



**Hermione van Zutphen** and **Marios Christou, Shell**, describe the validation of the FPSO LSM analysis suite, a probability-domain model based on the Spectral Response Surface

method (SRS) for predicting the motion and load responses of floating systems with turret or spread-mooring and estimating response-based metocean design conditions.

#### [ Key Fact ]

- Tromans and Vanderschuren introduced the load statistics method in 1995, allowing the efficient and fast calculation of responses to each sea-state in a long-term hindcast database.

# Ready to ripple

**H**istorically, independent extreme metocean conditions for wind, waves and current were provided for design. These were then combined to determine the loading on offshore structures.

For example, the 100-year wind, wave and current were all taken to act on an offshore structure simultaneously. However, this proved to be hugely conservative and led to several standards recommending various combinations of wind, wave and current with different return periods. For example, in the design of floating bodies, generally a combination of the 100-year wave, 100-year wind and 10-year current is recommended in design codes.

Although an improvement, the actual return period of such a combination is unknown and therefore it is also unknown whether this design condition will lead to an under- or over-designed structure. It was necessary to develop an alternative method, capable of deriving the response-based criteria using the initial design of the structure and a metocean database. Instead of deriving the extreme independent metocean parameters, the metocean hindcast database is used to calculate the governing responses of the structure. From the responses, the extreme response is derived using the knowledge of the environment and the behaviour of the structure in this environment.

Calculating responses for each sea state in a metocean database is a time-consuming task when using an industry

accepted method such as time-domain analysis, and non-linearities are difficult to deal with when using a frequency-domain method. Therefore, the SRS method was implemented, which enables the software to efficiently calculate most probable maximum responses in the probability-domain.

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Accordingly, this provides response-based criteria that achieve both significant cost savings while maintaining the required level of safety. The floating systems model has been successfully applied on Shell projects located around the world including Brazil, Nigeria and Australia, while the fixed structures version was employed for installations in the North Sea as well as in Australia.

In 1995, Tromans and Vanderschuren introduced the load statistics method (LSM), which uses asymptotic properties of extremes to calculate most probable maxima of the governing responses of a drag dominated (fixed) structure – overturning moment and base shear. The method used a simplified

response model, allowing the efficient and fast calculation of responses to each sea-state in a long-term hindcast database. This enabled analysts to calculate extreme waves, loads and response-based environmental design conditions in the North Sea. The method has been used extensively for the development of response-based design conditions and reliability assessments of fixed structures in the North Sea, Gulf of Mexico and the North-West Shelf of Australia.

Following the success of the LSM for fixed structures, an extension for turret moored floating structures was developed during the EU Joint Industry Project (JIP) 'Reliability based structural design of FPSO systems' (REBASDO) in 2002. As it's a more complex problem unlike the generic load models for fixed structures, it includes dynamics. It is dependent on both magnitude and directionality of metocean input variables such as wind, sea, swell and current. Therefore, a separate response module was needed to build the response database corresponding to the long-term metocean hindcast. The original LSM code is then used to calculate the long-term extreme responses including short-term variability. The combination of the two processes became FPSO LSM.

### Description of response model

A long-term database is calculated for the governing responses of the fixed or floating structure. The long-term database of metocean conditions and responses can be used to assess operability criteria of the system. The extreme responses of the floating system are then used when designing such structures so a response-based design condition can be obtained from the inverse calculation of a sea state.

For drag-dominated structures, the extreme base shear and overturning moment responses are governed by either extreme wave height or current speed. The inverse calculation of the response-based design condition for this kind of structure is therefore relatively straightforward – and can even be simplified to an extreme n-year wave condition or extreme n-year current speed as opposed to an extreme response-based design sea state. For floating structures, this inverse calculation

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is more complex and the response based design condition will be a combination of wind, waves and current and their relative directions.

The dynamic equations of motion of the system are solved using the spectral response surface method, which is substantially faster than an equivalent time domain analysis. Also, it incorporates non-linearities in loading, contrary to a frequency domain method, which is in principal linear. The spectral response surface method uses the stochastic nature of the governing variables wave height and wind gust in the equations of motion.

The wave and wind frequency components are transformed to standard normal variables by dividing them by their

### FPSO LSM analysis suite

The FPSO LSM analysis suite is a probability-domain model based on the spectral response surface (SRS) method for predicting the motion and load responses of floating systems with turret- or spread-mooring and estimating response based metocean design conditions. The advantages of using the probability domain as opposed to frequency- or time-domain models include its rapid execution time and the calculation of most probable maximum responses. These two factors allow FPSO LSM to be applied to large metocean hindcast datasets in order to develop metocean operational and extreme value design criteria, which are essential for the design of offshore floating structures such as FPSOs.

Given the environmental conditions (wave, wind and current), a set of hydrodynamic coefficients and the mooring configuration, FPSO LSM can calculate the first-order response motions, including heave, pitch and roll, and the second-order offsets. Extensive validations of the various responses with measurements and existing numerical models have been performed. The predictions from FPSO LSM compare favourably with measurements and other numerical models. This confirms the validity of the FPSO LSM for predicting responses from long metocean hindcast datasets and establishing reliable response-based design and operating conditions.

standard deviation. Phase information is included by the Hilbert transform of each variable. The resulting equations are now defined in the unit-variance normal space. A certain event can then be related to a probability of exceedance.

### Validation

The objective is to generate probability distributions for metocean and response variables from a metocean data set. These, in turn, are used to estimate an extreme design sea state corresponding to the desired n-year response. As there is no direct way of validating our probability distributions and the software might be used for reliability checks, the most obvious validation is through the comparisons of predicted responses to a single sea state, either with other vessel motions software, model test data or full scale measurement data.

Different validation exercises have been undertaken internally and externally since the first development of the vessel motions software RSP. For vessels ranging between block coefficients of 0.8 and 0.92:

- comparisons with other vessel motions software SPMsim (SeaSoft Systems International), Aqwa (ANSYS) and Dynfloat (Marin)
- comparisons with model test data for several projects and research JIPs
- comparison with full scale data.

### Roll

Roll is a difficult motion to predict. It depends on wave spreading and vessel heading. It is made more complicated as the motion is governed by linear and viscous roll damping and dependent on the actual roll velocity.

As RSP has been developed to analyse large numbers of sea states, with components spread over all directions and including wave spreading, it adopts a time and

computationally efficient method to account for viscous roll damping dependent on the encountered wave height. In particular, the viscous roll damping modelled in FPSO LSM is based on an empirical model derived from extreme roll amplitudes obtained during model tests and based on the following assumptions:

- The model is basically a drag model for the flow around the corners of the hull and bilge keels.
- The drag coefficient (at large Keulegan–Carpenter numbers) will be 1.5 to 2.5.
- The velocity at the keel will increase with distance from the roll centre to the keel.
- The roll and the damping coefficient will increase with significant wave height. The sensitivity to significant wave height will depend on the beam and draught of the ship.
- Current will increase the damping.

‘Inline cases without spreading in model basin tests often demonstrate some degree of roll motion even though this is not expected for symmetrical vessels.’

Generally, the comparison with Aqwa for the roll RMS motions is good. The main differences are due to the different formulation for non-linear roll damping used in the two packages and Aqwa not being able to model short crested seas. RSP calculated some roll motion in inline cases due to the short crestedness of the waves.

Inline cases without spreading in model basin tests often demonstrate some degree of roll motion even though this is not expected for symmetrical vessels. The theoretical approach in unidirectional waves results in zero roll, as demonstrated with the Dynfloat analysis (no spreading model possible) and RSP without spreading. However, when trying to account for the reflection side effects in the tank by modelling some amount of wave spreading (by using RSPs spreading model), the roll motions are overestimated. Spread sea states are more representative of reality (real oceans) than long crested waves.

### Offsets

The vessel offsets are due to wave, wind and current loading and low frequency wave effects. In RSP a simplified model of the mooring is used to enable a time and computationally efficient calculation of the mean offsets and a statistical description of the dynamics around the extreme. Validations have shown reasonable agreements with analysis tools and model tests.

In the REBASDO JIP, the probability distribution of the offset was calculated from the model tests, which compares favourably with the statistical description of the dynamics around the extreme derived with RSP.

### Cross-sea environments

In reality, sea states with two or more short crested wave systems from different directions are observed regularly. To obtain reliable metocean design conditions, it is important to describe sea states with multiple frequency components and directions accurately and to be able to analyse the effect of these components on the vessel motions. RSP accepts up to seven wave systems, each described with a significant wave height, peak period, wave direction and spectral parameter.

FPSO LSM uses the Ewans’ spreading models for wind sea and swell, which are then applied to calculate forces and responses for mean drift, slow drift and wave frequency responses. However, the amount of validation data available for cross seas is limited; most model tests are done with only one wave system or with relatively small angular differences between systems if more than one is considered, and full scale measurements are scarce.

For the validation of the analysis of cross seas, full scale measurements for a turret moored vessel offshore Brazil was used. Six sea states were identified for which sufficient information was available; loading condition, heading, heave, roll and pitch of the vessel and measured wave spectrum (wave buoy), wind speed and direction (on board anemometer) and current speed and direction (distant buoy).

An analysis that addresses the issue of how many wave partitions should be considered in each sea state when looking at long-term metocean hindcast data sets has been undertaken. In evaluating vessel response in a given single sea state, it is recommended that the wave spectrum should be represented as accurately as possible, but if this is undertaken for long-term datasets it has some implication on the processing time.

A sensitivity study was performed to look into the effect of running bimodal or multimodal sea states. The main differences in vessel heading and motions are observed at less severe sea states, where the occurrence of multi-modal sea states is more likely. However, there is no apparent long-term bias introduced in estimated vessel response when these same sea states are represented by bimodal sea states if we combine swell systems for sea states when there are more than two partitions. ●

### [ Hermione van Zutphen and Marios Christou ]

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