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Review of model testing requirements for FPSO's

Prepared by **BMT Fluid Mechanics Ltd**
for the Health and Safety Executive

OFFSHORE TECHNOLOGY REPORT

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EXECUTIVE SUMMARY

BMT Fluid Mechanics Limited (BMT) was commissioned by the UK Health & Safety Executive (HSE) to undertake a review of model testing requirements for FPSOs. BMT was specifically requested to:

- provide the HSE with an informed view on requirements for hydrodynamic and wind tunnel testing of FPSOs,
- identify key published papers relating to the model testing of FPSOs, and review salient conclusions, and
- discuss the role of model testing in the design and operation of FPSOs, the practical limitations of model testing, and the relative merits of numerical and physical modelling.

FPSOs are complicated dynamic systems which have complex responses to the metocean environment. Physical model tests usually play an important role in their design, though the analysis and interpretation of the results of such tests places increasing reliance on theoretical analyses and computer simulation. This tendency will become even more important as water depths increase and it becomes impossible to represent the entire FPSO, mooring system and risers in the model basin. Reliance will also have to be placed on ways of representing the deep parts of the system with passive or active equivalent components.

Key issues in the conclusions include the fact that there is usually no clearly identifiable worst case metocean condition in which to test an FPSO. Model test cases must therefore cover a broad range of conditions, and their results can normally only be interpreted for design with the help of a larger number of computer simulations which the model tests are used to calibrate.

The worst case design loads or motions for FPSOs will often be experienced in non-collinear metocean conditions, and extreme surge, sway and yaw responses are generally associated with low frequency oscillations of the vessel on its mooring system. Very long model test run durations (or assemblages of similar runs in different realisations of the environment) are therefore required in order to obtain reliable extreme values for design.

Viscous scale effects on the drag of mooring lines and risers can significantly increase the overall model mooring system damping, particularly in deep water. Unless steps are taken to counteract the effect (e.g. by reducing the diameter of the model mooring lines) this will result in reduced extreme excursions and non-conservative model test results.

Model tests for very deep water fields pose particular problems. It may be possible to develop ultra small scale model test procedures (say down to 1:200 scale) but in today's deepest existing and planned model basins this will still only represent a depth of about 2000m. Fields are planned in much deeper waters. Hybrid passive equivalent or active equivalent systems are the only practical way of performing model tests for such depths, and emphasise the inevitable increasing reliance on theoretical methods and computer simulation for these depths.

Turret moored FPSOs can be natural weathervaning or thruster-assisted. The former requires particular attention to be paid to the representation of realistic non-collinear environments, and careful selection of the turret location is an important design decision. Thruster-assisted systems offer the opportunity to place the turret much further aft, with the associated mooring and riser benefits, and it is easier to ensure that the FPSO takes an optimum heading to non-collinear metocean environments.

The potential for structural damage due to wave impact and green water on deck is now recognised as an important aspect of design for FPSOs operating in severe environments. Although a Joint Industry Project has done excellent experimental and theoretical work, this is at present confidential to the participants, and cannot yet be evaluated by industry as a whole. Consequently the methods for the prediction of such effects cannot yet be considered fully mature, and reliance must still be placed on model tests.

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Review of Model Testing Requirements for FPSOs

1. INTRODUCTION AND BACKGROUND

BMT Fluid Mechanics Limited (BMT) was commissioned by the UK Health & Safety Executive (HSE) to undertake a review of model testing requirements for Floating Production Storage and Off-loading Vessels (FPSOs). BMT was specifically requested to:

- provide the HSE with an informed view on requirements for hydrodynamic and wind tunnel testing of FPSOs,
- identify key published papers relating to the model testing of FPSOs, and review salient conclusions, and
- discuss the role of model testing in the design and operation of FPSOs, the practical limitations of model testing, and the relative merits of numerical and physical modelling.

This report describes the results from BMT's study, and is structured as follows:

- Section 2 discusses the features of FPSOs, why they have become a very popular oil production solution, and the general role of model testing in their design.
- Section 3 outlines the scaling laws that govern the various kinds of FPSO model test.
- Section 4 introduces the various issues which arise in the design and conduct of a model test of an FPSO, and some of the difficulties in interpretation of the results.
- Section 5 lists the main types of hydrodynamic model test which may be used to support the design of FPSOs. In each case the main objectives of the test, and a brief outline of the procedure is given. Section 6 provides similar information for wind tunnel tests.
- The main thrust of the report concerns ship-shaped FPSOs but Section 7 describes the other main types of floating production units, and suggests the main differences in model testing requirements.
- Section 8 contrasts the strengths and weaknesses of physical model tests versus computer simulations, and emphasises the important complementary nature of these activities, particularly as oil production moves into ever deeper waters.
- Section 9 discusses the role of full scale measurements in relation to model testing and numerical simulation.
- Finally Section 10 contains the conclusions drawn from the study, and summarises the key issues.

As part of an earlier review of stability criteria for jack-ups units in transit [1] [1], BMT carried out a review of model testing requirements and of available seakeeping model test data. This considered the role of wind tunnel tests, wave basin tests and full-scale measurements, and also discussed the complementary roles of numerical and physical modelling.

Many of the issues identified during the jack-up study are equally relevant to model testing of Floating Production Storage and Off-loading Vessels (FPSOs). There are also a number of issues more specific to FPSOs, however, such as the design of the mooring, riser and thruster systems, installation issues, exposure to very extreme sea conditions, green water loading on exposed production equipment, wave

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[1] *References may be found in Section 13 on page 65.*

motion effects on the performance of process plant, gas and smoke ventilation, hot gas exhausts and their effect on helicopter operations, and crew habitability issues.

For the purposes of this report an FPSO is considered to be generally ship or barge shaped, and the bulk of the report considers the model testing of these systems. However, Section 7 considers some of the additional model testing issues or changes of emphasis that relate to other competing designs for floating production.

2. MODEL TESTING OF FPSOS

2.1 A POPULAR OFFSHORE PRODUCTION SOLUTION

FPSOs have become a very popular offshore production solution in recent years, and have been installed in virtually every one of the world's offshore oil/gas regions. A notable exception is the Gulf of Mexico where the regulatory regime has yet to sanction the installation of such vessels owing to a perception that they pose a greater risk to the environment than other production solutions. D'Souza [2] reviews the history of FPSOs and then discusses the reasons why they have not been used to date in the Gulf of Mexico. It seems that the effective ban will be relaxed in the near future, and 'vessel-based production units' will be permitted, perhaps initially in the absence of significant on-board storage. An excellent summary of the regulatory regime for FPSOs on the UK continental shelf is given in [3].

The FPSO can be applied in a very wide range of water depths and across the full range of environmental conditions. Henery and Inglis [4] describe the main field characteristics that influence production concept selection for an oil field, and show why the FPSO is a very flexible and economic solution. However, whereas fixed platforms, tension leg platforms and spar buoys can generally utilise vertical or rigid risers with 'dry' trees on deck, the FPSO must make use of flexible riser technology and 'wet' trees on the seabed. Riser technology therefore needs to develop in step with the FPSO if it is not to constrain FPSO applications.

Ship-shaped FPSOs were selected for the first two developments West of Shetland, and [5] examines why. An overview of the concepts considered for the deep water harsh environment is made against the business objectives and reservoir conditions which are the primary drivers behind concept selection. The paper is an interesting insight into the way in which FPSOs were selected for these two fields, and how the other possibilities came to be rejected over an intensive period of scrutiny and analysis. Vessel motions and mooring forces were confirmed in tank tests as part of the concept selection process for the *Schiehallion* field in 375m of water [6]. The dimensions of the FPSO were determined to provide the storage capacity required but also to keep the motions as low as possible and to limit the amount of green water on deck.

FPSOs can be installed in new fields remarkably quickly, and [7] illustrates this point by describing the design and installation of the *Zafiro* FPSO. The project was accomplished in record time with installation occurring less than one year after the start of concept engineering and 18 months after the discovery of the field. This FPSO is spread-moored in 600ft of water offshore Equatorial Guinea, and the design was performed under such time pressure that physical model testing of the FPSO was rejected because model basin availability did not permit it in an appropriate time scale. Consequently, the design, which is in a relatively benign environment, was made 'more conservative'.

The major attraction of the FPSO is that it is a self contained production facility, with its own on-board crude storage, which, at the end of useful field life, can be relocated relatively easily to a new field. The concept also became popular because of the large number of VLCCs available for conversion to FPSOs (although many of these conversions turned out to take much longer, and cost much more, than had originally been anticipated).

Turret mooring systems are used in harsh environments. These permit the FPSO to weathervane, allowing it to turn into a favourable heading to the weather in order to reduce the mooring loads or the wave motions. Spread-moored systems are often employed in more benign environments. In these systems the vessel cannot change heading, and the mooring system is usually carefully aligned so that the environmental loads and motions for the prevailing weather are minimised. The design of such systems then often depends strongly on the severest weather conditions that might be experienced from unfavourable directions (i.e. on the beam or the quarter). There is also a class of spread-moored system which does have some ability to change the FPSO heading to align itself to the weather. One such 'differential compliance' mooring system is described in [8].

A number of 'disconnectable' FPSO mooring systems have been designed. These are seen as attractive solutions in areas where rare cyclones or hurricanes occur, and the non-cyclonic conditions are relatively benign. Other non-permanent types of FPSO include fully dynamically positioned systems such as *Seillean* [9]. These systems generally have to comply with regulations for ships as well as permanent installations, and conflicts between these requirements can cause difficulties.

2.2 THE ROLE OF MODEL TESTING IN FPSO DESIGN

FPSOs sometimes appear deceptively simple, being based on conventional ship-shaped hulls, with which there should be plenty of experience in design and construction. However, the reality is that the duty of the FPSO is completely different from that of the trading VLCC, and although the hull shape may be similar, an FPSO is in fact a very complex system.

Some of the features that make it complicated are:

- The vessel is permanently installed at a fixed location, and so must survive the worst weather at that location (though some systems, mostly in typhoon or iceberg areas, have been designed to disconnect in the worst weather conditions);
- Process equipment on deck is vulnerable to green water damage, with potentially dangerous consequences;
- Being ship-shaped, environmental forces and motions vary greatly depending on relative heading to the weather;
- The vessel will often change heading (weathervane) in order to face in a favourable direction to the weather (though some FPSOs are spread-moored in benign areas, and therefore cannot change heading);
- Weathervaning is often facilitated by a ‘turret’ mooring system, and the turret, which must resist all the mooring loads, becomes a key mechanical component in design, and a major cost driver;
- The FPSO motions and excursions are the controlling design parameters for the associated riser system;
- Natural weathervaning properties can be uncertain in complex non-collinear metocean environments;
- There may often be a compromise required in turret location between the requirement to provide reliable natural weathervaning, but at the same time minimise dynamic mooring loads and inertial loads at the turret;
- Thruster-assisted mooring systems are sometimes included to permit active heading control and to reduce mooring loads.

All the issues listed above are related to the way in which the FPSO interacts with the metocean environment, and not all of these may yet be reliably estimated by calculation or computer simulation. Physical model testing is therefore still an important aspect of FPSO design, and is called upon to deal with design concept issues, such as verifying the effectiveness of the hull form or the selected turret location, and detailed design issues, such as the anticipated bearing loads on the turret caused by the FPSO motions and the dynamic mooring loads.

It has been pointed out [10] that the role of model-testing in relation to numerical simulation has changed over the years. Twenty years ago mooring systems were optimised mainly by model testing, whereas now much of the optimisation of both the vessel and mooring system is performed on the computer. Model tests are now mainly used more for validation and confirmation of the design calculations. Huang and Judge [11] also discuss key factors in the design of turret mooring systems for FPSOs in harsh environments and the role of model testing in the design process. Dyer and Ahilan [12] provide a broad description of the model testing issues for moored floating structures, and draw attention to the fact that project design engineers do not always have sufficient appreciation of the strengths and weaknesses of physical model testing to take full advantage of it.

2.3 HYDRODYNAMIC MODEL TESTING

2.3.1 Wave Basin Tests

The design of a new FPSO often involves a programme of hydrodynamic model tests in a wave basin. These tests may have several distinct purposes, such as:

- To evaluate mooring, riser and vessel installation procedures, and to identify possible difficulties during the installation process;
- To assist with training of personnel involved with the installation;
- To verify the vessel's predicted motions in extreme and operational sea states, for use in assessments of mooring and thruster capability, human habitability, vessel operability and weather downtime;
- To identify any unexpected and non-linear aspects of the vessel's behaviour, which are not predicted by a theoretical seakeeping model;
- To verify extreme mooring line loads predicted using standard mooring design and analysis procedures;
- To verify or investigate the dynamic behaviour of the mooring and riser systems;
- To verify the predicted capability of the thruster system to maintain the heading of a turret-moored FPSO in extreme and operational sea conditions;
- To assess the occurrence and severity of green water on deck;
- To assess the severity of wave slamming on the vessel's bow;
- To verify the vessel's predicted accelerations, which are used as input to structural loading and fatigue analyses of both the hull structure, and the loading on items such as seafastenings, cranes and production equipment;
- To verify predicted forces on the mooring turret, and to identify any unexpected features of the loading;
- To evaluate the combined behaviour of the vessel and shuttle tanker in various operating scenarios, and the possibility of 'fishtailing' or other undesirable motions;
- To provide visual evidence of the behaviour of the vessel, mooring, riser and thruster systems, during both installation and operation.

The list of possible reasons for carrying out wave basin model testing is long. The multi-purpose nature of such tests, the costs of hiring large test facilities, and the technical limitations of all facilities sometimes lead to compromises being made in selecting the model scale and test conditions.

2.3.2 Other Hydrodynamic Tests

Towing tank tests (either with or without waves) are sometimes undertaken in order to evaluate towing and installation procedures, especially in situations where strong currents are possible. Vortex-induced motions and unstable behaviour sometimes develop in these circumstances. Towing tests allow tow loads and possible motion suppression strategies to be evaluated.

Uniform currents are sometimes simulated by towing the installation in still water. The flow quality is far more uniform and steady than can be achieved in a wave and current basin, but towing the model limits the duration of the test run, and wave conditions may vary between the beginning and end of the test.

FPSO models are sometimes towed at various headings through still water in order to measure current force coefficients, for input to mooring and thruster analyses (see Section 5.4). These coefficients may alternatively be obtained by wind tunnel tests on the underwater hull form (see Section 6.1).

Towing tests may also be undertaken in order to determine the effect of a current on thruster performance, and to quantify thruster/hull and thruster/thruster interactions (see Section 5.5). Tests with thrusters require an especially large model, in order to achieve reasonable scaling of the thruster performance. Tests in a cavitation tunnel may also be required in order to evaluate the performance of an individual thruster unit (though these specialised tests in support of propulsor design have not been covered here).

Tests on riser bundles are sometimes required in order to assess their dynamic behaviour during tow or installation, to assess interactions between risers in a bundle, and to assess the effectiveness of any vortex suppression devices that may be required. These tests may require a large-scale trial in order to represent the dynamic behaviour of a long riser at an adequate scale.

2.4 WIND TUNNEL TESTING

2.4.1 Wind Loading

Wind heeling moments on the FPSO's hull and superstructure are necessary input to a stability analysis. Wind forces and moments are also necessary inputs to analyses of the mooring and thruster systems. These forces and moments are sometimes estimated using standard calculation procedures, such as those defined by the certifying authorities and the International Maritime Organisation. These calculation procedures are of uncertain accuracy, however, and may not take adequate account of interactions between the many different structures on the deck of an FPSO. Wind tunnel tests provide more reliable estimates (see Section 6.1).

2.4.2 Ventilation, Environmental and Safety Studies

Wind tunnel tests may also be used, in conjunction with computational fluid dynamics (CFD) modelling, to assess ventilation problems on board an FPSO, and as an input to various environmental and safety case assessments. Tests of this type have been used to assess and optimise regions over the helideck which are affected by disturbed flow and by temperature rises due to turbine exhaust emissions. These tests have also been used to model gas releases, fire scenarios and to identify regions of poor ventilation (see Sections 6.2 - 6.5). CFD and wind tunnel techniques are now regarded as complementary capabilities (see Section 4.15).

3. SCALING LAWS

3.1 FROUDE'S LAW

Hydrodynamic model tests on FPSOs are usually performed according to Froude's scaling law. Froude's law ensures that the correct relationship is maintained between inertial and gravitational forces when the full-scale vessel is scaled down to model dimensions, and is therefore appropriate for model tests involving water waves. Gravitational and inertial forces normally dominate the loading on large-diameter fixed structures and ships (except for viscous roll damping forces), and Froude scaling is therefore generally adequate.

Froude's law requires the Froude Number, F_n, to be the same at model and full scales, where:

$$F_n = U / \sqrt{g L}$$

L and U are a characteristic length and velocity, and g is the acceleration due to gravity.

Geometrical scaling is normally employed throughout, in order to ensure that correct Froude Number scaling is applied to all components of the structure. This means that all lengths involved in a particular model test are scaled by the same factor. Thus if the water depth is represented at a scale of 1: *k*, then so too are the vessel's length, breadth and draught, also the wave height and wave length.

A water density correction factor is also normally applied. Model tests are normally performed in fresh water, whereas the full-scale structure will be used in salt water. The ratio between standard salt water density and fresh water density, *r*, is typically 1.025.

Table 3-1 shows how Froude's scaling law is applied in hydrodynamic model testing to various commonly used physical quantities. *k* is the scaling factor applied to lengths, and *r* is the ratio between salt water density and fresh water density. Scaling laws for other quantities may be found by combining relevant mass, length and time dimensions in the appropriate way.

Table 3-1: Froude scaling of various physical quantities.

Quantity	Typical units	Scaling parameter
Length	m	k
Time	s	$k^{½}$
Frequency	1/s	$k^{-½}$
Velocity	m/s	$k^{½}$
Acceleration	m/s^2	1
Volume	m^3	k^3
Water density	tonne/m^3	r
Mass	tonne	rk^3
Force	kN	rk^3
Moment	kNm	rk^4
Extension stiffness	kN/m	rk^2

3.2 REYNOLDS NUMBER

Froude's Law ensures that the same relationship is maintained between gravitational and inertial forces at model and full scales. Certain aspects of hydrodynamic model testing also require viscous forces to be modelled correctly. One well-known example of such forces has already been cited: the viscous roll damping moment on a ship. Viscous forces are also important when evaluating forces on slender tubular structures, such as those making up the framework of a jacket structure, risers and mooring lines. The Reynolds scaling law ensures that the correct relationship is maintained between inertial and viscous forces, and requires that the Reynolds Number, R_e, is the same at model and full scales:

$$R_e = UL / \nu$$

where L and U are the characteristic length and velocity, as before, and ν is the kinematic viscosity. Very different values of the Reynolds Number may apply to different components of a structure, and these often have to be considered separately.

The two parameters g and ν are the same (or almost so) at model and full scales. It is therefore impossible to achieve both Froude and Reynolds scaling simultaneously in a particular model test. Froude scaling requires the model velocity to vary with the square root of length, whereas Reynolds scaling requires an inverse relationship. A compromise therefore has to be adopted.

In circumstances where the free surface is irrelevant (e.g. when measuring current force coefficients, or wind forces), the tests are normally performed at as high a Reynolds Number as practical. This generally means performing tests on as large a model as possible, at as high a flow speed as is achievable. It is not normally possible to achieve exact Reynolds Number similarity, because of physical limitations on the model flow speed, and the model Reynolds Number is almost invariably less than at full scale.

In circumstances where gravity waves are important, the model tests are normally performed at the correct Froude Number. The Reynolds Number at model scale may then be several orders of magnitude too small.

Differences between model and full-scale Reynolds Numbers may not be particularly significant, however, provided certain conditions are fulfilled:

a) if the component in question has sharp edges at which flow separation occurs;

b) if the flow is naturally very turbulent (e.g. there are many tubular elements close together, or its surface is covered with large enough protrusions); or

c) the Reynolds Numbers at model and full-scale are both high enough.

Many research experiments have been performed, in many different model and test conditions, in order to help shed light on what is, and what is not, an adequate Reynolds Number for carrying out a particular test. Certain laboratories favour adding roughness elements or other turbulence stimulators to help stabilise the flow and better reproduce full-scale test conditions. Other laboratories adjust the diameters of certain members to correct for errors in drag coefficients. Other laboratories prefer to perform the tests on geometrically scaled members, and then estimate (or correct for) the errors afterwards using suitable numerical models. There is no single ‘correct’ answer to the Reynolds Number scaling problems, and the topic still provokes much controversy, even after many years of research. In many circumstances the best approach will often be to accept the scaling deficiencies, to assess the consequences, and then ensure that the expected inaccuracies are not crucial to the success or safety of the full-scale system (although this may become increasingly difficult to achieve in very deep water).

3.3 OTHER SCALING PARAMETERS

3.3.1 Vortex Shedding

Vortex shedding is a common phenomenon in flow around bluff bodies where instabilities in the wake flow result in the periodic creation and shedding of eddies or vortices. This gives rise to alternating forces on the body which are strongest in the direction transverse to the flow, but much weaker alternating forces in line with the flow are also present. A flexible structure with low damping will respond to this forcing, and such responses will clearly be largest when the excitation frequency corresponds with one of the natural modes of the flexible structure. 'Lock-on' then occurs, allowing the development of vortex-induced vibration (VIV).

In the context of floating production systems the VIV phenomenon is most important for relatively small cylindrical elements, such as risers, although it has also been observed on the much larger cylindrical hulls of spar buoys (see Section 7.4). VIV may sometimes be caused by high amplitude, long wavelength waves, but is more commonly caused by currents.

The frequency of shedding of complementary pairs of vortices is defined by the Strouhal Number:

$$S = f\,D / U$$

where D is the diameter of the body, U is the flow speed and f is the frequency of the eddy shedding. It should be noted that the larger oscillatory transverse force occurs at a frequency f, whilst the smaller in-line force occurs at a frequency $2f$. For a cylinder in a smooth flow the Strouhal number is virtually constant at a value 0.2 for Reynolds numbers less than about 4×10^5. Above $R_e = 4 \times 10^5$ the value of S can more than double before returning to 0.25 at about $R_e = 4 \times 10^6$. This peak in S (which is associated with a drop in drag coefficient) tends to occur at a lower R_e if there is turbulence in the onset flow.

Sometimes the reciprocal of the Strouhal Number is used, and is termed the Reduced Velocity V_r:

$$V_r = U / f\,D$$

This parameter is often used when the response of a cylinder or riser has to be plotted against a non-dimensional velocity.

If a model test is to correctly represent the forces and structural responses due to eddy shedding then it is clear that the relationship between the vortex shedding frequency and the model structural response frequencies must be maintained. If no other factors are of importance in the model test then the model designer has the freedom to choose model structural stiffness and mass, and hence response mode frequencies, and then select an appropriate model flow speed which preserves the correct frequency relationships. A further objective might be to try to get the Reynolds Number as close to prototype as possible by using a large model. This approach has been used on a number of occasions when testing sections of risers in isolation in towing tanks, water tunnels or water channels.

However, if the riser model is part of an FPSO system, or if there is concern about vortex shedding from the hull of a spar buoy (both of which tests must be performed under Froude scaling laws because of the importance of the waves in the overall response), then the frequency scaling factor has already been determined ($k^{-½}$), and the mass and stiffness of components such as risers have also been pre-determined. Furthermore the velocity of the current must scale as $k^{½}$. Fortunately it can be shown that inserting these scale factors into the Strouhal Number equation above results in a scaling of unity for this number, so Froude Number equivalence scaling will automatically result in the correct representation of S.

Concerns about Reynolds Number scale effects on drag coefficients and on S, and difficulties in manufacturing small scale riser models with the appropriate structural properties, will sometimes lead to the conclusion that it is best not to attempt to model vortex shedding on these components. From the global FPSO response point of view the high frequency excitation of the riser, though perhaps the key issue for riser fatigue life, does not much impinge on the FPSO performance itself. In these circumstances it is probably better to concentrate on making sure that the total drag of the riser, which contributes to the overall FPSO system damping, is correctly represented.

3.3.2 Surface Tension Effects

Surface tension forces are generally unimportant in most offshore engineering problems, and the associated potential scaling effects are normally ignored. In certain circumstances, however, surface tension effects may start to become important in very small scale model tests where they are not significant at full scale. This is one factor, for example, which ultimately limits the scale ratio that can be used when testing models for very deep water conditions.

The main potential influence of surface tension in model testing is the effect it has on the properties of small waves. When the waves become small enough the surface tension exerts a significant straightening effect on the surface of the water, which is sufficient to change the relationship between wavelength and phase velocity. It is as if the surface tension behaves as an additional gravity term in the wave equations [13]. This effect is generally considered to start to become important for waves with a wavelength less than 0.1m, and such waves are commonly referred to as ripples. If we assume that in full scale offshore applications we are seldom interested in waves with a period shorter than 4s, and hence a wavelength less than 25m, we can see that the effect is unlikely to be of importance in modelling the external wave environment until model scales reduce to about 1:250.

However, it is not only the incident waves in the model basin that should be considered. Surface tension has a quite visible effect on the appearance of spray and green water shipped by a model when compared with full scale. The generation of droplets of spray, and the size of these droplets is a function of surface tension (as well as the local wind conditions), and droplets of spray generated on a model will be much too large compared with full scale. Despite this, it is not generally thought that there is much influence on the flow of the bulk of the green water, which will be dominated by inertial forces providing wavelengths are greater than 0.1m. It is generally this green water flow, and the forces it generates, that are of primary interest in the model basin. Visually it may look rather different, because at full scale the view of the green water may be obscured by large clouds of fine spray. The surface texture of the ‘green water’ may also be very different, with much aeration (white water) on the surface.

Surface tension may also have an effect when there are flooded internal tanks or spaces in a model with dimensions significantly less than 0.1m. In such cases there is the possibility that flows and sloshing may have the wrong dynamic properties.

Potentially there may also be hydrostatic errors introduced by surface tension. This might occur on a very small model where the total linear length of surface interface is large compared with the water plane area (e.g. a small model of a jacket with many surface piercing tubular components). In such cases the model might float at too shallow a draught due to the surface tension effect. Such effects are relatively easy to calculate if there is any doubt.

It is possible to add chemicals to the water to reduce surface tension, but the authors are unaware of this having been done in any form of offshore hydrodynamic model testing. It may become a useful option if ultra small scale model tests become popular for the testing of ultra deep water systems.

3.3.3 Compressibility

Effects of water and air compressibility are not normally considered in offshore engineering, except when designing ships’ propellers and thrusters. Propeller and thruster design are specialist issues, that are normally considered only by manufacturers and specialist testing laboratories, and are considered to be outside the scope of this particular review study.

Air compressibility is nonetheless a factor limiting the maximum speed (hence the maximum Reynolds Number) that can be used in wind tunnel tests. Air entrapment and compressibility may also effect the very short-duration acoustic shock pulse sometimes seen in wave slamming or green water impact experiments. This pulse is usually of too short a duration to have any structural significance for the design.

4. FPSO MODEL TESTING ISSUES

4.1 GENERAL

The following subsections discuss the main FPSO model testing issues, and also make reference to a number of the publications identified during the literature review study. Sections 5 and 6 respectively outline the various different types of hydrodynamic and aerodynamic tests which are performed in support of FPSO design, summarise the objectives and outline the test procedures.

4.2 SELECTION OF TEST METOCEAN CONDITIONS

The complexity of the FPSO system (Section 2.2) means that it is not easy to determine which metocean conditions should be selected as an Ultimate Limit State (ULS) for design. Fixed platforms tend to experience the severest loading in the severest wave conditions, and so it became common practice to treat the 100 year or 50 year return period wave as the ULS. There was the problem of selecting the wind and current conditions that would be likely to accompany the 100 year wave, but the loading due to these other factors was usually far less important, and their selection did not much influence the outcome. It was also usually a conservative assumption to assume that all the environmental effects acted in the same direction (i.e. collinear).

For complicated dynamic floating systems such as FPSOs the situation is far less straightforward. As noted in Section 2.2, it is usually not the case that loading is completely dominated by waves, and the severest responses to waves may occur in smaller waves than the 100 year return condition due to dynamic response of the hull on its mooring system. This is further complicated by the fact that the severest response or loading may not occur in collinear metocean conditions [11]. This means that it is generally not possible at the outset to select metocean conditions for model testing that can be regarded as ULS conditions, and in reality there are an infinite number of possible combinations of waves, winds, current magnitudes and directions which will all give rise to the ULS. It is not practical to model test a large number of these different conditions. There are also practical model testing difficulties imposed by the limitations of model basins which also reduce the possibilities (e.g. the ability of the basin to reproduce current profiles, realistic wind conditions, or non-collinear conditions - see Sections 4.6 to 4.8).

A metocean condition can be described by the following parameters:

- Significant wave height,
- Wave zero crossing period,
- Wave spectrum shape (potentially bi-modal with both waves and swell),
- Wave primary direction,
- Wave directional spreading,
- Wind speed,
- Wind gust spectrum,
- Wind direction,
- Current speed,
- Current speed profile,
- Current direction (potentially varying with depth).

Clearly, the number of possible combinations in the selection of environmental conditions is infinite. The logical conclusion is that model tests alone cannot provide the reassurance that a given design is satisfactory. A much larger number of cases may need to be analysed than is practical to perform in the model basin, and this implies that model tests must be performed alongside analytical methods and computer simulations, although regulatory requirements have not yet fully embraced these issues. The results also need to be assessed by means of a response-based or reliability analysis methodology if the risk of failure is to be estimated [14]. The correct role for model tests in this is to provide validation or calibration points in the analysis. Use of response-based design methods may sometimes require tests to be performed over a wider range of environmental conditions than conventional design methods.

Aalbers [10] discussed the selection of wave, wind and current criteria, and pointed out that two different types of sea conditions normally have to be considered for a permanently moored vessel:

- Collinear wind, wave and current conditions, generally based on the 100-year significant wave height, 100-year 10-minute mean[2] wind speed, and 100-year tidal and wind-driven current. The tests should consider sea states with periods other than the most probable maximum from the (H_s , T_z) joint distribution;
- Non-collinear conditions, based on the same wave height, wind and current speeds, but from a range of alternative directions. Initial computer simulations can help with the selection of appropriate directional combinations.

Tests are also often performed in a range of less severe operational or ‘fatigue’ sea states. These may include conditions such as the one-year storm. These tests may be needed to help assess the performance of the FPSO with a shuttle tanker attached, the disconnect and reconnect limits for the shuttle tanker, operational limits for process equipment, or to provide input to a fatigue analysis. Model tests may also be needed to investigate sloshing inside partially filled cargo holds.

As an example, the various directional combinations of winds and waves used in the model testing of the *Balder* FPSO are shown in Table 4 of reference [17]. Selection of suitable environmental criteria, including joint statistics, directionality and directional spreading, wave/current interactions are also emphasised as key issues in FPSO model tests in [18].

The field location for the FPSO also has an important influence on the strategy for the selection of metocean conditions for model tests. Hurricanes, eddy currents and winter storms are key environmental parameters in the Gulf of Mexico [19], whereas the design event in the Northern North Sea is the winter storm [11].

Several papers have described response-based methodologies for analysing turret moored FPSOs. Such techniques offer a rational way to deal with the problem of having infinitely many possible metocean combinations that can potentially lead to a ULS condition. Standing et al. [20] pointed out that non-collinear metocean conditions can sometimes be more onerous than collinear conditions for FPSOs, but this depends on the metocean climate at the location. Other researchers have found that collinear metocean conditions represent a worst case for an FPSO [21], and that response-based design techniques can offer savings over procedures based on a collinear environment and/or simultaneous extremes of loading. Results presented in [21] showed that mean total forces from a response-based analysis were 2.4% less than were obtained in a collinear environment, and 3.7% less than were obtained by assuming concurrent and collinear maximum forces.

Steep waves of moderate height can also be more severe for the FPSO’s responses than very high waves [22, 23]. Further complications arise in the selection of metocean conditions if the FPSO has an asymmetric mooring system. For example the design of the *Schiehallion* FPSO mooring system takes advantage of much lower extreme metocean conditions anticipated to come from the East and South, but any such asymmetry in the design clearly makes it even more difficult to identify the combination of weather severity and weather direction that represents a worst case.

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[2] API Recommended Practice 2SK [15] states that the analysis should be performed in 100-year waves with associated wind and current, and in 100-year wind with associated waves and current. The DNV POSMOOR code [16] requires the analysis to be performed in 100-year wind and waves with a 10-year current, and in 10-year wind and waves with a 100-year current. The design is then based on whichever condition gives higher loads. It is nonetheless common industry practice to analyse moorings for a permanent FPSO using combined 100-year wind, waves and current conditions.

Different metocean conditions can also be critical for different design parameters. The excursions of the FPSO are often most sensitive to its low frequency response, and these excursions will tend to dominate the riser design. Mooring line tensions may also be sensitive to wave frequency responses, and the tensions are also likely to be more sensitive to the weather direction.

It is clear that, as in many other aspects of marine systems design, the issue of selecting the right metocean conditions for testing can only be dealt with properly with the help of computational techniques. A response-based design procedure, as described in [20] or [21], can help to identify a number of realistic critical ULS conditions for the FPSO, which, subject to the practical problems of reproduction in the model basin, can then be model tested. Confidence in this approach may be gained by comparing the model test results with those obtained from the theoretical model. Clearly, if there are significant differences between the measured and predicted results, then the process of selecting the ULS conditions is thrown into doubt, and should be repeated after adjustments have been made to the computational model to improve correlation.

Most metocean conditions used for testing and analysis will be steady state. That is to say: the conditions are considered to be stationary for the storm duration (commonly assumed to be 3 hours). Most response-based analysis methods also assume steady state responses, and do not consider the transition from one three hour period of storm state to the next. However, the weathervaning properties of FPSOs offer the possibility that rapidly changing conditions (particularly wind or current direction) could find the FPSO at an undesirable heading to the conditions [19]. This suggests that model tests should sometimes represent these transient conditions. In an early paper describing model tests to investigate the feasibility of thruster-assisted weathervaning, Pinkster and Nienhuis [24] discussed tests performed in irregular waves, wind and current, including a cross-sea condition, and the effects of a rapid change in wind direction. It is known that this last issue is a concern for those considering the design of FPSOs to operate in the Gulf of Mexico, where the passage of the eye of a hurricane can lead to a change from a severe wind in one direction through a brief period of calm to a severe wind in another direction [25].

It is sometimes necessary to reproduce a particular wave sequence in order to investigate a particular event. A report commissioned by HSE [26] identifies limit states related to FPSOs influenced by metocean parameters, the main objective being to determine whether the metocean parameters being measured today are adequate for floating structures, and whether additional metocean parameters are particularly important to FPSO design and operations. The report concludes that enhanced measurements of winds, waves and currents would be beneficial. This would include continuous recording of raw data to improve understanding of joint probabilities and to identify particular critical sequences of waves. It may well be important to be able to re-create such critical sequences of waves in the wave basin (see Section 4.5.2).

4.3 SELECTION OF MODEL SCALE

4.3.1 Basin Considerations

The key issue in the selection of an appropriate model scale for wave basin tests is the wave generator's capability in relation to the sea conditions that have to be modelled. The maximum wave height to be represented in the model test programme will often determine an upper limit for the model scale. The frequency bandwidth of the wave generator, and particularly the ability to generate high frequency or short wavelength waves, may also limit the choice of model scale. The mechanical and control properties of the wave generator always place a limit on the generation of high frequency waves, and so an irregular wave spectrum will always be truncated to some extent. The truncation tends to be worse the smaller the model. Waves in the high frequency tail of an irregular wave spectrum can be important for the correct modelling of wave drift forces and low frequency second-order responses. Wave generator calibrations prior to the tests should ensure that the appropriate spectrum shapes are being adequately represented.

The physical size of the model may also be a consideration, particularly for wave tests performed in relatively narrow towing tanks. It is sometimes convenient to perform wave drift force tests in such tanks, but if the length of an FPSO model is significant compared with the tank width, and if tests are performed at heading angles other than 90^{o}, then wave reflections can occur from the sides of the tank which reflect back onto the model and contaminate the drift force/moment measurements.

In general the larger the model with respect to the basin, the more likely wave reflections from the model are to contaminate the test results. This brings into consideration the effectiveness of the wave absorber (or 'beach') system, and the duration of runs required in order to obtain statistically significant results (see Section 4.9).

The ever increasing water depth of offshore exploration and development now means that basin depth is also often a limitation which may constrain the model scale selection. For model tests to derive seakeeping performance characteristics (RAOs), drift force coefficients, hull drag coefficients, or drag forces, it may be possible to show that the basin depth is not important (as long as it is deep enough to leave the waves unaffected, and current blockage small).

For tests on complete FPSO systems, including moorings and risers, it is preferable that the complete water depth is available in the basin. For deep water fields this may constrain the model to be very small, which in turn may lead to difficulties with high frequency wave generation (see above, and Section 3.3.2), problems with scale effects (see Section 4.4), and with accuracy of model construction, and measurement technology (see Section 4.10).

However, there are ways of avoiding this problem by testing in a shallower water depth using truncated models of mooring systems and risers, and active or passive 'hybrid' or 'equivalent' systems (see Sections 4.11.1 & 4.11.2 respectively).

4.3.2 FPSO Hull Model

The primary requirement for the FPSO model is that it should be an accurate dynamic model of the prototype. This means that it must have the correct hull shape so that hydrodynamic loads are properly represented at Froude scale, and it must also have the correct mass properties (CG location, and inertias). Models are normally constructed from wood, high density foam, GRP or other composites.

It is generally the case that the smaller the model, the more difficult it becomes to build it light enough to permit the addition of sufficient ballast to control the CG location and inertias. It also becomes more difficult to ensure that these properties are represented accurately enough.

A larger scale model may also have to be constructed if internal flooding spaces are to be modelled (e.g. to represent and investigate tank sloshing or other free surface effects), so as to avoid making the side walls disproportionately thick.

4.3.3 Mooring Systems

The important properties of the mooring system may be considered on two levels. Firstly there is the essential restraint which it exerts on the FPSO, and clearly this must be accurately modelled if the model test is to represent the FPSO's dynamic low frequency motions and excursions. Secondly there is the dynamic response of the mooring system itself to the waves, and to the wave frequency motions of the FPSO.

Catenary mooring systems are usually modelled by means of miniature chains or wires which are designed to provide the correct weight per unit length. If the geometry of the mooring system (including water depth) has been modelled to scale, then this will automatically result in the correct Froude scaled catenary mooring system stiffness, although it may also be necessary to ensure that the elastic properties are also correctly modelled [27, 28]. Thus the primary scaling requirement for the mooring system relates to the basin water depth, and also the need to ensure that the full scope of the catenaries can be included within the basin. If this is not possible, then alternative means must be found to represent the mooring system (see Section 4.10).

As well as restraining the FPSO with its stiffness, the mooring system also provides a source of surge/sway motion damping, which may be particularly important in deep water. There may be a need to adjust the dimensions of the mooring system to compensate for viscous scale effects (see Section 4.4.2).

It can normally be assumed that the wave frequency dynamic responses of the individual mooring lines do not influence the wave frequency motions of the FPSO (though it is clear that they can have a major effect on measured peak line tensions). If a test is only intended to measure FPSO excursions, then correct representation of these dynamic effects may not be required, but if line tensions are to be measured consideration should be given to the line dynamic response. A complete Froude scaled model of a catenary mooring line would exhibit the correct dynamic responses if it were not for viscous scale effects tending to increase damping. Friction with the seabed has also been identified as another potential source of error in representing mooring line dynamics [29]. This reference is a summary publication from a Joint Industry Project performed in Norway, and known as FPS2000, which considered many aspects of modelling mooring systems.

Taut mooring systems utilising synthetic fibre ropes are becoming increasing popular for deep water applications, and [30] describes some of the work of a three year research programme JIP 'Alternative Configurations and Materials for Mooring / Anchoring' initiated in 1996 [3]. The potential advantages of taut moorings are: lower weight, increased stiffness (controlling horizontal offsets), smaller footprint, easier handling, and lower costs. An FPSO using a taut mooring system has been used in the 1420m deep *Marlim* field offshore Brazil (but in this case a chain segment is used at the bottom end to avoid vertical loads on the anchors). Taut systems are if anything easier to model than catenary systems once the required mechanical properties of the line are known [12].

A key issue is the possible change in the stiffness properties of the mooring with use. This has implications for the way in which the mooring system is represented in model tests, and may require more than one stiffness characteristic to be represented.

4.3.4 Risers

In many respects modelling of risers imposes similar problems to those identified for moorings in the previous subsection. Catenary risers require sufficient space and the correct scale depth, and there are significant questions about the viscous scale effects for the dynamic response of all types of riser.

Where it is necessary to model bending stiffness this will often require some imaginative model design and perhaps the use of novel materials or composite construction techniques. This is because Froude scaling requires the bending stiffness EI to be modelled in the ratio k^5. These requirements may introduce an important restriction on the use of smaller scale models, and may be incompatible with the water depth available in the model basin.

If the primary interest in the model test is the effect the riser has on the motions of the FPSO, then it may be possible to demonstrate that the bending stiffness of the riser is not important, and some kind of linked chain-like representation may be adequate. However, if the purpose of the model test is to examine local riser deflections and curvatures, in order to estimate stresses, then it will be necessary to model the bending properties correctly.

4.3.5 Thrusters

Model thrusters are expensive items to manufacture, and most model basins have a stock of standard units for use in model tests. This means that the FPSO model scale needs to be selected such that the standard thruster units fit. The primary requirement is that the model thruster should be able to supply the correct Froude scale thrust. The exact diameter of the prototype thruster may not need to be

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3 Funded by the Norwegian Research Council (NFR), BP, Elf, Conoco, Shell, Norsk Hydro, Saga, and Statoil. (DSND, Brown & Root, Rockwater, Kvaerner Oil and Gas, Bruce, and Vryhof, also provided work to the study.)

represented unless thruster interaction effects are to be investigated (see Section 4.12.2), in which case it is important that the thruster slipstream has the correct diameter and velocity.

Quite large models are often required when it is necessary to include working thrusters, and this may limit the metocean conditions that can be simulated in the model basin.

4.4 SCALE EFFECTS

Most hydrodynamic model tests are performed at the correct Froude Number. This means that most of the scale effects that influence model testing arise from fluid viscosity, and the fact that it is impossible to model the viscous (Reynolds Number dependent) effects correctly at the same time as inertial (Froude Number dependent) effects (see Section 3).

4.4.1 Motion Damping

For all types of moored floating system there is the likelihood of large amplitude resonant responses to low frequency (usually wave second-order) forcing. Such motions are primarily limited by damping (sometimes also to a lesser extent by the presence of stiffness non-linearities). Model tests performed where the damping is wrong for any reason will therefore experience extreme excursions and mooring line tensions which are not representative of the full scale behaviour.

Reynolds Number scale effects tend to make the viscous damping due to the hull, and the viscous damping due to the mooring lines, greater at model scale than will be the case on the prototype, and so there is a real risk that extreme motions and tensions experienced on the model will be smaller, and results from the model test non-conservative.

Huse and Matsumoto [31] investigated the surge damping and resonant surge motions of moored ships. They considered the damping due to viscous effects on the vessel hull, and adopted the concept of a ‘form factor’ in oscillatory flow, which relates the damping of the hull measured in experiments to calculations of skin friction damping based on data for flat plates. Not surprisingly the form factor turned out to be similar to values found in conventional vessel resistance tests. The paper discusses the scale effects associated with the model tests, and indicates that the effect of model scale on the resonant surge motion of the ship can be anything from a factor of 1 (no scale effect) to 2.

Larsen and Huse [32] discuss simple procedures for quantifying scale effects in hydrodynamic model testing, and note that low-frequency motion damping cannot be calculated on a purely theoretical basis. Model tests are therefore regarded as being the most accurate means of predicting these motions, but viscous effects generally make important contributions to both the low-frequency motion and excitation, and become increasingly important for floating structures operating in deep water, especially when the current velocity is high. An evaluation of viscous scale effects is therefore considered to be essential when assessing hydrodynamic model test results. The forces have to be separated into different physical components, so that each can be scaled in the appropriate way. Full scale forces and response may then be calculated. Time-domain simulations are sometimes used for this purpose. Larsen and Huse sought, however, to develop simpler and more analytic procedures for quantifying scale effects. These involved a number of approximations, however, the justification for which can only be evaluated by comparison with time-domain simulations. The authors recommended that their scaling procedure for viscous damping and excitation forces should be used in circumstances where resonant low-frequency motions are important for the overall response.

The roll motion of an FPSO is a further resonant response where viscous damping and scale effects can be important. Owing to the fact that the roll motion can cause problems limiting the operability of process equipment, some have proposed fitting much larger bilge keels. Novel analysis techniques have also been proposed to help analyse the damping components and facilitate scaling to prototype [33].

A series of systematic model tests to estimate the roll damping of a tanker-based FPSO is reported in [34]. Two different scales were tested in order to investigate scale effects. Calculations using a potential theory panel method were also used, and empirical viscous damping factors were determined and presented. Comparisons with results published by Vugts [35] showed reasonable agreement and trends.

It is common practice to fit turbulence stimulators to hull models to try to ensure that there is no risk of laminar flow during resistance or current tests simulated by towing. In such tests the absence of any turbulence in the onset flow might permit laminar flow to persist over a significant part of the hull. The persistence of laminar flow conditions is unlikely in wave tests or when a current is being generated.

4.4.2 Mooring and Riser Systems

References [28], [36] and [37] summarise the state of the art in prediction methods for mooring line damping of vessel motions. They deal with the damping of vessel motions due to the mooring system, and the effect of the wave frequency motions of the vessel, which tend to increase the mooring line damping available to control low frequency resonant motions. These damping effects are almost entirely viscous in origin, and therefore subject to potentially significant scale effects.

The damping due to the mooring system for the surge motion of a moored tanker can be anything from negligible to 80% of the damping, depending on the mooring configuration and water depth, and so it is particularly important that scale effects on this component of damping are compensated for, either in the model design or in later data analysis. The mooring system can also give rise to heave damping of the moored structure, but this effect is normally negligible for an FPSO (it can be significant for semi-submersibles, and dominating for the heave damping of spar buoys).

The effect of different mooring systems on the viscous damping is illustrated by a study of different alternative mooring systems for a 850m deep location in the Southern Adriatic Sea [38]. Here a conventional mooring system was compared with a stiffer system containing subsurface buoys, and the surge damping of the FPSO was seen to reduce from 34% to 24% of critical.

Adjustments to line or riser diameters may sometimes be necessary to compensate for damping errors due to the low Reynolds Number of the line model [39].

4.4.3 Thruster Systems

Viscous scale effects can also be important for model thrusters, where the additional skin friction that occurs at model scale on the propeller surface and on the surface of the duct tends to result in more torque being required to drive the thruster model, and less thrust being produced. In most cases the thruster torque or power requirements are not the primary objective of the testing of the FPSO, and it is only necessary to ensure that the thruster is producing the appropriate Froude scale thrust. This is normally calibrated against thruster speed prior to installation in the FPSO model.

However, this and other differences between the model thruster and prototype (e.g. the prototype being run at constant speed and variable pitch, whilst the model is more likely to be at fixed pitch and variable speed) all introduce the potential for differences in the thruster slipstream properties, which might in turn have an impact on thruster-hull interaction effects (see Section 4.12.2).

4.5 WAVE GENERATION TECHNIQUES

4.5.1 Regular Long Crested Waves

Regular wave tests are sometimes performed to aid understanding of non-linearities in responses, and also when correlating model test results with those from numerical simulations under idealised conditions. However, the bulk of model testing of FPSOs is conducted in random or irregular waves designed to simulate realistic ocean conditions.

When regular waves are used, careful attention needs to be paid to their quality, because they tend to degrade quickly as they propagate across the model basin, and when they are of poor quality the purpose behind their use (i.e. the investigation of an idealised forcing and response) can be lost.

4.5.2 Random Long Crested Waves

Real waves at sea are both random and multi-directional (or 'short crested'), but the uni-directional or 'long crested' random wave is often used in the model basin as an idealised representation of the ocean. For many offshore structures it can be shown that the long crested wave will represent a worst case for loading and response, but this is not necessarily the case for FPSOs, and this has resulting in a common desire to test in short crested waves (see Section 4.5.3).

The randomness of the waves generated in a basin is also of importance, particularly when the probability distributions of measured parameters are to be determined and used in analysis to estimate extreme responses, or as input to reliability analyses. Many basin wave generators use pseudo-random number generators to produce the wave generator control signal [40]. The advantage of such systems is that it is possible to exactly repeat long sequences of pseudo-random waves, so that model tests may be repeated in the same time series of waves. Used correctly, these systems can produce very good quality waves to the desired spectrum shape, and with the required Gaussian wave elevation and Rayleigh distributed peaks, troughs and ranges. Used incorrectly, however, they can produce waves which, although appearing realistic to the casual observer, may contain short repeating sequences of waves and/or unrealistic spectrum shapes. Unrealistic periodic repetitions in the wave sequence can result in resonant responses being excited in the moored system, or the complete absence of the low frequency mooring responses that ought to occur in the ocean.

Random waves may also be synthesised in the wave basin by the superposition of a number of sine wave components of varying amplitudes, frequencies and phases. However, such techniques need to be used with particular care in model tests where low frequency forcing and responses are important (nearly always the case for FPSOs). Adequate representation of low frequency responses will only be possible if a very large number of sine wave components is used [41]. A number of further questions also arise: how the amplitudes and phases of the sine waves should be selected, and whether it is sufficient to make the phases of the sine waves random, or whether the amplitudes should also be chosen randomly. The latter approach is preferred in order to represent wave group statistics correctly [42]. Correct wave group statistics are important when assessing the vessel's low-frequency response and mooring line loads. The issue of how waves should be generated is closely linked with the duration of the run which is to be simulated (see Section 4.9).

Another useful capability in the generation of random waves is the ability to reproduce a certain required wave time series at a particular location in the basin. Considerations of extreme motions or excursions of FPSOs, or reproducing green water or wave impact events (see Section 4.13) may particularly benefit from this capability. A report on FPSO metocean requirements [26] recommends enhanced measurements of winds, waves and currents, including the continuous recording of raw data to improve understanding of joint probabilities, and to identify particular critical sequences of waves. Clearly this implies the need for the ability to reproduce these sequences in the model basin. Such 'deterministic' sequences of waves have been advocated for some years. For example Funke and Mansard [43] promoted them as a technique to obtain a desired level of wave grouping and second-order wave forcing. However, this approach begs the question of how these critical sequences of waves are to be selected [44]. It may be necessary to perform extremely long runs in order to find the critical sequences. Even if it is already known that a particular sequence of waves causes a particular extreme response or green water impact, and it can be reproduced in the wave basin, there is a major difficulty in interpreting the results in terms of their probability of occurrence in the real metocean climate.

4.5.3 Random Short Crested Waves

An increasing number of wave basins are now capable of generating multi-directional or short crested random waves, and such waves obviously offer the potential of testing in an environment which is closer to reality. Wave generators for such waves usually consist of a large number of independently controlled paddles or flaps, electrically or electro-hydraulically driven, usually extending along one or more sides of the basin. With modern computer control of such wave generators it is theoretically possible to generate any multi-directional wave spectrum over a limited region in the basin.

However, practical constraints are imposed by the pitch of the individual paddles (which ultimately limits the directional control for higher frequency waves), the frequency response of the paddles, and the nature of the boundary condition at the walls perpendicular to the wave generator. This last is particularly important in determining the region of the basin over which the required multi-directional spectrum will exist. If the basin has straight reflecting walls, then theoretically every directional wave component will be reflected. In such circumstances it is possible to control the wave generator to create a homogeneous symmetrical multi-directional wave spectrum over the whole basin area [45] save for regions very close to the wave generator and wave absorber. Asymmetric multi-directional wave spectra can only exist in a part of the basin (whether side walls are reflecting or absorbing), and so the FPSO model must be designed to operate in this restricted region if such waves are needed.

The comments made in Section 4.5.2 about probability distributions, and the dangers of using sine wave summation methods, apply equally here. In theory there should also be the same benefit of being able to reproduce particular wave sequences, but unfortunately the ability to measure multi-directional waves in the real offshore environment lags far behind the capability to reproduce them in the wave basin.

Numerical simulations [46] indicate that the highest wave crests in short-crested deep-water waves can be about 2% lower than those occurring in corresponding long-crested waves, due to non-linear wave-wave interactions. This difference may be important when assessing green water or air gap.

4.5.4 Bi-modal and Bi-directional Wave Spectra

It is common in the ocean to experience a locally wind-driven sea at the same time as a lower frequency swell coming from afar. This manifests itself as a wave spectrum with two energy peaks (i.e. bi-modal). The two wave components will also often be from different directions (i.e. bi-directional). Such conditions can be quite important for moored floating systems such as FPSOs, because they may result in non-optimum natural weathervaning, which in turn may cause large wave motions.

These conditions represent a special case of the short crested random waves discussed in Section 4.5.3, and can in theory be generated in any wave basin with full multi-directional random wave capability. However, if the angle required between the wave components is 90^{o} or greater then it is normally only possible to generate these waves over an adequate area in a basin having generators on two sides. The swell component can often be considered unidirectional or long-crested, and so a basin with a uni-directional wave generator on one wall and a multi-directional wave generator on an adjacent wall [47, 48] will often be suitable for such tests.

4.6 GENERATING WIND OVER WAVE BASINS

It is often necessary to generate winds over waves in wave basins because the simultaneous forcing due to both the wind and wave effects are required if the FPSO model is to behave correctly. The presence of the wind may also have an effect on the shape of steep waves, introducing asymmetry which may in turn be important for such issues as wave impact and green water on deck.

Whilst a few small wave facilities have been constructed inside wind tunnels, so that good quality air flow can be produced together with good quality waves (e.g. [49]), it should be recognised that wind flows generated over wave basins generally fall far short of the quality normally expected for wind tunnel testing (see Section 4.14.3). In general the wind flow will vary in space and in time, and the wind speed profile and turbulence characteristics will not be representative of full scale ocean conditions.

Wind is usually generated over the wave basin using banks of open fans. The bank needs to be large enough and far enough from the model to ensure that an area of reasonably homogenous conditions exists over the likely excursion region of the FPSO. Lack of homogeneity and flow instabilities causing unwanted dynamic components can result in unrepresentative dynamic response.

In the ocean the winds interact with the water surface to create and sustain the waves, but this interaction takes place over very long distances (fetches). In the wave basin these effects clearly cannot be modelled correctly because of the very short distance over which the interaction can take place. However, the presence of the wind certainly tends to give the waves a more realistic appearance, and it is likely that some asymmetric profile shaping (the advancing face of the wave steeper than the trailing face) will be encouraged by the local wind shear stress.

Difficulties in modelling the wind flow often make the mean wind force and moment on the model markedly different from values predicted using the measured mean wind speed and force coefficients measured in a wind tunnel. It is therefore recommended that, when wind fans are used over a wave basin, the speed of the fans is set to reproduce the calculated mean offset on the mooring system, or the mean wind force and moment, rather than the required wind speed [50]. In principle it is possible to control wind fan speed in order to reproduce the low frequency component of a wind spectrum, which may excite low frequency responses of the FPSO on its mooring system, but this is not a regular feature of such tests.

It can be seen that wind fans can be quite time-consuming to set up, and they are not always available at smaller test facilities. These difficulties with wind fans over basins have resulted in the development of other methods to apply the wind forces. Apart from the influence the wind has on the shape of the waves, there are no strong interaction effects between the winds and the waves, and so the wind forces and moments can be produced in other ways. One method that has now been used at a number of basins is to use computer controlled 'force fans' mounted on the model. The control system senses the vessel's heading to the wind, and controls the fan speeds to provide the appropriate forces and moments as determined by a look-up table of wind forces versus heading. This is an example of an active equivalent system or hybrid model (see Section 4.11.2). Model tests using these systems are reported in [51], [52] and [53].

Other simpler mechanical ways of representing the wind force or moment have also been used. For example [54] describes a research study to investigate the feasibility of using a system of springs to model the effects of wind loading on turret-moored vessels. The results were compared with those obtained using conventional wind fans. The spring system was able to match the variation in the static turning moment about the turret with heading angle fairly accurately over a range of about ±90 degrees. Model tests were also performed in a wave basin, and yaw motions measured using the spring system agreed well with those obtained using wind fans.

4.7 GENERATING CURRENTS IN WAVE BASINS

The problems of generating a current in a wave basin, are in some ways similar to those for wind (see Section 4.6), but the effects of interactions between waves and currents are potentially much stronger, and it is therefore much more important to model the simultaneous effect of both on the FPSO. The presence of the current affects the properties of the waves, and can therefore influence the wave drift forces [55, 56]. The presence of the current can also have a marked effect on the damping experienced by the FPSO and its mooring system [8, 57].

One important question raised by generating a current is whether the target wave spectrum should have the correct shape when the current is on, or when it is off. The presence of the current will inevitably change the spectrum shape. There is also some doubt about whether the interaction between waves and current will be the same in the basin as it is in the ocean. The normal assumption is that the wave spectrum was measured in the ocean in the presence of a current, and so it should have this same shape when measured at the model location when the current is operating in the basin.

Some basins have been constructed with full flow or integral current generation and ducting systems [47, 58]. These full flow systems, with the return flow being ducted around outside the basin or under the floor, offer the best chance of producing a controllable current in the wave basin, but they are still often troubled by difficulties in producing the required steady velocity profile. It is also very difficult to measure the current in the presence of waves.

Other basins have made use of local water jet systems to induce a current in the vicinity of the model, with a return flow recirculating in other parts of the basin. These systems are even more difficult to control, and have the further disadvantage that the current velocity changes substantially in different parts of the basin. This varying current field can have a major effect on wave propagation, changing the direction of wave components and making it very difficult to calibrate the wave generator to produce the required wave field.

Many workers have simulated currents by towing the model in a towing tank. This can be very difficult to do, particularly if a mooring system is to be included and attached to the towing carriage, but at least the onset speed of the uniform current is accurately known. Some workers have proposed erecting a wake screen ahead of the model in order to simulate a current profile [59]. Run durations are obviously limited by the length of the towing tank. Wave conditions need to be modelled with care to ensure that the appropriate encounter frequencies are experienced by the model. There can also be problems with changes in the wave properties along the tank, due to natural dissipation and wave-wave interaction processes.

4.8 MODELLING NON-COLLINEAR ENVIRONMENTS

Non-collinear environments mean wind, wave and current directions that are not aligned with each other (the potential multidirectional nature of waves alone is discussed in Section 4.5.3 and 4.5.4 above).

It will have been gathered from Sections 4.5.3 and 4.5.4 that even basins with multidirectional wave capability, and more than one wave generating side, are nevertheless quite limited in terms of the primary direction of the waves that can be generated. Similarly full flow current systems (Section 4.7) are often limited in the current directions that can be produced. Consequently there may be an immediate limitation on the ability to generate currents that are at any particular desired angle to the waves.

Wind fan systems mounted over basins normally provide more flexibility in terms of direction, and can usually be set up at any desired heading angle. However, changing this heading angle for different test cases can be time-consuming and expensive, and this has been a strong motive for developing computer controlled force-fan systems (see Section 4.6).

4.9 RUN DURATION

One of the main factors influencing run duration is the need to determine magnitudes of extreme responses. A reasonable estimate of extreme, linear, wave frequency responses can be obtained directly from the standard deviation of the response, which can be determined adequately from a very short run. A key design issue for FPSOs, however, is to determine the large, non-linear, low frequency excursions that the vessel can experience when moored, and the way in which these combine with large wave frequency excursions, resulting in an extreme mooring tension or riser response. Extreme values obtained from an individual test will inevitably have a high level of statistical variability.

Extreme values cannot be extrapolated reliably from small quantities of data unless the shape of the response probability distribution is already known. The only reliable way of estimating extreme non-linear responses of a moored FPSO is by analysing long data records, which contain many extreme events [10, 29, 39]. The natural yaw period of the FPSO, in particular, can be very long, and the number of cycles in a typical 3-hour test period might be in single figures. Between 400 and 1000 cycles may be required, however, in order to obtain a reliable estimate of the extreme response [12].

It is clear that the need to obtain sufficient statistical information on vessels with low-frequency response characteristics may require very long test durations, and an example where the test duration was 48 hours full scale is given in [60]. The author states that no general guidance can be given about the model test duration required to obtain a given level of statistical reliability in complex situations, but he suggests an equation by Tucker [61] for estimating the ‘variance of the variance’ of the response of a simple one-degree-of-freedom system. Even longer durations are required for reliable estimates of extreme response.

One of the problems with estimating extreme values of wide bandwidth response systems is the mechanism for counting the low frequency cycles, and a new method described in [62] may in future prove to have useful application to the analysis of model test data.

Actual run times possible in model basins are usually restricted by the inevitable build-up of wave reflections, which eventually contaminate the incident waves and FPSO response to an unacceptable degree. The situation is best in tanks which have very efficient wave absorbers (beaches), where wave generators are of the absorbing type, and when the model is small compared with the plan dimensions of the tank. Variations in the standard deviation of the wave signal during the tests can be a useful indicator of a deterioration in wave quality, and the development of long-period seiches in the basin may be detected by continuing to collect data after the wave-maker has been switched off [60].

Clearly the effectiveness of the wave absorbers or beaches is a key factor in the ability of a wave basin to perform long runs which will yield statistically valid results. The best basins for this work are broad and rectangular in shape and have absorbers on all sides not occupied by wave generators. There are a number of different absorber designs, some being based on inclined planes on which the waves break (‘spending beaches’), others being based on arrangements of vertical or horizontal porous planes, or bulk porous material. Performance varies widely depending on the design and the chord dimensions. None of these passive devices work particularly well at very low frequencies, and this can mean that the build up of low frequency energy and basin resonance frequencies (or seiches) can go unchecked. These problems may be particularly severe when the incident wave periods being used are long (say to represent swell conditions offshore West Africa).

Second order wave effects can also result in the generation of long period waves in the basin. A first order low frequency wave can be created at the wavemaker and at the absorber which corresponds with the group frequency ‘set-down’. This low frequency, first order wave is an inevitable result of the wavemaker and absorber boundary conditions, and the effect is particularly marked in shallow water basins. Some researchers have proposed generating low frequency correction signals at the wave generator in order to compensate [63].

Large data sets can be built up from a number of separate discrete runs where the statistics of the metocean conditions are the same, but the pseudo-random time series realisation is different for each run. However, there may still be difficulties with these discrete runs if the system damping is very low, and there is insufficient time for the starting transients to damp out. If this is the case the method cannot be used to build up a very long data sample.

Design extreme values are usually based on a most probable or expected maximum from a theoretical distribution fitted to the upper tail of the measured data, rather than the actual measured maximum value. It is sometimes helpful to separate the measured time-history into low-frequency and high-frequency components (by means of low-pass and high-pass filtering) before carrying out the theoretical fit and deriving most probable maximum extreme values. The most probable maximum low-frequency and high-frequency extreme values then have to be re-combined using standard statistical formulae. However, the selection of the appropriate re-combination formula is itself a matter of some debate [64].

Special consideration also has to be given to rarely-occurring extreme events, such as the occurrence of green water or slamming (see Section 4.13).

4.10 ULTRA DEEP WATER FIELDS

In a recent evaluation of future deep water oil fields reported in [58] it was found that at least 25% will be in depths greater than 1000m. At conventional model scales (≈1:50) these depths will require water deeper than the 10m available at the MARINTEK basin [47] or in the new MARIN Offshore Basin [58]. Furthermore the deep pit available in the new MARIN basin will not help when the problem is to model a large spread of mooring lines.

There are three alternative solutions to this problem: ultra-small scale testing (less than 1:100 scale), or the use of passive or active equivalent mooring and riser systems (see Sections 4.11.1 and 4.11.2 respectively). A study into ultra small scale model testing of FPSOs is described in [65], where the results of model tests conducted on a turret-moored FPSO model at scales of 1:55 and 1:170 are compared. The authors note that there are a number of practical problems associated with the performance of ultra-small scale tests. Model accuracy and instrumentation accuracy difficulties can mostly be overcome if sufficient care is taken. There is however an absolute scale limit related to wave generation when capillary (surface tension) effects start to have a significant influence on wave propagation and shape. This does not seem to have been an issue at the 1:170 scale of the tests described in [65], but, as noted in Section 3.3.2, surface tension may become an issue at scales of around 1:250.

The comparison study between tests at 1:50 and 1:170 model scales showed some difficulties in generating equivalent current and wind conditions [66], but the errors introduced seem to have balanced out in the results. These tests also indicated quite a substantial difference between damping values for the two models, but, owing to the relatively high level of damping, these differences did not seem to have a large effect on the extreme motions and mooring line tensions, which agreed quite closely between the two models. The overall conclusion was that FPSO model testing at a scale of 1:170 is feasible, but particularly careful attention is required in model design, planning and execution.

An interesting comment is made in [12]: that the nature of mooring systems and riser systems designed for very deep water applications may actually help to simplify the model test and analysis problems. The example of taut fibre mooring systems is first given. Such systems tend to have more nearly linear behaviour than conventional catenary systems, and the dynamics of the lines themselves are also probably of less importance. Their characteristics are therefore readily amenable to simulation with shallower equivalent mooring systems (see next section). The authors also cite the example of the hybrid risers (e.g. as used on the *Girassol* project) where the riser dynamic responses are likely to be confined to the relatively shallow riser ‘jumpers’ connecting the FPSO to the top of the buoyant riser tower; the latter being deeply submerged and relatively static.

4.11 EQUIVALENT OR HYBRID SYSTEMS

4.11.1 Passive Equivalent Systems

It has already been noted in Section 4.6 that passive spring systems can be used to represent the wind yawing moment for an FPSO [54, 67], but a more important potential use relates to the simulation of mooring systems in deeper water than is available in the model basin. Equivalent passive mooring systems have the advantage that larger model scales are possible, and the model tests are relatively straightforward to design and build.

Equivalent systems can be designed to provide the correct quasi-static horizontal load/ excursion characteristics in a shallower water depth. However, mooring and riser damping and line dynamics are not necessarily represented correctly in such a model. A coupled mooring analysis may therefore be needed to represent the dynamic mooring line behaviour and damping of the real deep water system. This can only be done, however, if the numerical model of the low-frequency motions and line dynamic behaviour has already been validated and adjusted to match the passive equivalent mooring system. The use of the resulting numerical model in ultra-deep water then requires a certain leap of faith.

4.11.2 Active Equivalent Systems

The use of active equivalent mooring systems is being investigated in a number of laboratories. A computer-controlled system is used to represent the dynamics of the mooring line that should lie below the floor of the test basin. Buchner [58] notes that there are significant computational problems in simulating the behaviour of the mooring and riser in real (model scale) time. A similar system is also described in [68] and [69], and again it is emphasised that significant development is required to make such systems a practical reality.

However, these systems offer the possibility of modelling the full dynamic behaviour of the mooring system, rather than just its static behaviour. The model tests would then be able to provide design values directly, rather than requiring later adjustment in a numerical model. The use of the results still require an act of faith, however, in the performance of the numerical model and the active control system.

One of the earliest examples of a hybrid model system used in a physical model test was the force fan simulation of wind forces and moments described in [52]. However, although this system required the real time control of a computer, the wind force model was simple (being essentially quasi-static), and the update speed required was two orders of magnitude lower than that required for mooring simulation (being related to the slow yawing motions of the tanker rather than the high dynamic wave frequency responses of a mooring line).

The principle of using hybrid models to represent deep water moorings and risers in a model basin is well established, but turning this principle into practical reality still requires the development of accurate, low stroke, high performance underwater servo winches, as well as reliance on a numerical model of the dynamic mooring line or riser response.

4.12 DYNAMIC POSITIONING AND THRUSTER ASSISTED SYSTEMS

4.12.1 General

Thruster assisted mooring systems can have advantages over naturally weathervaning FPSO systems. Provided there is sufficient redundancy in the thruster power and control systems, the thrust from the system, and the ability of the system to select a favourable heading to the weather in non-collinear conditions, can be taken into account in the sizing of the mooring system, resulting in significantly reduced mooring loads and reduced mooring line costs [70]. Against this must be set the costs of installing and operating the thruster system.

Active heading control, thruster-assisted mooring systems are inherently easier to understand (and their performance is easier to define) than naturally weathervaning systems, because there are important uncertainties in the heading that the latter type of vessel will take up under certain conceivable non-collinear metocean conditions.

Not all such systems have active heading control, however, and [71] describe the development of a pure dynamically-positioned (DP) floating production system, based on a conventional tanker hull form. Cost savings were made by locating the thrusters at the forward end of the vessel, and allowing it to weathervane. Results from numerical simulation studies were correlated with model test measurements in wind, waves and current. However, the results indicated a need for a thruster in the aft end of the vessel in order to cope with certain environmental conditions. The authors point out that DP offers considerable flexibility, allows the vessel to be moved off station if threatened by a typhoon or ice, and is not limited by water depth. Operating costs can also be reduced if the DP system uses produced gas as the fuel to generate electrical power.

Model tests in support of the design of thruster-assisted mooring systems or DP systems are normally very closely linked with computer simulation studies, one feeding off the other. The roles played by model testing and simulation vary from one organisation to another. An early example of a model test where the model contained a full DP control system is described in [72].

Aalbers [10] describes the approach adopted by MARIN, where tests are performed on a model with a control and thruster system which mimic, as closely as possible, those of the full scale system. The model control system may have to provide both heading and position control, and may have to represent Kalman filtering. Scale effects, associated with the maximum dimensions of the thruster system, and the speed of response of the model control system may limit the accuracy of such tests. They can nonetheless be helpful to confirm the validity of computer predictions, to investigate effects of waves and vessel motions on thruster performance, and to investigate specific failure events and combined events, such as the effects of DP on reconnection.

In order to feed data into computer simulations of DP or thruster-assisted mooring systems, it is usually necessary to provide coefficients obtained from a number of specific model tests. These include: current force tests, wind force tests, thruster-hull interaction tests (in calm water, and in the presence of current) - see Sections 5.4, 6.1 and 5.5 respectively. English and Wise [73] described an early set of model tests to provide hydrodynamic data for use in the design of a dynamic positioning system. The tests included measurements of steady current force and moment coefficients for the hull as a function of the heading angle, flow visualisation to understand the current flow with and without bilge keels and turbulence stimulators, pressure measurements on the hull surface, measurements of ship motions, wave drift forces and moments in regular waves. Wind tunnel tests were also performed to obtain wind force coefficients. Tests were also performed to measure thruster/ hull and thruster/ thruster interactions, both with and without a current. The results from this very extensive test programme were then used as input to a numerical simulation model of the vessel and its control system.

4.12.2 Thruster-Hull Interactions

The slipstream from a thruster can impinge on and attach to the hull of an FPSO, or can influence the performance of another adjacent thruster. In either case the effect on the station-keeping ability of the vessel can be quite dramatic, and it is important to be aware of these effects at the design stage. Thruster-hull interaction tests are used to investigate thruster performance degradation due to thruster/hull and thruster/thruster interactions. A description of example tests in still water can be found in [25] and [71].

The overall objectives and general procedure for performing such tests are described in Section 5.5.

4.12.3 Thruster Assistance and Turret Location Optimisation

Model tests performed during the design of the *Balder* FPSO design are described in [17]. The *Balder* is one of a class of FPSOs which have sufficient thruster capability to enable the vessel to be turned around in moderate sea conditions in order to unwind the hoses. Because the weathervaning performance of such a vessel is less important, the turret is often placed relatively far aft, which in turn offers advantages in reducing dynamic loads on moorings and risers. These model tests are an example of those used to optimise the DP control system for the azimuthing thrusters, and to determine the limiting sea state in which the vessel could be turned. (It is also an example of a model test of a passive equivalent system, where the model mooring lines had to be modified to correct for the limited water depth in the test basin.) These tests used a closed-loop DP system for thruster control.

Simulation results described in [19] for a Gulf of Mexico FPSO design show the influence turret location has on a number of the design parameters, including mooring line tensions, heave motions and riser offsets.

4.12.4 Dynamic Positioning Optimisation

Similarly to the tests described in the previous section, model tests are also often performed to optimise the performance of pure dynamic positioning systems. An example is given in [25] which describes a programme of model tests on a large deep-water combined FPSO/ drill ship, the *Discoverer Enterprise*. The objectives of these tests was to optimise the DP control system for the six azimuthing thrusters, to measure the motions of the vessel in limiting design conditions, and to determine the limiting sea state in which the vessel could be turned around against the weather. The tests also involved the use of a closed-loop DP control system, with a Kalman filter, on the model, and the programme included ‘squall tests’ to investigate the system’s response to transient conditions.

4.13 GREEN WATER AND WAVE IMPACT

Bow damage has been sustained by a number of floating production systems as a result of wave impact and green water on deck (e.g. *Alba*, *Schiehallion*, *Norne* and *Varg* [74, 75]). Damage has also occurred on several North Sea FPSOs at amidships and further aft. Although this latter damage has generally been minor (e.g. handrails, cable trays, etc.) it could represent an important hazard to personnel working on deck. It is clear that this potential problem should be evaluated during the design of FPSOs.

The damage does not necessarily occur in the most severe weather conditions. For example, the damage sustained by the *Schiehallion* FPSO in 1998 is understood to have occurred in a sea-state much lower than the design extreme, but the waves were steep and the vessel was pitching strongly [74]. The suggestion is therefore that the damage occurred when a large pitch motion combined with a particularly steep wave to produce a very high intensity impact on the bow.

These processes therefore depend on the relative motion between the water surface and the FPSO hull, and the occurrence of green water and slamming or impact are sometimes estimated by assuming that the probability of exceeding the relevant freeboard level or keel emergence is Rayleigh distributed. However, calculations of this type are seldom reliable, and it is particularly difficult to assess the severity of green water loading and slamming. Model tests are the only reliable way to assess these effects, which are much dependent on non-linear properties of the waves, and the motion responses of the FPSO hull. A useful review of the issues is given in [76].

Berhault et al. [77] presented results from a numerical and experimental investigation into green water on the deck of an FPSO. In this case the model test was limited to head seas only, with the model free to pitch and heave only. Most of the tests were in regular waves. Variations in bow shape and freeboard height were investigated, these being important parameters controlling the incidence of green water on deck. The vessel motions were predicted using a linear wave diffraction program, and the results were compared with measurements. The green water appeared to affect the vessel’s pitch response near its natural period, and this reduction in pitch response increased with wave steepness. The flow across the deck was modelled numerically using a dam breaking theory. The authors comment that the design of the bow shape involved a balance between reducing pitch response and mooring loads, and reducing the effects of green water on deck.

Results from model tests on a weathervaning FPSO are also described in [78], where green water was able to come onto the deck over the ship’s sides. Model tests showed that waves from 15 to 30 degrees off the head direction came over the side, resulting in green water flow over the deck. Surprisingly high transverse flow velocities across the deck were reported. The waves running along the side of the vessel were highly non-linear (very peaky), and linear wave diffraction theory seriously underestimated the relative motions. The author proposed a procedure for estimating the occurrence of green water, including an empirical correction factor, and a possible procedure for estimating the flow velocities and loads.

Another series of model tests to investigate the occurrence and severity of green water on the deck of an FPSO in head waves is described in [79]. The tests were designed to investigate the influence of environmental parameters, such as the wave height and period, the current speed, bow shape, the position of equipment on deck, and the shape of breakwaters. Tests were performed in both regular and irregular waves. Most of the tests were performed in waves alone, but the effects of a current were simulated in a few cases by towing the model. Significant differences were found between measured and predicted vessel pitch motions and relative water surface motions at the bow. The author concluded that these results showed evidence of considerable non-linearities. A simple theoretical model based on dam breaking theory was used to predict the motions of the water on deck. The author noted that the development of a complete numerical impact model is likely to prove very difficult, because of the importance of local effects such as air entrapment.

The results showed that green water effects were sensitive to wave period, wave height and current. Bow flare was also important, but had several different effects, some tending to increase and others to decrease impact loading. Both the amount of water on deck and its velocity affected the loads. Green water loading is an aspect of design where adequate model testing is considered to be essential.

Buchner [80] described the influence of bow shape on wave drift forces acting on the vessel, and on the occurrence of green water on deck. This investigation was based on results from linear wave diffraction theory and model tests, and considered three alternative bow shapes: a traditional tanker bow, a sharp alternative bow without flare, and the same bow with flare. Mean wave drift forces and low-frequency wave drift forces on the vessels with the alternative bow seemed to be smaller than those on the traditional tanker form, but it was not clear whether mooring loads were lower, because the wave-frequency motions of the alternative hull forms were higher. The relative motions at the bow were higher on the vessels with the alternative bows, resulting in more water on deck. Impact pressures on a structure on deck were also significantly (almost three times) higher. Tests were performed in both regular and irregular waves. The results were compared with predictions made using a linear wave diffraction theory, in which the effects of bow flare were not represented. Predicted pitch motions and relative motions at the bow of the conventional tanker form agreed well with measurements in small waves. In more extreme conditions the theory seemed to over-predict the vessel motions, but in shorter waves the theory tended to under-predict the motions.

The flare of the alternative bow was not represented in the theoretical model, but had a significant effect on the vessel's motions and on relative motions. The differences between measured and calculated motions on the model with flare were larger than those measured on the same model without flare. A substantial difference was noted between the measured and predicted pitch phase angles of the vessels with the alternative bow. These differences had a significant effect on both wave drift forces and green water. The author attributed these differences in vessel response to the weight of green water on deck. The small amount of buoyancy at the bow of the alternative hull made its motions very sensitive to variations in loads and non-linearities, especially those associated with the flare going into and out of the water in high waves. These non-linearities make the use of linear wave diffraction theory, especially for predicting wave drift forces, questionable for such vessels in extreme wave conditions.

Buchner [80] recommended that linear diffraction theory should only be used in preliminary design of a vessel with a fine alternative bow, and that final results should be based on model test measurements in a realistic environment. He also noted that if the bow is optimised for green water loading, mooring forces may be increased, and vice versa.

A considerable amount of research work on green water loading on FPSOs has been performed under the FPSO Green Water Loading Joint Industry Project [81].[4] The results of this project have been encapsulated in a software product known as *GreenLab* [82], which is an assessment tool for use in FPSO design, and incorporates 3D visualisation of the hull motions and wave crests (based on linear diffraction theory), coupled with a more detailed design tool (which includes predictions of non-linear relative wave motions), and a database of hull motions. *GreenLab* is only available to the members of the Joint Industry Project.

4.14 WIND TUNNEL MODELLING

4.14.1 General Requirements

Wind tunnels used for studies on FPSOs must have a number of important features. Principal amongst these is the ability to simulate, at the chosen model scale, atmospheric turbulent boundary layer wind conditions. If the wind tunnel is also to be used to measure current forces acting on the hull, then a uniform low turbulence flow capability is also required.

Other wind tunnel requirements include the provision of the following instrumentation systems:

1. Six component force transducers for measuring steady state wind forces and moments;
2. Two component hot wire anemometry for measuring mean and turbulent flows;
3. A system for simulating, at model scale, the hot gas flows from the various exhausts and measuring mean and peak temperature at designated locations;
4. A system for simulating, at model scale, prescribed gas releases and fire scenarios and measuring mean and peak local gas and smoke concentration at designated locations.

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4 Participants: ABB, Bluewater, BP Amoco, Chevron, Conoco, Exxon, FMC Sofec, Germanischer Lloyd, UK HSE, Maersk, Mobil, Samsung, SBM, Gusto, Shell and Texaco.

Wind tunnel testing has been applied to the design of offshore structures for over 20 years, and the general nature of air flow disturbances created by offshore platforms is examined and described in [83].

4.14.2 Basic Elements of Wind Tunnel Tests

The significant parameters for scale testing on FPSO vessels are the Reynolds Number, Froude Number and density ratio. It is impossible to achieve the prototype Reynolds Number on a scale model in a wind tunnel operating at atmospheric pressure. This would require the wind speed to be increased by at least two orders of magnitude which, apart from being physically impossible in most wind tunnels, would introduce errors due to effects of compressibility (Mach Number).

The argument for permitting tests to be conducted at low Reynolds Number is based on the principle that the flow around bluff shapes with sharp corners is insensitive to changes in Reynolds Number inherent in the model test. FPSO vessels, and offshore structures in general, are deemed to satisfy this requirement.

The relaxation of the Reynolds Number requirement allows tests to assess wind flow over the helideck and wind loads to be carried out at wind speeds which are convenient for the test. The results are then referred to the wind speed at a reference location (typically 10m above the helideck).

For gas turbine exhaust and gas and smoke dispersion tests, the buoyancy of the plume has a direct influence on its path. In order to simulate this effect, it is necessary to satisfy the appropriate full scale Froude Number and density ratio.

4.14.3 Simulation of Atmospheric Wind Conditions

For tests on FPSO superstructures the wind tunnel must be able to demonstrate that full scale wind conditions are being adequately simulated. The longitudinal mean wind speed and turbulence intensity profiles measured in the wind tunnel should be compared with target full scale profiles, such as found in reference [84], which are characteristic of wind flow over the sea.

The characteristics of the incident flow are critical in determining the flow patterns. If full scale wind conditions are not modelled satisfactorily, the final results will be unreliable.

4.14.4 Simulation of Uniform Underwater Flow Conditions

It is sometimes convenient to measure current drag forces and moments on the submerged hull of an FPSO in a wind tunnel. A uniform non-turbulent wind profile simulation is required for tests of this type. Test requirements are discussed in more detail in Section 6.1.

4.14.5 The Wind Tunnel Model

The wind tunnel model scale is dictated by two conflicting issues. Firstly, the requirements for high Reynolds Number and resolvable physical quantities (in particular gas and exhaust concentration) require the model to be as large as possible. However, for force measurements especially, blockage effects have to be minimised, and the model’s rigidity and natural frequencies have to be maximised. These requirements dictate that the model should be as small as possible. Blockage effects are dictated by the cross sectional area of the wind tunnel, which limits the size of model to no more than about 5% of the cross sectional area of the working section.

The choice of model scale is either a compromise between these two sets of effects, or alternatively, different models and different scales can be used for the different tests. A scale of approximately 1:100 is typical of tests to investigate the various flow phenomena, whilst for force and moment measurements a scale of about 1:200 will often be used.

4.14.6 Reynolds Number Effects

Although a key aspect in the choice of model scale and test wind speed is keeping the Reynolds Number as high as practically possible, it is unavoidable that the model scale Reynolds Number will be about two orders of magnitude lower than full scale.

For above waterline tests this shortfall in Reynolds Number is generally not considered important. The sharp edged nature and low aspect ratio of most topside details mean that the flow separation points are fixed and local reattachment is unlikely. These are the classical requirements for independence of Reynolds Number. On this part of the model, therefore, no measures are usually taken to compensate for the low Reynolds Number.

However, when current forces are being measured on the underwater hull, the shape is generally relatively smooth, with local curvatures and a large aspect ratio. These features mean that the flow around the hull may have some or all of the following properties:

- occurrence of laminar flow compared to full scale turbulent flow,
- a transition from laminar to turbulent flow occurs at the wrong place,
- separation, if any, occurs at the incorrect place, and
- re-attachment, if any, occurs at the incorrect place.

With these properties, the flow is said to be Reynolds Number dependent, and measures are required for compensation. Typical measures for compensating for Reynolds Number effects involve the application of roughness elements at designated locations on the hull. The essential function of these elements is to trip the flow at the correct place, and force it to be turbulent.

4.15 COMPUTATIONAL FLUID DYNAMICS

4.15.1 Introduction

Computational fluid dynamics (CFD) modelling involves the solution of the fundamental equations of fluid motion using numerical techniques. The region of the flow, and the boundaries constraining it, are divided into numerous small volumes, or cells, and equations which describe the conservation of mass, momentum and energy are solved within each cell. Values for velocities, temperatures, pressures, turbulence quantities and mass fractions are determined in each cell, and so a comprehensive assessment of their variation within the entire flow domain is obtained.

One day CFD will offer the complete solution to all aerodynamic and hydrodynamic flow problems, and may make the wind tunnel and the wave basin redundant. However, for the foreseeable future the practical limitations imposed by available computing power mean that there is a limited range of flow problems that can be tackled reliably and economically using CFD. Limitations on the number of cells that can be included in a model make the representation of complicated external geometric shapes (such as the superstructure of an FPSO) difficult, and important small scale and time-dependent flow phenomena like turbulence have to be represented by empirical means.

The limited range of problems for which CFD is the best solution was borne out by the results of this literature review. The conclusions offered by the papers found were very wide-ranging, and sometimes in conflict. Some authors did not consider CFD modelling even worth using on certain problems, whereas other papers concluded that CFD modelling is a cheap alternative to wind tunnel testing.

The main advantage of using CFD over wind tunnel testing is the ability to solve flow fields over a more comprehensive domain without any scale effects. Hot process equipment can be accurately represented, and the effects of small changes in geometry are easily quantified (subject to the resolution afforded by the meshing). Phenomena such as explosions, which are extremely difficult to study in physical models, can easily be modelled. However, as noted above, the capability of CFD is currently limited by computer hardware performance and by the indirect, empirical modelling of turbulence which means that the solution of large models with complicated physics are computationally expensive, and the solution of peak and near wall values are liable to inaccuracies. This effectively prohibits the use of CFD for applications such as wind loading, helideck wind flow and gas dispersion, where measurements of peak concentrations or temperatures are important.

Guidance on the use of wind tunnel modelling, CFD and full-scale field measurements is provided in [85]. It recommends that the wind tunnel is used for modelling smoke plumes in an open site, whereas CFD gives the potential for extracting the estimated concentrations at many locations simultaneously. In the example given both techniques were used to predict smoke concentrations and wind speeds within an offshore platform module. Comparing predictions with full scale field measurements showed agreement to within the required accuracy. The paper therefore concluded that both CFD and wind tunnel modelling could be used to predict global smoke movement in complex offshore structures.

4.15.2 Requirements for Application to Wind Effects on FPSOs

In the current context of considering CFD capability for solving wind related issues for FPSO design, the general requirements can be broken down into three areas: hardware, software and personnel. In order to create a numerical model of an FPSO, a model containing several hundred thousand cells is required. The computer hardware clearly must have sufficient memory to handle a grid of this size and a processor capable of solving the associated equations in a reasonable time scale. Modern workstations and high-power PCs are capable of this modelling, but some of the most complex CFD models are still run on supercomputers.

Today there are many commercial CFD software packages available on the market, and their very low cost, when compared with the cost of physical wind tunnel or wave basin facilities, means that they have made fluid flow modelling available to a much wider user-base. However, as with the operation of physical test facilities, the most important requirement is a skilled and experienced fluid dynamicist/CFD user. The software has become more user-friendly and can be operated by anyone, but there are many important decisions which need to be taken in the setting up of the flow model (e.g. the model meshing scheme, boundary conditions, time stepping, etc.). CFD is also quite well known for producing plausible-looking results which are actually wrong, and engineering judgement and specialist fluid mechanics experience are required to determine whether the results are sensible, and what has to be done to modify an incorrect or non-convergent solution. Particular skill is therefore required to build a CFD model which will fulfil particular project objectives.

When reviewing the results of CFD work, the most obvious question often asked is ‘What software package was used?’. However, in view of the above, the most *important* question to ask is ‘Who performed the CFD analysis, and what previous experience and validation was there for this particularly flow problem?’.

4.15.3 Checking Procedures

There are some checking procedures that can be used to see if the CFD model grid resolution and time step independence are adequate, and these should always be carried out as a matter of course. Insensitivity to grid resolution (i.e. grid density) may be checked by refining the mesh until the results no longer vary (within an acceptable tolerance). A solution is time step independent when the results do not vary substantially with time step size. This is checked by reducing the time step size until the change in results becomes insignificant. Clearly the extent to which the grid and the time-step can be refined depends on the computational power of the hardware being used.

4.15.4 Validation

As with all modelling techniques, validation of CFD is extremely important. Validation can take the form of comparisons with full scale measurements or with wind tunnel test results. For example, results obtained using an initial CFD model representing the external geometry of the platform may be compared with wind tunnel results at the same scale. Progressive refinement of the external geometry can then take place until such time as acceptable agreement is reached between the CFD predictions and wind-tunnel measurements. This will provide validation of the level of geometrical complexity and mesh density used in the model.

Commercial CFD packages have numerous validation papers supporting their products. However, the results from these papers are generally only valid for the specific flow problem considered, and they do not take into account the variability in results with user experience.

4.15.5 CFD Experience and Validation Reported in the Literature

Four different generic ways of modelling smoke and gas ingress in offshore structures are evaluated in [86]. The techniques evaluated were: empirical (dilution curves), phenomenological, CFD, and wind tunnel tests. The general conclusions were that empirical models were simple and robust, and useful for a quick estimate of dilution at a given distance from a source, whilst the phenomenological models gave more detailed predictions, and were relatively cheap and easy to use. CFD models permit the flow conditions to be specified in great detail, but computer limitations mean that they are best suited to studies focusing on certain detailed aspects of the dispersion problem. Finally, it was concluded that physical models are best suited to studies of dispersion around an entire offshore structure.

Wind load predictions on a seagoing ferry and on a semi-submersible offshore platform, using both CFD and wind tunnel methods, are described in reference [87]. Good agreement was obtained between all measurements for this essentially sharp edged body. However, it was concluded that, due to the time involved in generating a suitably detailed computational mesh and in computing the solution, the CFD method was not at present economically competitive when compared with routine wind tunnel testing.

Direct comparisons between CFD and wind tunnel methods for three dispersion case studies are presented in [88]. The cases included dispersion within an enclosed process module, from a pair of exhaust outlets on an FPSO, and downwind of an offshore platform. The paper demonstrates that apparently plausible, but wrong, CFD solutions can easily be obtained if the initial conditions are not modelled carefully. The main conclusion is that skilled users are required to obtain reliable CFD results. Another paper dealing with gas dispersion [89] highlights the important choice of the gas properties for the initial release.

A number of papers have been presented on explosion modelling, including [90], [91], [92] and [93], whilst [94] is a more general description of the flexibility of CFD methods, giving results for both water impact modelling and for external wind flows around a ship superstructure. Modelling of natural ventilation of offshore platform topsides is described in reference [95], and the flow over a helideck in reference [96].

5. REVIEW OF FPSO HYDRODYNAMIC MODEL TEST REQUIREMENTS

5.1 RESPONSE AMPLITUDE OPERATORS AND WAVE DRIFT FORCES

5.1.1 Objectives

- To determine the wave motion Response Amplitude Operators (RAOs), and associated phases. These are normally required because, subject to assumptions of linearity, they permit the calculation of the vessel wave motions in any sea state. They also permit the calculation of the motions experienced at any point on the vessel (say at the intended location of a separator unit). On smaller FPSOs operating in moderately severe conditions, they might also be important for considerations of human habitability and human performance (e.g. occurrence of sea-sickness).
- To determine the wave drift force and moment coefficients. These may be required as input to a mooring or thruster analysis. In principle these coefficients permit the mean and dynamic (low frequency) components of the wave drift force to be calculated in any sea state.

It should be noted that this type of model test is focused on delivering coefficient information which can be used in further analysis and modelling, rather than direct measurements of mooring loads, motions and excursions under realistic conditions, which are the subject of the tests described in Section 5.3.

5.1.2 Measurement Technique

The FPSO hull model needs to be prepared and ballasted to float at the desired draft, and also balanced to ensure that it has the correct moments of inertia about the roll and pitch axes (for a ship hull it is normal to assume that the moments of inertia about the pitch and yaw axes are the same).

Despite the fact that the balancing process should ensure that the centre of gravity is in the correct location and that the roll inertia is correct, it is also normal good practice to check that the roll natural period of the model when floating in still water compares closely with that anticipated. Any discrepancies are more likely to be due to errors in the vertical location of the centre of gravity (and hence *GM* and roll stiffness) than in the roll inertia. If necessary an inclining test can be performed to confirm that the metacentric height (*GM*) is correctly represented.

The FPSO model is mounted in the wave basin (or possibly a towing tank) on a compliant mooring system. This system dos not necessarily represent the anticipated prototype mooring system, and is often a set of horizontal elastic lines, designed to provide sufficiently low natural surge sway and yaw natural periods, so that the mooring loads do not influence the wave frequency motions of the FPSO [5].

Other ancillary systems such as risers are not normally modelled in these tests.

The model is fitted with a six degree of freedom non-contacting motion measuring system (either optical or inertial), and the mooring lines are connected to the model through force balances such that the total restraining forces and moments (in three degrees of freedom - F_x, F_y, M_z) can be determined.

Tests are often conducted in both regular waves and irregular waves over a range of vessel headings (see Section 4.3.1 for comments on the potential problems of performing these tests in a relatively narrow towing tank).

Regular wave tests permit the direct determination of the wave motion amplitudes and hence the RAO value and phase at any particular wave frequency. By running waves with different amplitudes at the

[5] This is a common assumption which is made in the analysis and interpretation of vessel wave frequency motions. Clearly the moorings *do* have a *major* influence on low frequency motion responses.

same frequency it is also possible to investigate the assumption of linearity implied by using RAOs for motion calculations in random waves.

Similarly measurement of average restraining forces and moments in regular waves allows wave drift force coefficients to be calculated. The assumption that the coefficient is independent of wave amplitude (i.e. the mean drift force depends on wave amplitude squared) may then be investigated by performing tests over a range of different regular wave amplitudes.

There is a clear role for regular wave testing, but the designer of the test programme needs to consider carefully whether they are worthwhile, and what he is going to do with the results. RAOs are only useful in situations where the response is reasonably linear (or can be linearised). It may be a waste of time to measure responses in regular waves, however, if the model's behaviour bears no resemblance to what happens in survival conditions (if these responses are the main objective). It has also been shown [80] that wave drift forces on vessels with highly flared bows can be very non-linear, and it is doubtful if tests in regular waves are then very helpful in determining real ocean performance.

Cross spectral analysis of the motions measured in irregular wave tests can also be used to determine RAOs and phase relationships. This approach is in principle much quicker than testing in regular waves, because information is gathered from one sea-state on the motions of the vessel over a wide wave frequency range. However, if low coherence is experienced in the analysis of the motions in irregular waves, whilst this indicates the presence of non-linearities in the wave forcing or response, it does not provide much information on the nature of these non-linearities - something that can be investigated in regular waves.

For some purposes it may be acceptable to ignore the non-linearities and the RAO generation step altogether, and present the motion data more simply in terms of significant responses divided by significant wave height. However, it must be remembered that such motion response data is only valid for a particular wave spectrum shape and, if motion non-linearities are important, only for a particular relationship between the significant wave height and zero crossing period. Such data also does not permit the later calculation of significant motions at some other point on the vessel. [6]

Once obtained, the wave motion data can be used to determine the properties of the motions or accelerations at any point on the vessel, and might be combined with wave climate statistics data to determine how many days in the year the process will have to be shut down due to motions beyond the capability of the separators, or how many days helicopters will be unable to land due to excessive motions at the helideck. The data may also be used to derive measures of seasickness or human performance (e.g. Subjective Motion Magnitude), and relate this to the number of days in the year when human operator performance may be significantly impaired. In fact there is a large range of statistical analyses that can be performed using this data, which can in general be referred to as operability or downtime analyses.

Drift force and moment coefficients may also be determined, in principle, from the results of tests in irregular waves, using cross-bispectral analysis methods [97], but these involve either an analysis of the low frequency motions of the moored vessel, and accurate determination of the stiffness and damping in the mooring system, or else use of an active force measurement system which restrains low-frequency motions but allows the vessel to move freely at wave frequencies. Both techniques are difficult to apply in practice.

It should be noted that low frequency motions and excursions measured in irregular wave tests of this type are unlikely to be directly representative of those to be anticipated on the prototype. Even if the model mooring system stiffness is correctly represented (which it does not have to be for the purpose of the above tests), the damping due to the mooring system will not be correct, and the damping due to the riser system will also be absent. These damping components can be particularly important for the excursions of deep water systems (see Section 4.4.2). A numerical model of the complete system will

[6] Motions at another point on the vessel *can* be calculated provided that time series data from the model tests are available.

then be needed to help interpret the data generated by the tests, perhaps using different estimates of damping, to arrive at estimates of extreme excursions for the prototype FPSO on its mooring system.

The tests described above may also be performed in the presence of current in order to identify the effects of the current on the wave forces and motions. Current effects on damping [8, 57] and wave drift forces [55, 56] can be extremely important in the estimation of extreme excursions. Sometimes the current may be simulated by towing in a towing tank. Care must be taken to ensure that the wave properties are analysed on a consistent basis (e.g. in terms of encounter frequency or absolute wave frequency, as appropriate). The absence of a realistic mooring system model in these tests means that current effects on the static and dynamic/damping forces due to the mooring system will not be represented.

It is not normally desirable to model wind, or simulate wind forces, in these tests.

5.2 MOORING STIFFNESS, NATURAL PERIODS, AND MOTION DAMPING

5.2.1 Objectives

- To determine the properties of the mooring system, and the dynamic behaviour of the FPSO on the mooring system.
- To ensure that static and dynamic properties of the mooring system are correctly represented.
- To provide information on damping which may later form the basis of the correction of any viscous scale effects.

These tests would be a normal precursor to the model test of the entire FPSO and mooring system described in Section 5.3 below.

5.2.2 Measurement Technique

With the FPSO model installed on its mooring system and riser system in the model basin, a known force is applied horizontally (usually by means of a dead-weight acting via a light string over a pulley), and the resulting offset of the model on its mooring system measured. The applied forces are stepped through a number of values so that the load/displacement characteristic of the mooring system is defined over a range covering the expected vessel excursions. Measurements will also normally be taken, both increasing and reducing the force, in order to check for any hysteresis. The process will normally be repeated for the two orthogonal directions, in FPSO surge and sway, but other directions may also be appropriate for highly asymmetric mooring systems.

Comparisons between measured load/displacement curves and calculated target curves confirm that the mooring system has been correctly represented, is providing the correct restoring forces, and that any necessary additional connections to the model (e.g. instrumentation cables) are not influencing its behaviour. This static offset test is also a useful check that all the various other instrumentation systems operate correctly over the full range of model excursions.

Once these tests have confirmed that the mooring system’s static properties are correctly represented, further tests are then performed to investigate its dynamic properties. These involve first applying a horizontal force to offset the FPSO on its mooring system, and suddenly removing the force, so that the FPSO model is free to return to its equilibrium location. A system which is less than critically damped will exhibit a number of oscillations on the mooring system, and a record of the surge or sway displacement can be analysed to determine the natural frequency of this oscillation, and the log decrement of the oscillations can be used to calculate the percentage of critical damping.

It is more difficult to determine the system’s natural frequency and damping if the damping is high (e.g. for a very deep water mooring system). Also the concept of a percentage of critical damping relates primarily to linear damping. In many cases is may be appropriate to attempt to fit non-linear damping and stiffness terms to the record [98], particularly if such terms are more likely to represent the physics of the situation (e.g. where the damping force depends on velocity squared).

The natural frequencies and damping coefficients derived from the above may now be compared with those derived theoretically. If the static stiffness properties measured earlier were correct, then significant discrepancies in the natural period may indicate errors in the estimation of hydrodynamic added mass for the vessel concerned. The damping in still water will primarily come from the resistance/drag of the FPSO hull and from the mooring system - the latter being the more important component in deep water. Theoretical estimates of the damping from the mooring system may have been derived from numerical analysis programs, which may make quasi-static assumptions about mooring line shape, but these would be expected to agree reasonably with results from tests in still water because the vessel motion is too slow for higher mode dynamic responses to be excited in the mooring lines. Scale effects on damping can be significant, and the data derived from the tests can help to show the extent of the effect, or to demonstrate that steps taken to reduce the effect (e.g. smaller diameter mooring lines) have been successful.

Natural frequency/damping tests can be performed in principle for the surge or sway directions of the vessel. When the FPSO is free to weathervane, however, it is unlikely that motions in the sway direction can be excited without causing large coupled yaw and surge motions at the same time. These coupled motions make it virtually impossible to derive the required data from the motions [10]. Results from free-decay tests may be seriously affected by coupling with other modes of motions, especially where the natural periods of several modes are close together. The only practical alternative is to use a Planar Motion Mechanism (PMM) to force the vessel to describe the required trajectory, and to measure and analyse the force exerted by the PMM to derive the required mass and damping coefficients.

These natural frequency and decay tests can in principle be repeated in the presence of waves, in the presence of currents, and in the presence of both, with the objective of determining the separate components of additional damping. However, these are extremely difficult tests to perform, particularly if the damping is reasonably high. It is very difficult to analyse free decay motions in the presence of higher frequency wave motions. Other methods that have been utilised to estimate damping from the vessel's motions in waves include random decrement [99], spectral moment [100] and system identification techniques [101], but these methods tend to work only if the damping is low and the response has a clear natural period component.

5.3 FPSO MOTIONS AND MOORING LOADS

5.3.1 Objectives

- To provide direct data on vessel motions, excursions and mooring loads (plus perhaps turret loads) under realistic operating conditions. Extreme excursions, mooring line tensions, and the weathervaning performance are likely to be of particular interest.
- To provide data on riser behaviour.
- To provide information on any potential physical clashing: e.g. riser to riser, riser to mooring, or hull to mooring or riser.

Data derived from these tests, whilst giving a direct indication of system performance, may not be as useful as those described in Section 5.1 for understanding the various components of the behaviour, or for feeding empirical data into analytical work or computer simulations. It may also be difficult to correct the results of these tests for known scale effects without some of the basic empirical data derived in Section 5.1.

5.3.2 Measurement Technique

FPSO model preparation needs to be much as described in Section 5.1, but with the additional possibility that a representation of the superstructure may be required if wind is to be generated over the wave basin. A non-contacting, six degree of freedom FPSO motion measurement equipment will normally be required, and if wave frequency motions are being detected using an inertial system it will normally be necessary to have an additional separate system (e.g. optical) to ensure that low frequency motions and mean offsets are accurately recorded [7].

A model of the mooring system is also required, together with a representation of the correct attachment points to the model (perhaps in a model turret assembly). Each mooring line will normally be fitted with a tension transducer. Additional force transducers may be installed to measure the loads on the turret as a whole.

The mooring system model needs to be designed to have the correct stiffness and dynamic properties, and these should be checked using the procedure described in Section 5.2 above. Obtaining the correct mooring properties may be a particular problem for very deep water fields where it is not possible to find a wave basin which can provide the depth and lateral space required for the full mooring system at a reasonable model scale (see Sections 4.10 and 4.11). It may also be necessary to reduce the diameter of mooring elements in order to compensate for scale effects on drag and mooring system damping (see Section 4.4.2).

As noted in Section 4.2 the selection of the metocean conditions to be used in the tests is a critical decision, which must be taken with full understanding of exactly how the results are to be used in the FPSO design process. In many cases the model test results will be used as calibration points in a larger numerical modelling and simulation exercise.

A prime test objective will often be to determine the FPSO's natural weathervaning performance in a range of challenging non-collinear metocean conditions, and the way in which the vessel's heading relative to the environment affects its motions, mooring tensions and turret loads. Different turret positions might be tried (but it is not particularly easy to design a model with this capability). The results of these tests can be used in a design trade-off between motions/dynamic mooring loads and weathervaning.

Thruster assistance may also be modelled in such tests (see Section 5.6).

Extreme excursions, and the associated extreme riser deflections and mooring tensions, are usually the most important output from these tests, but it is unlikely that the measured extreme values will be used without some statistical analysis to obtain the expected maximum values for a given period of exposure. This requires that the duration of the runs (or the total assemblage duration of several runs) should be sufficient to estimate the extremes to the required degree of accuracy. Note that this may not always be possible (see Section 4.9).

Tests in moderately severe, but commonly occurring, metocean conditions may be required as input to a fatigue life analysis (in addition to tests in extreme conditions). Tests in moderate sea conditions will also often be needed to provide calibration points over a large array of numerical modelling cases, or to confirm design parameters identified using a response-based analysis.

Minimum tensions may be of interest for a fibre mooring system, because of the risk of compressive fatigue [30]. Compressive loading can also sometimes be a problem for risers.

[7] This is because inertial systems commonly used in model basins are not sufficiently accurate to integrate the horizontal plane mean positions or low frequency motions, and these excursions are usually of fundamental importance to the model test input into design.

5.4 CURRENT FORCE AND MOMENT COEFFICIENTS

5.4.1 Objectives

- To determine current force and moment coefficients, usually over a range of vessel heading angles. These coefficients may be required as input to a mooring or thruster analysis. They are also an essential precursor to tests for determining thruster interaction effects in currents (see Section 5.5).

5.4.2 Measurement Technique

Owing to the very low Froude Number associated with current flows around hulls, and the consequent minimal wave-making resistance component, current force tests are often performed in wind tunnels. The test technique is described in Section 6.1.

If thruster interaction effects are to be established, however, the tests should be performed under the same conditions in the towing tank. The FPSO hull model needs to be prepared and ballasted to float at the desired draft. It is not necessary to balance the model for correct inertias because these tests are essentially static, and dynamic hull motions should not be excited.

The FPSO hull model is mounted in a towing tank under the carriage on a three axis force balance measuring the global (F_x, F_y, M_z) forces and moments acting on the hull. Sometimes it is convenient to use 2 $\times$ two-axis (F_x, F_y) force balances at bow and stern. Sometimes these force balances may be connected to the carriage (their 'earth') via compliant links in order to limit impulsive loading of the sensitive balances. This arrangement is satisfactory provided mean forces and moments only are required, and provided the compliance does not permit undesirable dynamic oscillations or excessive yaw deflections. Sometimes the model restraint system may be the same as that used when wave drift forces are being measured (see Section 5.1).

The model is towed down the tank at a range of heading angles, and a range of speeds. These speeds will normally be low enough to ensure that form drag dominates, and to minimise the effects of wave-making resistance. For streamlined hull forms (as opposed to sharp-edged rectangular barges) skin friction drag may be a major component when heading directly into the current, but the drag forces at this heading are usually so small, when compared with other headings, that it is not usual to make any scale correction for this (such as would be made when estimating the resistance and powering of a conventional ship). It is the much larger forces and moments that occur at significant angles to the current that are normally of main interest, and it is therefore most common to determine a simple drag coefficient or moment coefficient, and to assume that this coefficient is true for the prototype. The tests do not, therefore, strictly have to be performed at the anticipated Froude scale current speed.

It would be normal practice to fit ship hull models with turbulence generators (studs or trip wires) at the bow to ensure turbulent flow. For rounded bilge hull forms without bilge keels some workers have also added turbulence generators at or near the bilge to try to ensure that turbulent flow is stimulated, and that flow separation at the bilge occurs at the correct point (see Section 4.4 on scale effects).

5.5 THRUSTER-HULL INTERACTION TESTS

5.5.1 Objectives

- To determine the extent to which thruster performance is influenced by the proximity of the FPSO hull, particularly in the presence of a current.
- To provide data on this interaction, and if necessary define thruster 'no-go' areas that can be mapped into the thruster control system.

Model thruster units used by model basins are usually standard units, and their size will therefore define the model scale that can be used. This may require a larger model than can be used for model tests in waves.

5.5.2 Measurement Technique

Measurements of conventional model thruster performance are first made in 'open water', that is when distant from any boundary such as the vessel hull, and mounted on a suitable streamlined support. The results of these tests may be expressed as K_t versus J curves, or more simply in terms of thrust versus revs. It should be noted that it is not necessary for the model thruster propeller and duct to be of exactly the same design as the prototype. It is the diameter of the propeller/duct that is of greatest importance, because this determines the speed and diameter of the thruster slipstream for a given thrust value, and it is these properties of the slipstream that largely determine the nature of the interaction.

The thruster(s) are then installed in the model FPSO hull, and this is installed under the towing carriage in a towing tank mounted on a three axis force balance measuring the global (F_x, F_y, M_z) forces and moments acting on the hull. This is likely to be the same system as used in current measurement tests described in Section 5.4.

As with the current tests, the FPSO hull model needs to be prepared and ballasted to float at the desired draft only, and correct inertias are not required.

The thruster(s) are run, initially with the hull model stationary in the water, and the total force and moment on the hull measured. These forces and moments can then be compared with the open water performance of the thruster determined earlier, and an interaction factor determined for the thruster mounted on the hull. There are a number of ways of expressing the interaction, the most common being an efficiency (i.e. thrust is x % of the open water performance) or a thrust deduction factor (i.e. 1-t %).

The process is then usually repeated for a number of current speeds and vessel headings, and in the analysis account must be taken of the hull naked drag (as determined in the tests described in Section 5.4) in determining the interaction. For azimuthing thrusters the process must also be repeated for each azimuth angle of the thruster. When two or more thrusters are located in close proximity it may also be necessary to run different combinations of thruster speeds and azimuth angles together.

Clearly this is a process where the number of runs required can quickly multiply to unreasonable proportions, and so it is usual to limit the cases tested to particular orientations of the hull to the current, and of the thruster to the hull, which (a) are expected to be subject to significant interaction, and (b) are likely to occur in practice, given the anticipated thruster control strategy.

5.6 THRUSTER ASSISTED MOORING TESTS

5.6.1 Objectives

- To demonstrate the satisfactory performance of the combined mooring and thruster system in controlling the excursions and mooring loads of the FPSO in extreme and normal operations conditions.
- To demonstrate sufficient capability to control the vessel's heading and excursions in the face of thruster or mooring line failure in extreme conditions.
- To demonstrate sufficient heading control in day-to-day operating conditions, to facilitate critical operations such as shuttle tanker loading, or full FPSO rotation (e.g. to unwind jumper hoses on systems not fitted with swivels). To help set the metocean limits for these critical operations.

Many thruster-assisted moorings FPSOs have been designed and installed without the benefit of these tests, which require a model to be fitted with working thrusters, and with a control system that emulates the behaviour of the full scale thruster control system. Size limitations on model thrusters and wave generation capability may be impossible to reconcile except in the largest model basins (the thruster interaction tests described in Section 5.5 may be performed with a larger model).

5.6.2 Measurement Technique

These tests are similar to those described in Section 5.3, but with the addition of the working thruster system. In order to facilitate comparison with numerical simulations, it may be appropriate to perform a number of non-thruster assisted tests, as well as those with the thruster control system operational. One of the features of the thruster assisted mooring system is its ability to remove some of the slow oscillations of the FPSO on its mooring system under the influence of wave second-order effects.

A key feature of these tests is likely to be the investigation of the FPSO's performance in a series of different non-collinear metocean conditions. This is because the main benefit of an active thruster system is the ability to select the FPSO's heading in order to control the balance between wave motions, and wind or wave forces and moments. Consequently the tests need to be performed in a series of challenging non-collinear conditions which are credible combinations for the field location.

As with the tests described in Section 5.3, the key outputs are likely to be the FPSO's excursions and mooring line tensions. It may be possible to compare these measurements directly with results from numerical simulations for the prototype. It is also possible, however, that viscous scale effects in the mooring system, scale effects on the performance of the thrusters, and differences in the control algorithms represented on the physical and numerical models, may have to be corrected before comparisons are possible.

5.7 GREEN WATER OCCURRENCE AND LOADING REQUIREMENTS

5.7.1 Objectives

- To determine the frequency of green water on deck.
- To determine the severity of impacts on hull or topsides structures.
- To permit the design to be changed to reduce frequency and/or severity, or for the structure to be designed to an adequately low risk of structural failure.

5.7.2 Measurement Technique

Model preparation is similar to that described in Section 5.3, although additional instrumentation is required to measure the occurrence and severity of green water occurrences, and also perhaps impact pressures. Miniature resistive wave gauges can be mounted onto the FPSO model deck to measure the depth of water during green water occurrences. Pressure transducers can be mounted on deck or hull sections to measure impact pressures. It will also be appropriate to mount wave gauges over the side of the model to obtain a continuous measure of freeboard. It is normal to install close-up video to record the green water and impact events, and the model is usually painted with prominent grid markings to facilitate measurements from the video records, if these are required later. Video records are often the most useful way of assessing green water because individual point measurements are seldom in quite the right places.

Fundamental research into green water effects has made extensive use of regular and irregular long crested waves, but model testing in support of FPSO design needs to be performed in realistic extreme conditions. These metocean conditions will not be easy to select (see Section 4.2), but are likely to include non-collinear conditions or multi-directional waves (which can result in green water coming over the side, rather than just over the bow). As noted in Section 4.13, green water and wave impact may occur in relatively moderate conditions, where wave steepness and vessel motion response together conspire to create the impact velocity or the temporary loss of freeboard.

Interpretation of the various quantitative measurements itemised above is not easy. The measurements from the wave probes and depth gauges tend to become unreliable when the surface of the water is aerated and includes spray. Measurements from pressure transducers subject to impact or slamming loads tend to be influenced by air cushioning effects (which are not correctly scaled - see Section 3.3.3), and can also be contaminated by local structural effects. Interpretation is further complicated by the fact that the severest impacts are likely to be very rare events, and so many repetitions of severe sea-states may be required before sufficient data has been collected to permit a probability distribution for the green water, or for the impact load to be determined with any degree of reliability (see Section 4.9).

It may be particularly useful to analyse specific events in very great detail, perhaps obtaining additional data on inherent variability by repeating a test in the same wave sequence a number of times. This information, together with continuous measurements of relative wave elevation (rather than just rare deck overtopping events), may allow the designer to make changes which reduce the frequency of occurrence, or else the severity of green water or wave impact events.

The problem with modelling specific wave sequences or wave impact events is that it is usually very difficult to set the model test results into the context of the entire wave climate, and determine a probability that these conditions will occur. Furthermore, if the consequences of the impact or green water event are considered to be particularly severe, then very rare sea conditions may have to be considered (e.g. probabilities of 10^{-3} or 10^{-4} per year).

5.8 BEHAVIOUR OF AN FPSO AND SHUTTLE TANKER

5.8.1 Objectives

- To demonstrate that a shuttle tanker will be able to approach and connect to the FPSO safely.
- To demonstrate that the shuttle tanker will be able to remain safely connected to the FPSO.
- To help identify limiting metocean conditions for the above, and to identify what active station-keeping control is necessary (e.g. shuttle tanker maintaining astern thrust whilst connected).

The low frequency surging and yawing motions of an FPSO can in some circumstances make the approach by a shuttle tanker difficult and hazardous. This is particularly the case if the shuttle tanker is a trading ‘vessel of opportunity’ and does not have a dynamic positioning capability, or if the FPSO has no thruster assisted heading control capability.

Once connected to the FPSO by a hawser there is the risk that uncontrolled or excessive fishtailing, or surging motions of the vessels, could cause the shuttle tanker to overrun and collide with the FPSO.

The potential for collision between shuttle tanker and FPSO is an issue of considerable concern (e.g. [102, 103, 3]), and it is known that a number of collisions have occurred.

5.8.2 Measurement Technique

These model tests require the FPSO model to be set up on its mooring system, much as per the tests described in Section 5.3, but in addition a similarly prepared model of the shuttle tanker is required. The hawser connecting the FPSO and shuttle tanker must be represented, with a model hawser having the correct scale mass and elasticity properties. It may also be appropriate to include a model of the oil transfer hose system if the behaviour of this is to be part of the performance assessment. The shuttle tanker model may also be fitted with working thruster(s) and an appropriate remote control system. For thruster assisted FPSOs and DP shuttle tankers it may be appropriate to model the behaviour of the control systems (see Section 5.6).

Both vessels will be fitted with instrumentation to determine their location and heading, but owing to the fact that a primary concern may be the minimum clearance between the vessels, it may also be appropriate to install instrumentation to measure this specifically, such measurements being more accurate than clearances calculated from other measuring systems.

These tests are likely to be performed in conditions which are significantly less than the extreme conditions for the location, and it is therefore necessary to ensure that these conditions can be simulated adequately in the basin at the model scale, which may have been determined with the extreme conditions of Section 5.3 primarily in mind. The selection of metocean conditions will concentrate on those that are considered to be close to limiting for the shuttle tanker operations, and non-collinear conditions are likely to be of particular interest, particularly for FPSO systems without any active heading control.

The results of the tests of primary interest are likely to be measures which illustrate how close the operation is to acceptable limits. Thus hawser loads, minimum clearances between the FPSO and shuttle, and thruster activity are likely to be of greatest interest.

It must be recognised that the issue of safety of approach of the shuttle tanker to the FPSO has important human factor aspects associated with ship handling. These are difficult to deal with in the model test because, although it is possible to include a 'human in the loop' controlling the model shuttle tanker approach, at model scale there may be some handling advantages relating to the time scaling and to improved (birds-eye) view, which both need to be controlled.

5.9 INSTALLATION TESTS

5.9.1 Objectives

- To demonstrate that the FPSO installation procedures are practical.
- To refine and optimise these procedures.
- To identify metocean limitations on the installation process.
- To train personnel in the installation technique.

5.9.2 Measurement Technique

These tests will normally be conducted in a wave basin in realistic irregular, perhaps multidirectional, waves, and currents. The metocean conditions tested in the basin will normally be at the severe end of the likely installation weather envelope. This is due to the likely difficulty of reproducing low height and period sea-states at model scale (the model may have also been used for tests in extreme conditions, and the scale will have been set with these in mind). It is also driven by a desire to demonstrate a significant margin of safety in the severity of metocean conditions that can be accommodated.

In some parts of the world (e.g. West Africa) the dominant metocean factor may be a long swell condition which is invariably present whatever the weather conditions.

The installation issues to be investigated will depend on the specific design of the FPSO, its mooring / riser system, and the particular installation process being envisaged, and so it is difficult to generalise here. However the main issues are likely to be:

- Installing the anchor system (e.g. reference [30] emphasises the potential importance of vertical resonant motions of suction anchors during installation. This is because the inertia of these anchors is about 5 to 10 times the steel mass of the anchor.)
- Demonstrating the important avoidance of contact of synthetic mooring systems with the seabed during the installation process.
- Hooking the FPSO up to the mooring system.
- Demonstrating the adequacy of an incomplete mooring system in the largest credible storm in case the installation process is interrupted by bad weather.

Apart from gathering engineering data that can be used in the design of the installation process, these model tests can also be used as an invaluable training aid. Attendance at the model tests by personnel who are going to control the installation process, and hands-on experience of performing the installation at model scale, can provide physical familiarisation with the vessels and the systems to be employed. One difficulty is the inevitable Froude time scaling, which means that everything happens $k^{½}$ times faster than it will on the prototype. It might be assumed that this should make the task more difficult, and therefore a more powerful training experience because it gives the operators less time to think, but it has also been shown in the past that reducing the time scales can make the control of large ships (which are very slow to respond) easier because it brings their response times into a domain which it is easier for the human to relate to. It may also be appropriate to introduce delays into some of the control systems (e.g. thrusters) so that they do not respond too quickly to operator demands.

5.10 RELEASE AND RECONNECTION TESTS

5.10.1 Objectives

- To demonstrate that, for disconnectable FPSO mooring systems, the release process occurs in the intended manner in the appropriate design limiting weather conditions without causing damage.
- To demonstrate that the reconnection procedure is practical in the appropriate design limiting weather conditions.
- To help identify the safe limiting weather conditions for these operations.

5.10.2 Measurement Technique

Comments made in Section 5.9.2 about the difficulty of modelling relatively mild weather conditions in wave basins may apply here also, especially for the reconnection process.

It is difficult to generalise about test procedures, because much depends on the details of the mooring system and the disconnection and reconnection procedure. Details of measurements to be made, and visual records to be taken, will depend entirely on the connection design and the process being verified.

Specific tests for disconnectable systems include turret release and reconnection tests. The trajectory of the turret after release has to be considered, and this may depend on the instant at which release occurs in the sea state. This implies that the test may have to be repeated many times, releasing the turret at different points in the wave sequence, in order to identify whether there are any particular difficulties with particular wave sequences, or with the phasing of release relative to the waves. It has been pointed out [10] that a suspended buoy or riser will always pass through a condition of resonance with the sea state during reconnection, and the resulting enhanced loads should be considered. Several possible modes of oscillation may have to be investigated.

An example of a set of FPSO model tests including investigation of disconnection and re-connection were those performed on the Terra Nova FPSO described in [104].

6. REVIEW OF FPSO WIND TUNNEL TEST REQUIREMENTS

6.1 WIND AND CURRENT LOADING

6.1.1 Objectives

- To measure the mean forces and moments acting on the FPSO, and to present the results as non-dimensional coefficients which permit the full scale loads to be calculated for any given wind or current speed.

6.1.2 Measurement Technique

An initial series of tests should be performed to establish that the results are independent of Reynolds Number. This objective is achieved by repeating a set of tests over as wide a range of wind speeds as possible. If the results are independent of Reynolds Number, then the tests may be carried out at a single wind speed.

The force balance used for the tests should be capable of measuring all 6 components simultaneously. The forces and moments will usually be defined with respect to a system of co-ordinate axes fixed relative to the model. These are referred to as body axis forces, with the major components acting longitudinally, transversely and vertically.

For stability assessments, measurements on the below waterline parts might also be required. The results should be transformed to the wind axes system (defined as along and normal to the wind flow) along with the wind loading measurements. The wind and current measurements can then be combined to determine heeling moments for a stability analysis.

Wind forces and moments are usually required for a vessel operating at even keel. However, on occasions, there may be a requirement to test the model at a prescribed heel angle. This will normally be the case when it is necessary to consider damaged conditions, or when it is required to verify the wind overturning moment for the complete heel stability curve. This is more commonly done for semi-submersible production platforms than for FPSOs.

It is not particularly easy to perform wind force and moment measurements at a number of different heel angles. The model can either be sliced at a number of different waterlines corresponding to each heel angle, or it can be installed on a heel table which allows the model to penetrate the floor of the wind tunnel. This latter procedure is relatively flexible although it does require an appropriate aperture to be cut into the tunnel floor, and introduces the possibility of undesired flows and pressures being transmitted to the part of the model under the floor, or the possibility that the side of the aperture may touch the model causing errors in the force measurements.

Another method used for heeling tests is the so-called ‘slime tank’ method. The wind tunnel model is installed in a basin set into the tunnel floor, and a highly-viscous liquid is poured around the model until it is level with the tunnel floor. The model can then, in theory, be heeled at any angle without different tunnel floor cut-outs being required. However, in practice, this method involves extensive set up costs and introduces a number of practical problems, the most important being the distortion of the surface of the viscous liquid under the action of the wind pressure, and the effect this may have on the wind flow around the model.

As noted in Section 4.14.6, it is usual to run these tests at the highest convenient wind tunnel speed, in order to obtain the highest possible Reynolds Number. Force and moment results are normally presented in non-dimensional coefficient form.

6.2 WIND FLOW OVER THE HELIDECK

6.2.1 Objectives

- To quantify the effect of wind down-draft and turbulence on helicopter operations, and to ensure that, as part of the Operational Safety Case, the meteorological conditions that give rise to hazardous helicopter operations are passed to helicopter operators, and that the risk to personnel is as low as reasonably practical. This is achieved by measuring the mean and standard deviation, longitudinal and vertical components of wind velocity over the helideck and comparing the results with the appropriate criteria.
- To ensure that the platform design is optimised so that down-draft and turbulence do not compromise the safety and operational capability of the platform. This is achieved by combining the results with the site wind frequency data to predict the percentage of time that the helideck does not satisfy the criterion.
- Where any exceedances of the thresholds exist, to recommend modifications to the helideck or to issue notification to the relevant helicopter operators.

6.2.2 Measurement Technique

The technique for wind speed and turbulence measurements is usually based on constant temperature cross-wire anemometry. The cross-wire probe measures both the along-wind and vertical components of wind velocity and, prior to use, is calibrated against a reference anemometer used as a secondary standard.

6.2.3 Assessment Criteria

In the UK the criteria used are based on the vertical wind speed recommendations as set out by the UK Civil Aviation Authority in CAP 437 [105]. In summary, the vertical component of air flows resulting from horizontal wind velocities of 25 metres per second (48.6 knots) should not exceed $\pm$0.9 metres per second (1.75 knots) over the landing area at main rotor height.

As a result of recommendations made in [106] research is currently underway to devise a safe turbulence limit for helicopter operations, and to add this criterion to the UK guidance documentation. It is also likely that a new Helideck Design Guide will be developed and issued to provide a more comprehensive data source than is currently available in [105].

6.3 EXHAUST PLUME DISPERSAL

6.3.1 Objectives

- To quantify the effect of hot exhaust gases on helicopter or other platform operations, and to ensure that, as part of the Safety Case, the meteorological conditions that give rise to hazardous helicopter operations are passed to helicopter operators, and that the risk to personnel is as low as reasonably practical. This is achieved by measuring the mean and 3 second peak temperature rises above the helideck and at selected target points (typically HVAC intakes, muster stations, crane cabins and any other areas where personnel are likely to be working, or where temperature sensitive equipment is located) caused by the hot gases released from the exhausts, and comparing the results with the appropriate criteria.
- To ensure that the platform design is optimised so that hot exhaust gases do not compromise the safety and operational capability of the platform. This is achieved by combining the results with the site wind frequency data to predict the percentage of time that the helideck does not satisfy the criterion.
- Where any exceedances of the thresholds exist, to recommend modifications to the helideck or to issue notification to the relevant helicopter operators.

6.3.2 Modelling Technique

Modelling the exhaust plumes requires representation of the hot full scale exhaust by a gas mixture in the wind tunnel of the equivalent density. To achieve this, it is usual practice to create an appropriate mixture of helium and air which has the correctly scaled buoyancy. The flow rates at model scale are based on the Froude Number scaling requirement that wind speeds and exhaust velocities are scaled according to $k^{½}$.

The dilution of the model plume due to mixing with ambient air, and the resulting decay in concentration, are then used as an analogue of the decay in the heat content of the full scale plume. On this basis, it is possible to predict the full scale plume temperature rise from measurements of model plume concentration. [8]

Most offshore platforms and FPSOs will have a number of different gas turbine power generation units installed on board, and, if gas concentrations from each of the different sources are required, then it is usual practice to carry out separate tests for each source. An alternative approach would be to seed each release with a different gas and then use appropriate instrumentation designed to respond only to a single gas. This approach offers the advantage that any interactions between the different release sources is modelled, and may also result in a reduced requirement for wind tunnel time to perform the tests. However, tests of this type are relatively complex in terms of equipment, test set up and analysis, and also require that the likely operating combinations for the gas turbines are known at the time of the tests.

6.3.3 Measurement Technique

The model plume concentration is determined by measuring the local helium concentration using sampling instrumentation such as aspirating probes, which detect changes in the thermal conductivity, or flame ionising detectors. Prior to testing, the instrumentation is calibrated against known concentrations of the gas.

Because Froude scaling requires the wind speed, as well as exhaust flow rates, to be scaled, it is usual to repeat the test sequences over a range of speeds. This range is usually limited by the lowest wind speed at which the wind tunnel can operate in a stable manner.

6.3.4 Assessment Criteria

In the UK the results from the helideck tests should be assessed against thresholds defined by the UK Civil Aviation Authority in CAP 437 [105]. In summary, where ambient temperature, in the vicinity of the flight paths and over the landing area, is increased by more than 2°C the BHAB (British Helicopter Advisory Board) should be informed.

For areas where personnel are likely to be working, the criteria for noxious gas concentration should be used. This is based on safety requirements laid out by the Health & Safety Executive [107]. These specify long and short term exposure limits for a variety of gases which may be contained within an exhaust plume. Based on exhaust data supplied by the client, the wind tunnel results can be transformed into local concentration of these gases.

Criteria for other temperature sensitive equipment or systems are usually specified by the duty holder.

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[8] A correction is required due to the thermal expansion at the exhaust outlet, which is not modelled in the wind tunnel because the temperature of the plume is not modelled directly.

6.4 EMERGENCY GAS RELEASES AND FIRE SCENARIOS

6.4.1 Objectives

- To provide data on the likely impact of serious emergency conditions such as major gas releases and fires, which can be used in the Safety Case to demonstrate that the risk of key locations such as the Temporary Refuge, Muster Points, and the Primary Means of Escape (the helideck) becoming uninhabitable are as low as reasonably practical. This is achieved by measuring the mean and 3 second peak temperature rises above the helideck and at selected target points resulting from the accidental gas release and fire scenarios.
- To ensure that the platform design is optimised to keep this risk as low as reasonably practical. This is achieved by combining the results for any sites which do not comply with the criterion with the site wind frequency data to predict the percentage of time that they do not satisfy it.
- Where any exceedances of the criteria exist, to recommend modifications to the platform design.

6.4.2 Wind Tunnel Modelling and Measurement Techniques

For large scale gas releases and fire scenarios, where the flow field around the FPSO is the most important factor in dispersing and mixing the resultant plumes, and when peak concentrations as well as mean concentrations require measuring, wind tunnel testing techniques provide the most efficient and effective method.

The wind tunnel modelling and measurement techniques are similar to those described in the previous section for the exhaust plume dispersal tests. The density of the release at source is again represented by a gas mixture in the wind tunnel of the equivalent density. For fires and for buoyant gas releases this is achieved by a mixture of helium and air. For heavier than air releases, the correct density ratio cannot be achieved using a helium/air mix, and so alternative model test gases have to be used. For instance, a cold release of liquid propane, or a mixture of freon and argon, can be used. For near-neutral buoyancy releases, a mix of helium/ carbon dioxide can be used.

6.4.3 CFD Modelling

For small scale gas releases or fire scenarios within a process module or enclosed area, where the boundary conditions are well defined, CFD methods provide the most efficient and effective approach. For large scale gas releases or fire scenarios, when the flow rates are too high to be modelled in the wind tunnel, CFD provides the only way of obtaining a comprehensive set of results, even if the dispersion is dominated by the external wind flow.

CFD modelling is also a useful tool for modelling the spread of smoke, for example within an enclosed accommodation module, where the boundary conditions are again well conditioned. This can be used to aid the planning of evacuation times and strategies.

The results are normally presented in the form of isothermal sectional maps of temperature above ambient, and are assessed against various criteria of impairment such as optical density/visibility, oxygen depletion, carbon monoxide concentration, etc. Velocity vector plots may also be included if the air flow patterns require explanation.

6.4.4 Assessment Criteria

For areas where personnel are likely to be working, the criteria for noxious gas concentration should be used. These are based on safety requirements laid out by the Health & Safety Executive [108]. These specify long and short term exposure limits for a variety gases which may be contained within an gas or smoke plume. Based on source data supplied by the client, the wind tunnel results can be transformed into local concentration of these gases.

Criteria for other temperature sensitive equipment or systems are usually specified by the duty holder.

6.5 NATURAL VENTILATION

6.5.1 Objectives

- To assess the natural ventilation within the process areas of the FPSO, combine the results with wind frequency data and compare against the relevant criteria.
- To recommend any necessary modifications to the platform design to improve the ventilation conditions.

6.5.2 Natural Ventilation Assessment

The flow within an FPSO process area is highly three-dimensional, with the location of any poorly ventilated areas difficult to predict and partly driven by buoyancy flows from hot process equipment. In order to predict the ventilation rates at a large number of locations, CFD techniques represent the most appropriate method. CFD models can now use CAD data files as input to the model construction phase, which improves accuracy, and affordable computing resources allow items greater than about 0.5 m diameter to be represented explicitly, and congested regions of pipe work, cabling, etc. to be represented implicitly as porous regions with an associated pressure drop.

The boundary layer profile for the oncoming wind is specified according to well established profiles such as those recommended by ESDU [84].

The analysis is conducted in two phases. Firstly, a steady state CFD analysis is carried out to establish the flow field around and through the platform. Based on the steady state solution, a transient analysis will then be conducted with a neutrally buoyant tracer introduced at time zero to the process areas. As the solution continues with time, the tracer will be gradually diluted or replaced by fresh air. The model will be run for 300 seconds (corresponding to 12 air changes per hour). Regions within the process areas without significant amounts of tracer gas present at this time will therefore have achieved the 12 air change rate criterion.

The results obtained are then combined with the site wind frequency data to predict the percentage of time that the process areas do not satisfy the criterion. If the results do not meet the criterion, then recommendations for modifications to the platform layout can be made.

6.5.3 Assessment Criterion

The criterion to be used for this assessment is specified by the HSE [109] as 12 air changes per hour for 95% of the time.

7. ALTERNATIVE TYPES OF FLOATING PRODUCTION

The term FPSO is normally taken to mean a ship shaped vessel, and the principle feature of such floaters is that the environmental loading experienced is highly dependent on the relative direction from which the environment comes. Motion responses, natural frequencies and damping are also quite different in the longitudinal and transverse directions.

The other principle alternative types of floating production, discussed in the following, tend to have less directionally-dependent properties, but some have other special properties which have important implications for model testing and its input to the design process. Their mooring systems do not normally permit any change in heading, and so they do not have the mechanically complicated and expensive turret mooring systems often fitted to FPSOs.

7.1 BOXES

There have been a number of box-like designs proposed for floating production. These are rectangular constructions with length and beam dimensions the same, or similar. They are generally intended for installation in less severe environments, and their attraction lies in simple robust construction coupled with significant oil storage capability, and relatively low cost deck space and payload carrying capacity.

The main distinguishing features of their performance and model testing requirements, when compared with a conventional FPSO, are:

- Broadly omni-directional performance.
- If sharp edged, then there is the probability of less scale effect on current drag forces.
- Green water on deck may be an issue in extreme conditions.
- Wave drift forces may be high. Consequently second-order low frequency excursions may be large.
- Large amplitude roll/pitch motions may occur if particular unfortunate wavelengths of incident waves are encountered.

A special intermediate case between the conventional FPSO and the ‘box’ is a very short broad beam hull form such as the Ramform *Banff* FPSO. Although fitted with a turret mooring system and in principle able to weathervane, environmental responses are likely to be more omni-directional than a conventional hull form, and most of the points noted above for a ‘box’ apply to some extent.

7.2 SEMI-SUBMERSIBLE PRODUCTION PLATFORMS

There have been a number of purpose-built and drilling vessel conversion semi-submersible floating production systems. These are normally chain/wire catenary moored, although some taut synthetic mooring line systems are now being pioneered in very deep water.

The motions of semi-submersibles in waves are generally much less than those of FPSOs, but are still generally too large to allow permanent rigid risers and ‘dry trees’ to be used, and so production is invariably through flexible or catenary risers from subsea well heads. The design issues relating to these risers are therefore similar to those for FPSOs. However, a new design of dry tree semi-submersible production system has recently been announced [110]. This is intended to employ a self supporting riser system similar to that used on Spar Buoy Production Units (see Section 7.4).

The main distinguishing features of a semi-submersible’s performance and its model testing requirements, when compared with a conventional FPSO, are:

- Semi-submersibles are designed specifically to minimise wave motions, and so their seakeeping properties will usually be superior to FPSOs. Natural frequencies of all the six degree of freedom motions are low, and generally outside the most common wave energy frequency bands experienced in the oceans.

- Wave drift forces are much lower than for an FPSO, and consequently low frequency second-order responses of the mooring system are much less important.
- Although most semi-submersibles do not have quite the same properties for beam and head environments, their responses are much more nearly omni-directional than for an FPSO. Consequently there are usually no particular difficulties in dealing with non-collinear metocean environments.
- By careful choice of column diameters and pontoon immersion depths it is also possible for the designer to arrange for there to be virtually zero heave forcing at certain wave frequencies. There is a similar situation for pitch and roll forcing, and this gives the designer some scope to design a vessel that will respond as little as possible to a given target operational wave environment.
- At the longest wave periods, and in the highest waves, the vessel will normally tend to heave and pitch more. The heave motion is likely to be beneficial in maintaining clearance between wave crests and the underside of the deck ('air-gap'). However, unfortunate phasing of roll or pitch motions can sometimes result in reduced air gap at the deck edges. Measurement of air-gap may therefore be a key model testing parameter (see also Section 7.3). In this context it is worth noting that there have been a number of occasions when the undersides of semi-submersibles have been hit by waves in circumstances where calculations suggested that they should not have been. Model tests have shown narrow 'jets' and sheets of water projected upwards between the legs of a semi-submersible [111], and apparently similar phenomena have been observed between the legs of gravity structures [112]. These phenomena cannot be explained by simple linear wave diffraction theory, and occur when the legs are of only moderate diameter.
- Larger purpose-built semi-submersible production units may be designed to operate continuously at a single draft, and with no adjustments to the mooring system. However, drilling vessel conversions operating in severer environments may be required to ballast up to a shallower 'survival' draft when severe weather is anticipated, in order to maintain an acceptable air gap, and perhaps also adjust pay-outs in mooring lines in order to share the mooring loads. Consequently model tests may be required at more than one draft, and with more than one mooring system configuration. The selection of appropriate metocean conditions for such tests may therefore also need to consider the severest credible un-forecast storm.
- Semi-submersible production platforms are not large enough to contain any significant production storage, so there may be further model testing issues relating to a separate storage unit and/or a loading buoy system.

7.3 TENSION LEG PLATFORMS

Early large tension leg platforms (TLPs) were of the multi-column semi-submersible design (e.g. *Hutton*, *Heidrun*) with four or six large diameter columns. More recently smaller platforms designed for the Gulf of Mexico have tended to have thinner columns or even a deck supported on a single column.

The unique mooring system consists of vertical tethers connecting the hull to the seabed, and the hull is de-ballasted after installation so that there is sufficient excess buoyancy to ensure that the tethers remain in tension, even in the most extreme wave conditions. The relatively stiff vertical tether restraint means that the vertical motions (roll, pitch and heave) are restrained to very small amplitudes and have quite high natural frequencies. The horizontal motions (surge, sway and yaw) experience much lower stiffness, and these responses are thus similar to those of a catenary moored semi-submersible.

The main distinguishing features of a TLP's performance and its model testing requirements, when compared with a conventional FPSO, are:

- Importance of wave deck impact as a design issue. This is because, unlike a semi-submersible, the hull cannot heave in phase with the longer frequency higher amplitude waves. Also relatively large diameter columns can result in significantly higher wave amplitudes underneath the hull due to wave diffraction/refraction effects. Furthermore, the geometry of the mooring system means that the TLP 'sets down' in the water at the extremes of surge motion, further reducing the available air gap.

- The parallelogram-like geometry of the tethering system, which restrains the TLP from moving in pitch whilst permitting large movements in surge, also means that there is usually a large pitching moment which must be resisted in the tethers. This pitching moment arises partly as a result of the TLP's surge motion, because its centre of gravity tends to be very high. Accurate modelling of the vertical centre of gravity is therefore essential if tether tensions are to be properly represented in the model tests.
- Importance of second-order wave forcing, but whereas for the FPSO it is only the low (difference) frequency components which are important, for a TLP it is also possible for the high (sum) frequencies to excite high natural frequencies of heave and pitch/roll. These high frequency, small amplitude motions may be important for the fatigue life of the tethers and anchor system [113, 114].
- The occurrence of the phenomena of tether 'ringing' [115], which can occur in steep random waves, may also be important for fatigue.
- Potential scale effects on the damping of these small amplitude motions may also be problematical [116, 117].
- Mention has been made of the likely importance of including risers in the model testing of FPSOs because of the motion damping component in deep water. In the case of the TLP, the modelling of the risers can also be important because of the tethering force provided by the risers. Although this is unlikely to be a large proportion of the total tether tension it is nevertheless usually too large to be ignored.
- TLPs tend to be designed with a large number of parallel and redundant tethers. It should be remembered that appropriate load sharing between these redundant tethers will not be represented in the model test unless the TLP hull model is constructed with appropriately scaled structural stiffness characteristics. This is usually impractical, and so in a model test the tether redundancy will often be eliminated or reduced (say by replacing four tethers at one corner with a single equivalent tether). Each model tether or its anchor point will normally be fitted with a spring to represent the appropriate full scale axial stiffness.
- The installation of TLPs poses some difficult issues which may require model testing. Holding the TLP accurately in position, so that the tethers can be connected, may require a separate temporary mooring system and/or the use of a number of DP vessels operating in close proximity. The transition experienced during de-ballasting from free-floating to seabed-tethered is also difficult. Model tests may be required specifically to demonstrate that bad weather experienced at these critical times in the installation will not be disastrous.
- As with semi-submersibles, TLPs are not large enough to contain any significant production storage, so there may be further model testing issues relating to a separate storage unit and/or a loading buoy system.

7.4 SPAR BUOYS

Spar buoys have become a popular production platform concept in recent times, particularly in the Gulf of Mexico. They generally consist of a large deep draft vertical cylindrical hull. Those installed to-date have been quite large platforms with full production and drilling capability, but there are currently also plans for smaller systems with more limited top-side capability (e.g. no drilling). These systems have to date employed chain/wire catenary mooring systems.

The hull is large enough to accommodate a significant amount of oil storage. Risers are usually rigid vertical and self-supporting, using buoyancy cans which can slide inside the spar to accommodate the (small) spar heave motions, and the riser set-down when there are large surge excursions. Dry trees can be installed on the tops of these risers.

The large size and deep draft of the spar buoy mean that natural motion frequencies are very low and wave frequency motions are therefore small. However, there is the possibility for low frequency resonant motions driven by second-order wave effects and wind gusts.

The main distinguishing features of a spar buoy's performance and its model testing requirements, when compared with a conventional FPSO, are:

- Amplitudes of the low frequency motions are, as usual, much dependent on the hydrodynamic damping induced by the hull and mooring systems. These are potentially subject to significant scale effects (see Section 4.4) and require care when model testing.
- There may be a major scale effect on the current drag experienced on the cylindrical spar hull.
- The cylindrical spar hull may suffer from vortex shedding in a current (or in the largest/longest waves) - see Section 3.3.1. This might induce large transverse oscillatory motions. Spars installed to date have included some strake vortex suppression devices on their hulls. These strakes have themselves resulted in some hydrodynamic loading fatigue design issues [118].
- Transportation from the building yard is likely to be made with the hull horizontal, and so installation will involve first an upending to the vertical followed by the installation of an integrated deck. These aspects may each require special model testing.

7.5 OTHER SYSTEMS

There have been a number of other deep draft floating production systems proposed which mostly have model testing requirements similar to the spar above. One example is the Deep Draft Floater (DDF) described in [119].

Another type of buoy floater design, but not a spar, is the Buoyform FPSO proposed by Maritime Tentech [120]. This is a conical shaped buoy with a skirt at the bottom. The design is claimed to have excellent motion characteristics and a high degree of damping.

There are also a number of cases where combinations of floating systems operating in close proximity have been proposed. An example is given in [121] which described the results from a conceptual study to develop a new structure combining a TLP and barge.

Four different floater designs are described in [122], including the Mono-Column Type, the Floating Dock Type, the Three-Islander Type, and the Angular-Hat Type. The paper compares the wave motion characteristics of these designs, which were developed in an attempt to combine the reliable hull structure of a ship with the good motion characteristics of a semi-submersible.

Clearly there are almost infinite possibilities to develop new floating concepts and new combinations of existing ideas, and their model testing requirements can only be evaluated following a detailed investigation of their properties and likely static and dynamic responses to the metocean environment.

8. MODEL TESTING AND COMPUTER SIMULATION

It has been noted in Section 2.2 that the role of model testing has changed over the past years. Whereas at one time model tests were used as the primary source of design information, today it is much more common for the model tests to be used as a calibration check on numerical simulations. With FPSOs this has become essential owing to the very large number of different metocean conditions that may have to be analysed in order to obtain design data in extreme loading conditions (Section 4.2).

Model testing and computer simulation have always been complementary techniques. It is often necessary to complement model tests with analysis in order to gain understanding of the system performance. Numerical models usually provide much greater scope for parameter variations than is possible in a model test programme [39].

Although a physical model guarantees complete modelling of the physics, it may be the ‘wrong’ physics, being affected by model scale. Furthermore model tests do not explain why things happen [58]. It is only possible to be confident about why things happen when the physics is represented well in a numerical model. Numerical simulations aid understanding of complex systems, and allow behaviour to be assessed over a wide range of different environmental and operating conditions, but they only include known effects.

There are a number of aspects of offshore hydrodynamics which cannot yet be solved by numerical simulation alone. These include viscous effects, such as roll damping of ships and vortex-induced vibrations of risers. Major advances have been made in computational fluid dynamics (CFD), but as yet these techniques can only be regarded as a partial solution to the problem. Further examples of difficult areas for numerical simulation are wave drift force and relative motion prediction in extreme waves [80], interactions between FPSOs and shuttle tankers, and DP thruster interactions.

In the context of deep-water moored FPSOs the integrated use of model tests, numerical simulations and full-scale measurements are all clearly essential components in the determination of system performance. It may be important to take account of the effects of mooring and riser dynamics on low frequency motion damping of the FPSO, line and riser dynamics on the quasi-static line and riser loads, and also direct current and wave loads on the riser and moorings. These effects can become very significant in very deep water, and, as has been seen in Section 4.10, it is not always possible to represent them even in the most up-to-date model basin [123]. For ultra deep water (>1000m) passive equivalent mooring systems or active equivalent mooring systems are preferred to ultra small scale testing (1:>>100), and these require numerical simulation to facilitate the determination of the characteristics of the hybrid or equivalent system.

9. THE ROLE OF FULL-SCALE MEASUREMENTS

Model tests fully represent the physical processes, although they may be influenced by scale effects, whereas numerical models contain only those physical processes that are known and understood, and often require certain empirical coefficients to be input. These coefficients are themselves often subject to scale effects. Measurements made at full scale in the ocean fulfil an essential role in filling in some of the gaps in knowledge.

In terms of meeting the practical need for validating a numerical model, or evaluating scale effects in a model test, the advantages and disadvantages of full-scale measurements may be summarised as follows:

- There are no scaling problems;
- The metocean environment is realistic;

but:

- No control is possible over the metocean environment, and it may be necessary to make measurements over a very long period in order to obtain the required range of conditions;
- Measurements may be impossible or unreliable in the severest conditions (just when they are of greatest interest);
- It may be difficult to measure the metocean environment in sufficient detail or with sufficient accuracy or reliability (e.g. wave directional spreading);
- An investigation cannot advance in a gradual and logical manner, validating each element of the numerical model in turn.

An example of a full scale measurement project related to an FPSO is given in [124] which presents results from a full scale surge decay test made with a tanker in a relatively protected area off the Brazilian coast. This made it possible to check the damping of the hull and mooring lines. Theoretical models predicted about 75% of the measured damping, and the remaining 25% could not be accounted for, but was believed to be due to the metocean conditions and due to mooring friction with the seabed.

An example of a project which made use of tests on small and large scale models under controlled conditions, as well as full scale trials, is the STRIDE joint industry project [125]. Tank tests were performed at small scale on a long catenary riser model, to investigate response to motions of an attached floater. Vortex-induced vibration and suppression devices were then tested at large scale in a towing tank, and then in a current, and finally tests were performed on long full scale riser strings by towing in a Norwegian fjord. The measurements were correlated with numerical predictions using a finite element model. Work is continuing, with full scale trials underway at a coastal location where strong tidal flows provide the required VIV excitation.

Other measurements of system performance are made on systems in service, and [126] describes the analysis of drilling riser accelerations measured at the *Schiehallion* field, and interprets the riser response and current profile measurements in terms of better understanding of the single and multi-mode response behaviour. The authors obtained best fit estimates of the reduced velocity bandwidth for drilling riser modes observed in the response data. The results are being used to improve VIV response prediction tools.

One of the largest full scale measurement programs performed to date on an FPSO is the 'FPSO Integrity' JIP [9] conducted on the *Glas Dowr* [127, 128, 129, 130, 131, 132]. The project has focused particularly on fatigue loading.

9 The project is run by MARIN, Bluewater, and BV, and is funded by the EU Thermie Programme, the Dutch Government, ABS, Amerada Hess, Astano, Bluewater, BV, Chevron, Conoco, DnV, Exxon, Germanischer Lloyd, HSE, Hyundai, Lloyd's Register, MARIN, Mitsubishi, Nevesbu, Petrobras, Shell, Statoil and Texaco.

10. CONCLUSIONS AND KEY ISSUES

FPSOs are complicated dynamic systems which have complex responses to the metocean environment. Physical model tests usually play an important role in their design, though the analysis and interpretation of the results of such tests places increasing reliance on theoretical analyses and computer simulation. This tendency will become even more important as water depths increase and it becomes impossible to represent the entire FPSO, mooring system and risers in the model basin. Reliance will also have to be placed on ways of representing the deep parts of the system with passive or active equivalent components.

The main conclusions on the key issues influencing the model testing of FPSOs are summarised in the following:

1. There is usually no clearly identifiable worst case metocean condition in which to test an FPSO. Model test cases must therefore cover a broad range of conditions, and their results can normally only be interpreted for design with the help of a larger number of computer simulations which the model tests are used to calibrate. Ultimately the design basis may rely on response-based or reliability methods which can be used to identify the worst credible metocean conditions and estimate the risk of failure.

2. A number of different metocean conditions may be required for the study of different FPSO design issues.

3. Worst case design loads or motions for FPSOs will often be experienced in non-collinear metocean conditions.

4. Extreme responses in surge, sway or yaw are generally associated with low frequency oscillations of the vessel on its mooring system. Very long model test run durations (or assemblages of similar runs in different realisations of the environment) are therefore required in order to obtain reliable extreme values for design. Tests to define extreme responses in a single metocean condition may have to run for up to 18 hours (or longer) at full scale. Extreme values for heave, roll and pitch are dominated by wave frequency effects, and can be determined from much shorter runs.

5. Viscous scale effects on the drag of mooring lines and risers can significantly increase the overall model mooring system damping, particularly in deep water. Unless steps are taken to counteract the effect (e.g. by reducing the diameter of the model mooring lines) this will result in reduced extreme excursions and non-conservative model test results. Alternatively model test results need to be corrected for these effects via computer simulation.

6. Hydrodynamic model tests for very deep water fields pose particular problems. It may be possible to develop ultra small scale model test procedures (say down to 1:200 scale) but in today's deepest existing and planned model basins this will still only represent a depth of about 2000m. Fields are planned in much deeper waters. Hybrid passive equivalent or active equivalent systems are the only practical way of performing model tests for such depths, and emphasise the inevitable increasing reliance on theoretical methods and computer simulation for these depths.

7. Turret moored FPSOs can be natural weathervaning or thruster-assisted. The former requires particular attention to be paid to the representation of realistic non-collinear environments. Careful selection of the turret location is an important design decision, it being necessary to ensure that it is placed sufficient far forward to provide the required weathervaning properties, whilst not be so near the bow that dynamic mooring loads and riser responses are excessive. Thruster-assisted systems offer the opportunity to place the turret much further aft, with the associated mooring and riser benefits, and it is easier to ensure that the FPSO takes an optimum heading to non-collinear metocean environments. Model testing emphasis may therefore switch to optimising the thruster arrangement, determining thruster hull interactions, optimising the DP control system, and demonstrating that adequate station-keeping capability still exists following the most serious credible failure.

8. The potential for structural damage due to wave impact and green water on deck is now recognised as an important aspect of design for FPSOs operating in severe environments. Theoretical methods for the prediction of such effects are not yet mature or reliable, and so reliance must be placed on model tests. The Joint Industry Project on FPSO Green Water Loading has produced the *GreenLab* software for green water design assessment, but this product is currently still confidential to the JIP participants, and cannot therefore yet be evaluated and validated by the industry as a whole. It is clear that the occurrence of severe green water events can depend very much on the exact sequence and shape of the waves, however, and it may therefore be very difficult to interpret model test results in terms of the risk of damage to the prototype operating in the real metocean environment. If the consequences of such impacts of green water events are considered to be severe, then tests in conditions with very low probabilities of occurrence may be required (e.g. 10^{-3} or 10^{-4} per year).

9. Operability or downtime is an important issue in the design of FPSOs for harsher ocean climates. One special aspect of operability, which can also have safety connotations, is the occurrence of seasickness and the possibility that human performance may be significantly degraded.

10. Wind tunnel tests can play an important role in providing FPSO design data, particularly for the estimation of wind and current loads. It is not possible to obtain this information reliably from tests where current and wind are also modelled in a wave basin. In view of the much inferior wind and current flow quality in the wave basin, wave tests should seek to reproduce the wind forces measured in the wind tunnel and current forces measured in the towing tank (or wind tunnel) rather than setting the scale wind/current speed.

11. Wind tunnel tests are also used to demonstrate that helidecks do not suffer from excessive turbulence, downdraft or hot gas exhaust problems, and are also important in providing evidence in support of Safety Cases, particularly for predicting the dispersion of gas releases. However, a number of the flow issues, including internal ventilation, can now also be tackled economically using Computational Fluid Dynamics (CFD). CFD is also being used extensively for modelling explosion scenarios.

11. ABBREVIATIONS AND NOTATION

Abbreviations:

BMT	BMT Fluid Mechanics Limited
BHAB	British Helicopter Advisory Board
CAA	Civil Aviation Authority
CFD	Computational fluid dynamics
CG	Centre of gravity
DP	Dynamic positioning
ESDU	Engineering Sciences Data Unit
EU	European Union
FPSO	Floating Production, Storage and Offloading unit
HSE	UK Health & Safety Executive
JIP	Joint Industry Project
RAO	Response amplitude operator
TLP	Tension leg platform
UK	United Kingdom
ULS	Ultimate limit state
VIV	Vortex induced vibration

Notation:

D	Diameter
f	Frequency
E	Young's modulus
F_n	Froude Number
F_x	Force acting in the X (surge) direction
F_y	Force acting in the Y (sway) direction
g	Acceleration due to gravity
GM	Metacentric height
H_s	Significant wave height
I	Moment of area
J	Thruster advance coefficient
k	Scale ratio
K_t	Thrust coefficient
L	Length
M_z	Moment about Z axis (yaw)
r	Ratio of salt water density to fresh water density
R_e	Reynolds Number
S	Strouhal Number
t	Thrust deduction factor
T_z	Zero up-crossing wave period
U	Velocity
ν	Kinematic viscosity
V_r	Reduced velocity

12. INDEX

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