] *Wilhelm Kaiser showed in the 1950s that a cyclically-loaded sample of material only produces AE significantly when loaded beyond the level at which it emitted previously. AE from a repetitive load cycle would therefore decrease rapidly.*

13 APPENDIX C

FPSO Corrosion Monitoring
Operator Interview: Discussion with a Naval Architect responsible for an operating FPSO, 15th July 2004

The objective of the discussion was to get an operator s point of view on the priorities for monitoring the structural condition of FPSOs. Our conversation was referred mainly to the FPSO for which the interviewee had responsibility (hereinafter FPSO 1). Cracks have been found is some parts of his vessel s hull structure.

The interviewee said that experience with FPSO 1 had not put the operator off, rather the reverse. As with tankers, the operator s intention is to manage the risk of mishaps by ensuring it has direct control of inspection & maintenance. It will therefore continue to manage FPSOs directly and to take a direct interest in the design and build of new vessels.

The interviewee pointed out that FPSOs fall betwixt and between fixed offshore installations and tankers. Some operators choose to have them classed as tankers (which means that there is a prescribed system of inspection & maintenance) whereas others choose to have them regarded as installations. In the UKCS area this means that the HSE requires the operator to identify safety-critical elements and define performance standards. These must be supported by an appropriate inspection and verification regime. From the operator s point of view the choice depends on the reason for using an FPSO rather than a fixed structure. If the FPSO is there because the producing life of the field is expected to be short (say 5-10 years), then the FPSO can be dry-docked when it comes off station, and tanker classification is appropriate. If the FPSO is there because the water is too deep for a fixed structure, and it is likely to be on-station for all of its working life, then it makes more sense to treat it as an installation.

Some operators choose to self-insure their FPSOs. This apparently removes any need to classify it.

Turning to the subject of monitoring, in the interviewee s opinion operators are likely to be more interested in corrosion monitoring than cracking (leaving aside the specific case of FPSO 1). FPSOs are built like tankers: they are made from low-grade steel using low-grade fillet welding, with a high degree of structural redundancy (in sharp contrast to say submarine hulls which are built using high-grade steel and extremely high construction standards, and are consequently astronomically expensive). This means that cracks can be expected and are not regarded as significant until they have reached an extent that is immediately obvious from close visual inspection.

Corrosion occurs mainly in the floor of the crude oil tanks because this is where the produced-water content of the crude collects. Produced water typically has a high dissolved-salts content making it corrosive. It causes pitting corrosion: finger-shaped penetrations of corrosion into the steel floor. The epoxy paint layers applied to the steel are generally expected to maintain their integrity for at least ten years. Some localised coating breakdown can be expected after 5-10 years, particularly if solids build up in the tank. Once breached, it may take a further five to ten years for through-thickness pits to develop.

The conventional method of inspection is to drain down a tank, flush and purge it. Visual inspection is then carried out, using squeegees to clean the floor and locate ruptures in the coating. A pit is easily recognised. It is treated by grinding a patch around it down to bright steel and then re-painting. On FPSO 1 there is a rolling programme of inspection in which pairs of tanks are taken out of production for a period of order two weeks. This does not cause major disruption; it merely reduces the storage capacity by one seventh, meaning that tanker visits need to be slightly more frequent.

In areas where crude is sour , sulphate-producing bacteria can colonise a tank and produce accelerated corrosion, and condensation of sulphurous acid can corrode the tank roof. This is a problem in the Middle East but not in the UKCS area.

We discussed possible automated means of inspection or monitoring. Magnetic crawlers are available to inspect hulls externally in dry-dock. This approach would not find ready acceptance: the interviewee referred both to spark risk and to the possibility of a robot dropping components into the tank which could then foul the cargo pumps. In addition there would be the difficulty of the many ribs, stringers, frames and other stiffeners that festoon walls and floors of FPSO tanks. These would not be easy for a crawler to negotiate.

Another alternative is acoustic emission. I relayed one technology supplier s statements that a maximum of 12 sensors per tank would allow cracks to be located, and that active corrosion could be detected as well, provided background noise were low enough. This depends on using vibration sensors mounted on bulkheads to pick up fluid-borne noise[11]. I quoted the provider s very rough and ready estimate of the equipment cost for a vessel the size of FPSO 1 (£300,000) and the interviewee did not regard this as too high to be entertained.

I am myself a little sceptical of that figure because it relies on the provider s idea of sharing sensors between tanks to reduce the number of channels. I think that, since signals are likely to be obtained from all tanks at once, the full complement of 12 per tank will be needed in order to be able to tell which tank a given signal came from. All the more so if we try to locate corrosion.

Otherwise we are probably looking at using guided structural waves to obtain reflections from pits. The interviewee said that the system would need to see pits before they reach 30% of wall thickness to be useful. Ideally therefore we need a wave mode that looks like a Rayleigh wave, i.e. one that produces plenty of motion near the plate surface. It will also need to be pretty high frequency to see something that small. Unfortunately we then run into problems with scattering from ribs etc, with fillet welds in unpredictable conditions. This will produce large scattering and reverberation and prevent the energy travelling very far. It will also probably detect cracks in the fillet welds much better than it detects pitting. It would certainly have to be used in time-lapse mode (i.e. looking at changes in the pulse-echo signal at a fixed transducer over time). Thus it would require many transducers.

The interviewee suggested that the way to try out a monitoring system would be to install it in a slop tank. These are much smaller than the CTs (on FPSO 1 they measure 5×17m) and hold oil and water mixtures which may sit there for months, making bacterial corrosion much more likely. It could even be done on a tanker so that it can be fitted in dry-dock; this would make fitting much easier and cheaper than trying to do it on an FPSO on station.

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[11] *See Appendix D.*

14 APPENDIX D

FPSO Corrosion Monitoring
Operator Interview: Discussion with Operator 2,
20th July 2004

This operator designs, builds and operates many FPSOs. From what the interviewee says, it would be more accurate to say that they specify the size they want, and select a shipyard which then builds an FPSO hull according to the yard s standard design. The operator then takes this hull to another yard to have the hull outfitted as a FPSO. The outfitting is specified by the operator. For example, a so-called lifetime extension programme is specified to improve the fatigue life of the structural details. The reason for doing this is that it is cheaper and easier to modify details at the outfitting yard, than having a yard vary its standard design according to customer specification.

Currently, the operator runs most of its FPSOs in the UKCS area. Typically they are on station for at least five years. When an FPSO comes off station it is given a dry-dock refurbishment, which includes renewing anti-fouling treatments, and a full internal tank inspection. Internal coatings are not renewed unless defective.

The operator has a clear policy on lines of defence against degradation of FPSO structure:

1. Coatings applied at time of construction.
2. Cathodic protection.
3. Inspection.

Coatings are designed for a 15-years+ life, and provided they are correctly applied they are expected to last this long. In one case however, incorrect application by the shipyard caused wholesale failure after only 7 years service. Main cause of this failure was chloride pollution below the coating. Epoxy coatings seem to be especially vulnerable to this type of pollution. In general high quality coatings only fail locally ; these defects are picked up by scheduled inspections and are straightforward to repair. Failure usually occurs around welds and in corners places where the coating is most likely to be faulty.

The interviewee suggests the seawater ballast tanks (BTs) are not difficult to inspect since there is no great problem to access them. The main method of inspection is simply visual inspection and the extent of anode consumption. This gives a good measure of coating integrity, and plenty of advance warning of possible corrosion if the coating is breached. The operator has not experienced problems and the interviewee sees no need to continuously monitor BTs for corrosion.

Cargo tanks (CTs) do have cathodic protection only in the bottom part. They are inspected on a five-year cycle. This inspection regime normally does not cause any interruption to production. The interviewee does not think that corrosion is a problem here either. The only places it could occur are the bottom and the deck head. The tank bottom is without stiffeners (all the operator s FPSOs are double hulled and the stiffeners are on the underside of the CT bottom) so the plating is easy to inspect. It is always coated. In cases where the deck head is not coated, deck head corrosion has been slow (<0.1mm over seven years in one vessel). However, it is preferred to have the deck heads coated.

Slop tank coatings are vulnerable for coating failures and do corrode. They are usually warm and can contain sand (which provides a breeding ground for sulphate producing bacteria) and acid produced water (which contains aggressive chemicals). However, when appropriate coating systems (which differ from the slop tank coatings in as applied in trading tankers) are applied, there is no particular problem.

Thus overall, the interviewee is not very interested in continuously corrosion monitoring. The only application that could conceivably be of interest would be deck head corrosion over long periods of time. If the classification societies were persuaded that continuous monitoring may be substituted for inspections, his opinion could change.

Fatigue damage is another matter. All tanker-type hull structures crack; there is a lot of attention paid to structural integrity from this point of view. Of particular interest to the operator is side shell fatigue, caused by wave pressure fluctuations on the vessel sides. There is an ongoing monitoring project in which the operator, Delft University of Technology, Marin and DNV participate to measure structural response and loading, for predicting remaining fatigue life (the study is linked to a JIP on FPSO structural integrity). This prediction appears to be difficult, because predicted fatigue life is extremely sensitive to wave loading.

The accuracy of fatigue life prediction could be considerably enhanced if it were possible to continuously monitor the initiation and growth of cracks in critical areas. The interviewee is interested in this type of monitoring. One FPSO is due to go into dry dock in a few years time, and the interviewee said it would be conceivable to fit an experimental monitoring system then. He was not suggesting that the operator would pay: that would most likely require a JIP to be set up. The FPSO is presently moored at a position where sea conditions are much more likely to lead to fatigue induced damage than in the North Sea. This would obviously make it a good subject for an accelerated trial.

15 APPENDIX E

FPSO Corrosion Monitoring
Operator Interview: Discussion with an FPSO research engineer, 28th June 2004

The objective of the discussion was to get an operator s point of view on the priorities for monitoring the structural condition of FPSOs. Our conversation was referred mainly to an FPSO designed and built for purpose. This has been found to have cracking in parts of the hull structure.

The research engineer was very interested in the possibility of introducing monitoring technologies that do not involve an FPSO in being taken partly or wholly out of service during the inspection process. He explained that on FPSO 4, inspection is carried out as a rolling programme with a two-year cycle (inspection interval varies with tanks and components 2 years is order of magnitude for crude tanks). Tanks were inspected as transverse pairs, i.e. the two cargo tanks in one section are inspected together. This is a lengthy process taking one to two weeks per section, involving draining, purging and washing out the tanks. It does not prevent the remainder of the tanks being used, but it can slow down the rate of processing.

FPSO 4 has a 25-year design life. It is not planned to take it off-station during this time.

The research engineer explained that tanks are lined with an epoxy coating that has had no problems as far as he is aware (i.e. it has maintained its integrity and there are no signs of water ingress or corrosion under the coating). The water ballast tanks (BTs), which lie between the crude oil tanks (CTs) and the sides of the hull, are entirely coated. The CTs have their floors and ceilings coated, but the walls are only coated for 2m above the floor and below the ceiling. Corrosion is not expected to be a problem between these zones because the water content of the crude is very low, certainly less than 1%.

The design of the coating is intended to maintain full integrity for the full service life. Performance is monitored closely, since experience with FPSO and Tanker tank coatings indicate potential for some breakdown after 15 years of service.

I described the main categories of acoustic technique that could conceivably be used. These include:

Global structural modes: likely to be insensitive to local damage;

Local structural modes: likely to be more sensitive, but the variation of fluid loading as tanks are filled or emptied may cause too much disturbance to mode shapes and frequencies;

Statistical Energy Analysis (SEA): might work well for detecting the weakening of say a weld seam between plates by corrosion, but not so good for detecting isolated patches of corrosion.

Acoustic Emission: not enough known yet to predict capabilities.

Transfer function methods: this is a generic term for methods in which the structure, or a part of it, is excited at one or more points, and its response is measured at one or more points. Generally speaking the sensitivity of the method increases with the number of transducers deployed. It covers a huge number of sensor technologies, including so-called guided waves (signals generally between 20kHz and 100kHz that use the plate as a waveguide). The trade-off between cost and sensitivity will have to be explored for the more promising technologies.

The research engineer s main comments were firstly that there would probably be reluctance to see sensors sited inside tanks. This would be the case even if (as I suggested) the sensors could be rendered wireless, by using infra-red or radio transmission to communicate between them, and powered by scavenging energy from structural vibrations. He asked whether they could be placed on the deck plates immediately above the bulkheads instead (unlikely).

Secondly he pointed out that the tank structures are complex because of the large number of frames, decks, stringers and ribs that are installed to stiffen the hull, bulkheads, and hull plates. These are necessary because of the varying hull loads resulting from wave and tank-contents loading as well as from large hydrostatic loads that result when one tank is empty and the next is full. Would this lead to a requirement for larger numbers of sensors?

I replied that this would require some thought. The complexity on FPSO 4 is certainly high: a transverse bulkhead has well over a dozen vertical ribs and several horizontal stringers within each CT; each section has several internal frames; longitudinal bulkheads have more than two dozen longitudinal ribs in addition to several decks.

16 APPENDIX F

FPSO Corrosion Monitoring
Interview with a Trials & Monitoring expert
20th July 2004

The expert has experience of measuring strain and motion on FPSO and tanker structures.

His employers have been involved in FPSO JIPs for several years. The expert has been involved in instrumentation projects directly.

The expert s view was that corrosion is not an issue for FPSOs in which coatings have been properly applied. He said this depends on the priorities of the company that controls the construction: one company known to us both sets high standards and generally does not experience problems. Some companies, he hinted, are not as careful.

The expert was much more concerned about structural stress and fatigue. Tankers and FPSOs are not built to the high standards of say jacket structures, which have little structural redundancy and cannot tolerate significant fatigue damage. FPSOs and tankers are built with high levels of structural redundancy and are built to standard designs using low-grade materials and techniques. Consequently they emerge from the shipyard with significant levels of misalignment and residual stress. This necessitates a shakedown period: after launch, the vessel should be subjected to moderate sea loads without any cargo loading. This allows stresses to be relieved via plastic yield near welds. If this is not done the structure can fail long before it reaches its design life; indeed ships occasionally collapse on launch. Once past this stage, however, an FPSO can suffer a great deal of fatigue damage without becoming unseaworthy.

Much larger vessels are planned, up to 400m long, to handle LNG. The reason for the large size is the high stability requirements for LNG carriers: bigger vessels will respond less to wave motion. The potential problems with structural stresses will increase. So presumably will the potential for fatigue.

The expert is therefore interested in the possibility of monitoring crack initiation and growth. He is acquainted with acoustic emission techniques through Lloyd s Register s work in this area. He believes that the constant high level of background noise on board an FPSO is likely to be an issue, although I suggested it may be possible to separate crack emissions from machinery noise because it has a much higher bandwidth, and by using array beam-steering techniques. However we agreed that noise from high pressure fluid flow through valves may be a particular problem.

The expert is sceptical of the idea of restricting monitoring to critical areas of an FPSO structure. He believes that the high level of structural redundancy means that criticality is distributed over the entire vessel. In his opinion this would be a problem for acoustic emission methods, which usually require several sensors to be within a metre or two of an active crack to give accurate results, as in the Bruce project being run by Physical Acoustics. I explained one technology provider s system to detect and monitor active corrosion growth. The approach is based on vibration sensors attached to the outer wall of a land-based storage tank. These detect sound transmitted from the corrosion through the fluid. An analogous system might use sensors on the walls of a CT or BT to monitor crack growth. The expert was interested, but we agreed that the issue of background noise levels would be critical.

The expert outlined a few of the changes he would like to see made to FPSO design. One would be to place stiffening frames, stringers and ribs <u>above</u> the deck-head plates. This would (as a by-product) make tank inspection easier. He also mentioned changes to bow and hull shape which would not make any substantial difference to monitoring systems.

17 APPENDIX G

FPSO Corrosion Monitoring
Naval Architect Interview: Discussion with a marine consultant, 30th June 2004

The objective of the discussion was to get a designer s point of view on the priorities for monitoring the structural condition of FPSOs.

The naval architect s view was that, as far as monitoring the hull and bulkheads is concerned, a significant concern is likely to be pitting corrosion. This is most likely to occur in the tank floors, which will typically be 18mm thick. He would expect a patch of corrosion to be at least 40mm across. They are produced by sulphide-reducing bacteria which can develop damaging acids. He does not share the confidence of those who believe that epoxy coatings will easily maintain their integrity for at least ten years. Local design is also important. For example on one FPSO main deck there is no camber and hence water collects which is causing early deterioration.

I asked about the possibility of stress-promoted corrosion at welds; the naval architect suggested we contact Lloyd s of London who would be more knowledgeable on the distribution of corrosion. Bluewater & SBM will be able to advise on deck & processing gear corrosion problems. There may also be further information in proceedings of IRR & IBC conferences on FPSOs.

The naval architect also believes that cracking is likely to be a significant problem on a large number of FPSOs. Their designs are often based on tankers (ULCCs or VLCCs), which can be overhauled every few years in dry-dock, and which frequently suffer from local cracking during trading. FPSOs will remain on station for decades and are likely to suffer worse problems.

There are also likely to be problems where process equipment (usually mounted 3m above deck) has not been mounted flexibly enough to avoid high stresses and fatiguing caused when the vessel flexes (because of the emptying & filling of tanks or of wave loading).

18 APPENDIX H

Using Acoustic Emission to monitor corrosion in crude oil tanks

The potential problem with this approach is that there are likely to be many noise sources. There may be many active cracks. There may be other, perhaps much louder sources of broadband noise such as fluids passing through valves at high pressure. All of these will be far louder than the level of emission produced by a growing corrosion pit.

This problem can be ameliorated by using an array of sensors which can be focussed on one source at a time. The simplest approach is to focus on all possible locations in turn, and identify the positions at which large signal amplitudes are found. However if the sources are of unpredictable magnitude this approach can require a very large number of sensors.

To estimate the number of sensors required, we will treat the AE signals as being very wide band, random and Gaussian. We will assume that signal amplitudes do not vary between different transducers. We will treat the focussing process as consisting of shifting the timing of the signals from different transducers to allow for the acoustic delay from the assumed source position. This is crude, but captures the essential physics behind the problem. To make any more refined analysis would go beyond the scope of this report[12].

Suppose there are M transducers and N noise sources, and that the signal $S_i(t)$ from transducer number *i* is made up of signals from the noise sources *n*, thus:

$$S_i(t) = \sum_{j=1}^{N} n_j(t - \Delta t_{ij})$$

where Δt_{ij} is the travel time to sensor *i* from source *j*.

The simplest approach search for the different sources is carried out by subtracting time delays from the signals S_i to correspond in turn to the travel times from all possible physical positions of the sources, and averaging them. When the delays correspond to the position of the first noise source for example, the signal P_1 obtained is:

$$\begin{aligned} P_1(t) &= \frac{1}{M}\sum_{i=1}^{M}\sum_{j=1}^{N} n_j(t - \Delta t_{ij} + \Delta t_{i1}) \\ &= n_1(t) + \frac{1}{M}\sum_{i=1}^{M}\sum_{j\neq 1}^{N} n_j(t - \Delta t_{ij} + \Delta t_{i1}) \end{aligned}$$

The signal contains the actual noise source at position 1, but it is inevitably contaminated by all the other noise signals, which contribute even though they are incorrectly focussed . The extent to which this interferes with source estimation can be measured by taking the variance of P_1, assuming that the timing errors Δt_{ij} are always longer than the coherence times of the signals n_{ij}:

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[12] *The problem is in some ways equivalent to seismic imaging, and in some ways to acoustic microscopy. Unlike either however it requires effective estimation of target strength and location both in the acoustic near field and in the far field, problems which are usually tackled in distinctly different ways. Some compromises are likely to be involved in finding a suitable imaging method. The proposed model is simple and crude but would probably be quite effective.*

$$\left\langle P_1^2 \right\rangle = \sigma_1^2 + \frac{1}{M}\sum_{j=1}^{N}\sigma_j^2$$

Thus the estimate of the strength of source 1 will be accurate only if the number of sensors obeys the inequality

$$M >> \frac{\sum_{j=1}^{N}\sigma_j^2}{\sigma_1^2}$$

In other words, the number of sensors must be much larger than the ratio of the total power of all other noise sources to the one currently being imaged.

If we apply this criterion first of all to the general case where we are trying to image an unknown number of corrosion sources in the presence of an unknown number of very much louder sources, it becomes clear that M may have to be very large indeed: at the very least we will need a number of sources equal to several times the ratio of the power of the loudest possible source to the quietest. If we have even a single crack emitting acoustically, this will require thousands of sensors.

A simple strategy for reducing this number is to locate the loudest source first, subtract its contribution from the signals of the array sensors, and then locate the loudest remaining source. This process is repeated until no more sources can be reliably discerned. Our criterion now merely requires that, at each estimation, the number of sensors is large compared to the ratio of the power of the remaining un-estimated sources to that of the source currently being imaged, which by definition is louder than any of them[13].

If we are able to make a reasonable a-priori estimate of the possible number of sources, then we should operate with an array several times larger than this. For example if we allow for say ten background sources (valve flow noise, active cracks etc) and another ten active patches of corrosion, then an array of order one hundred sensors should be sufficient to give useful estimates of source amplitudes and locations. This is obviously a large improvement on the simplest approach , but it depends heavily on our a-priori estimate of the number of noise sources.

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[13] The situation is in fact slightly more complicated than this because the estimate of the loudest source will be slightly contaminated by the other sources, and subtracting this estimate from the sensor signals will then slightly distort the estimate of the next source, and so on. In practice this will worsen the accuracy of the source estimates. However since the severity of the effect decreases with the number of sensors used, it is simply an additional reason for being conservative in estimating the number of sensors needed.

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