An Evaluation of the Fatigue Performance of Subsea Wellhead Systems and Recommendations for Fatigue Enhancements

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Abstract
The specification and selection of subsea wellhead systems is typically based on the use of generic system designs which have a defined extreme load capacity. However the fatigue performance of the wellhead system is also a critical aspect of the equipment which may not always be fully evaluated at the specification and selection stage, as the fatigue life is specific to field design parameters. These parameters can include local environmental loading, drilling rig motions, marine riser stack-ups and BOP configurations, and soil conditions, as well as operational parameters such as riser tensions and mud weights which can vary during different stages of the drilling, completion and work-over operations.

This paper will highlight through the use of analytical results the sensitivity of typical wellhead system designs to changes in these design parameters. This will provide an indication of the significance of these parameters on fatigue life predictions for subsea wellhead and conductor systems, and identify scenarios where fatigue is most likely to be of concern.

Where fatigue lives are marginal, restrictions on usage such as environmental or connected riser duration limits may need to be imposed for operations. Alternatively fatigue enhancements to the conventional wellhead and conductor system designs and configurations may be required. If identified at an appropriate stage, some of these enhancements can be readily achieved and implemented during the equipment design and manufacture process.

This paper shall discuss the potential for the use of these enhancements, identify how best they can be achieved, and show how making these enhancements in the conductor system design can have significant effects on the fatigue life of the wellhead installation. Designing the correct conductor system by determining the fatigue life of a wellhead installation can be critical, whether in shallow water, deep water or in TLP/SPAR applications.

Introduction
Subsea wellhead systems are used worldwide for wells drilled in both shallow and deepwater, in a wide a range of environmental conditions, and using many different types of drilling rig. The industry has a number of established well system suppliers, who can offer a range of wellhead products based on designs which have been field proven in many worldwide applications over a number of years.

When selecting a wellhead system for a new well, the specifications defined for such equipment typically focus on parameters such as size, pressure rating and extreme load capacity. These parameters are able to be defined based on the well designers understanding of the well geology and expected reservoir characteristics, and their required well configuration. Relatively straightforward analysis can also be undertaken to evaluate the maximum extreme loading expected to be applied to the wellhead and conductor system during service from the reservoir, drilling rig and environmental conditions, and the result of this can be used to confirm the suitability of the selected subsea system from an overall strength and well stability perspective.

However, when attempting to define the required fatigue capacity for a wellhead system, operators and wellhead system suppliers are faced with far greater uncertainty. The fatigue damage rate for a wellhead can be sensitive to a number of uncontrollable parameters, and, as is often the case, even the drilling duration can be highly uncertain. This uncertainty can lead to difficulty in determining exactly what fatigue capacity should be defined for a wellhead and conductor system.
Historically, when justifying the fatigue performance of a wellhead, the industry has often simply referred to experience (i.e. there wasn’t a fatigue problem on the last well, so why should there be a problem on this one?). As there have been many wells successfully drilled which have not suffered a fatigue failure, this may seem a reasonable position. However, while this approach can be justifiable in many cases where a fair comparison can be made between two similar wells, it can also lead to oversights where unevaluated design parameters do not necessarily produce an identical fatigue response.

As the industry seeks to drill wells in more challenging locations, with harsher environments, longer drilling durations and using drilling rigs with larger BOPs, the wellhead fatigue damage rates incurred during drilling increase. It therefore becomes increasingly important to ensure that the mechanisms which influence wellhead fatigue are understood, and that the fatigue resistance requirements of wellhead system are more accurately defined upfront.

If the fatigue resistance requirements for a specific well are adequately defined in the wellhead specification, it is possible to ensure that the appropriate attention is given to the fatigue resistance of the wellhead system during the design and fabrication process. This then helps to avoid the risk of fatigue problems being experienced with the wells during life, and allows well productivity to be increased through enabling further intervention and workover operations to be undertaken without risk of excessive fatigue being incurred in the wellhead and conductor system.

Background
In order to define the fatigue life of a system, it is necessary to first define the criteria which have the most significant impact on fatigue response. These are listed below:

i) The fatigue loading regime;
ii) The fatigue capacity of the system (i.e. the ability of a system to withstand fatigue cycling).

These two parameters are independent, but are both equally important in determining fatigue life. For a subsea wellhead and conductor system, the fatigue loading, and fatigue capacity for a typical system are discussed in more detail in this section.

Fatigue Loading
A subsea wellhead is typically subject to cyclical fatigue loads due to environmental forces. For most applications however direct environmental loading on the wellhead is minimal, and the majority of fatigue loading acting on the wellhead is generated from the environmental forces acting on the drilling vessel and marine drilling riser which are transmitted along the riser, and into the wellhead.

A typical drilling riser stack-up for a subsea well drilled from a MODU is presented in Fig. 1. The drilling riser is subject to direct loading from waves and currents, together with associated vessel motions due to the environmental forces. As the wellhead and conductor system is connected to the seabed, it acts as the reaction point through which the environmental forces are transmitted from the drilling riser into the seabed. The environmental forces are cyclical, either from wave loading, or through vortex induced vibration (VIV) of the drilling riser produced by vortex shedding in high current scenarios. These forces produce cyclical bending moments in the wellhead and conductor system, and this load cycling leads to the accumulation of fatigue damage in a system.
Fatigue Capacity

The fatigue capacity of a system can be defined as the ability of the system to accommodate cyclical loading before experiencing failure. For a typical wellhead system, cyclical loading will result in the growth of flaws (cracks) which are present in the system from the time of manufacture. Once the flaw reaches a certain critical size, a failure can be considered to have occurred. This failure may either be defined as a loss of pressure containment, due to the presence of a through thickness flaw, or an unstable fracture, where a flaw will suddenly propagate through a component under extreme load, resulting in a loss of structural integrity.

The rate of growth of these flaws is dependent on two parameters:
The stress intensity (i.e. the magnitude of the cyclical loading)
The properties of the material through which the flaw is growing

A further consideration in determining the fatigue capacity is to also the initial flaw size present in the material in its original manufactured condition (i.e. in an un-fatigued state), which is dependent on manufacturing / fabrication processes.

Typically a system may have a number of fatigue weak-points, where the fatigue resistance may be lower than in other locations. These are often called fatigue hot-spots, and may be located at the change of geometry which causes a stress concentration (i.e. a change to the stress intensity) or at a weld, where a change in the material properties is present. A schematic of a typical wellhead and conductor system is presented in Fig.2. The areas which are generally of concern for fatigue are highlighted on the figure below.

Figure 2 – Typical Wellhead and Conductor System
Wellhead Fatigue Analysis

Introduction
In order to evaluate the fatigue performance of a typical subsea wellhead system, and to assess the impact of variations in parameters on the fatigue response, a series of fatigue analyses are performed. A typical drilling application is considered, with a conventional 21in marine drilling riser deployed from a semi-submersible MODU in a water depth of approximately 130m. The wellhead and conductor system considered in the model is based on a Cameron STM-15 wellhead system, which is a relatively conventional wellhead design that has been provided by Cameron on a wide number of well applications worldwide.

Analysis Methodology
The methodology used for the fatigue analysis is as follows:

A finite element (FE) analysis model of the system is developed using the non-linear time domain finite element analysis software Flexcom [1] to define the combined drilling riser, wellhead and conductor system. The model extends from the base of the conductor at approximately 60m below the mudline, to the elevation of the drill floor of the drilling rig. The drilling riser, wellhead, conductor and other equipment are modelled as pipe elements, with appropriate properties to represent their mass, stiffness and hydrodynamic drag. The soil support provided along the length conductor is modelled using non-linear springs to represent the lateral resistance provided by the soil which acts as a restraint to deflections of the conductor.

A series of time domain dynamic analyses are undertaken to simulate the effect of wave loading acting on both the vessel and the drilling riser. Vessel motions are simulated in the analysis through the use of RAOs (Response Amplitude Operators) which are obtained from third party wave diffraction analyses undertaken for each of the specific vessels considered. The time domain analyses consider irregular wave seastates, and from each simulation a series of response time traces for the deflections and loads in each element of the FE model are obtained. Fourier integration is then used to convert the time traces to response transfer functions using 2H in-house software, such that the loading or stresses obtained from one seastate can then be correlated to other seastates using a process of linearisation.

Using the response transfer functions, the bending cycle stress intensity can be estimated for all seastate conditions present in a typical seastate scatter distribution diagram, and the subsequent fatigue damage rate anticipated from each seastate can be established. The fatigue damage accrued from a number of seastates is then added using the Miner rule to determine the overall fatigue damage rate associated with the system.

The analysis process is then repeated considering parameter variations made to the original model such that the fatigue damage rates for each variation are obtained.

Parameter Sensitivity Results
The results of the wellhead and conductor fatigue assessment are presented in this section. For each analysis, fatigue lives are extracted for the fatigue critical locations as identified in Fig. 2. For the majority of the assessments, the critical locations is at the weld located between the LP (low pressure) housing and the start of the conductor.

Note: To simplify the results presented and for ease of trend comparison, only the fatigue response of the outer conductor is presented, and effects such as rotation of the HP wellhead housing within the LP wellhead housing, or cement shortfall between the 20in surface casing and the conductor are not considered.

The results presented in the sections below are for a variety of DNV [2] weld classifications and stress concentration factors (SCF) (example: D-1.3). The classifications selected are those defined by DNV as being appropriate for girth welds in pipelines; however the impact of the variability in these classifications will be discussed in greater detail later in this paper.

Rig Type Comparison
A fatigue analysis is undertaken to consider the fatigue response of the same wellhead and conductor system for wells drilled using two different types of drilling rig. The rig type can have a significant effect on the fatigue damage imparted into the wellhead system. Every rig has a set of motion data known as RAO’s (Response Amplitude Operators). This data simulates the rig response to external hydrodynamic forces which are transmitted down the riser to the wellhead. These forces, and those of wave and currents acting directly on the riser and LMRP/BOP stack, combine to produce fatigue cycling of the wellhead system. Each rig also has differences in drilling equipment including marine riser stiffness and drag diameter, and importantly the BOP/LMRP stack size and weight.

The 2 rigs considered for the study are as follows:
- Rig #1 - A 250 ft by 300 ft moored semi-submersible, with 220 ton BOP.
- Rig #2 - A 200 ft by 250 ft dynamically positioned semi-submersible, with 120 ton BOP.

Figure 3 compares the fatigue damage rates obtained for the two semi-submersible rigs. For this comparison, the conductor size used is a 30in OD, 1.5in wall pipe. While the two rigs appear relatively similar, they are very different in the fatigue damage rate they cause to the wellhead. Rig #1 has a fatigue damage rate of two to three times that of Rig #2. This can be attributed to at least two parameters. The first is the greater size and weight of the BOP/LMRP stack employed on Rig #1 which is almost twice the size of that used on Rig #2. The larger BOP/LMRP stack causes greater bending forces to be imparted into the fatigue critical sections of the wellhead, resulting in significantly higher fatigue damage rates in these regions for the same environmental loading. The second is the motion response characteristics of the rigs for the same environmental loading. Since the rigs are working in 130m of water depth, the riser systems are relatively stiff, and the motions and forces generated by the rigs are transmitted to the BOP/LMRP stack. Rig #1 generates larger motions than Rig #2 for the wave periods considered in the region assessed, thus producing a higher fatigue damage rate.

From the results presented Rig #2 may appear to be the better choice considering the lower wellhead fatigue damage rate expected, however Rig #2 does not have the ability to stay connected to the wellhead during bad weather due to limited station keeping capability, causing delays and extended drilling schedules. Rig #1 can remain on the wellhead during more extreme weather, thus reducing the drilling schedule, but at the cost of a higher fatigue damage rate. So this trade-off must be evaluated to determine an acceptable amount of fatigue damage in order to optimize the drilling schedule.

![Wellhead Fatigue Damage Rate for Varying Rig Type](image)

**Figure 3 – Fatigue Damage Rate vs. Rig, Riser & BOP for a 30in OD 1.5in Wall Conductor Housing Joint – Spring Season**

**Weather / Seasonal Effects**

The effect of variations in seasonal weather conditions on the fatigue response of the wellhead and conductor system is considered. The wave data used is taken from a region which is known to exhibit variability between seasons, with relatively harsh conditions with large waves and long wave periods during the winter months, and smaller waves with significantly shorter wave periods during the spring and summer months.

The results of the assessment are presented in Figure 4, which presents the fatigue damage rates observed at the critical weld between the LP housing and the top of the conductor for each season. A 30in x 1.5in wall thickness conductor is considered for this example, and results for two differing weld fatigue capacity classifications are presented.

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As can be observed from the results, a significant variation in fatigue damage rate can be obtained when drilling at differing times of year in the same region. However, what is also noticeable is that the differences between the fatigue lives observed for the different seasons and different weld classifications do not follow a consistent trend. While the winter season events provide the highest fatigue damage rates, which is expected due to the increased severity of the wave loading during this period, for the D-class weld detail, the damage rate obtained during the summer period is also of a similar magnitude. The spring period however gives consistently lower fatigue damage rates. This effect is explained by the fact that during the summer period there is a high probability of occurrence of waves with a period close to the natural period of the riser system. The wave excitation close to the systems natural period results in an amplification of the riser and BOP/LMRP system displacements, which in turn leads to higher amplitude stress cycles in the wellhead and conductor.

![Wellhead Fatigue Damage Rate By Season](image)

**Figure 4 – Fatigue Damage Rate vs. Weld Class-SCF for a Range of Seasons for a 30in OD 1.5in Wall Conductor Housing Joint**

**Conductor Size**

The size of the conductor has a significant effect on the fatigue damage rate experienced in the wellhead and conductor system. A set of parametric analyses are undertaken to consider the impact of increasing conductor size (both diameter and wall thickness) for an otherwise identical set of input data (i.e. environmental loading, rig type etc.). Four different combinations of conductor size are considered:

- 30in OD x 1.5in WT
- 36in OD x 1.5in WT
- 36in OD x 2.0in WT
- 38in OD x 2.0in WT

The results of the comparison are presented in Fig 5 below, which presents the fatigue damage rate at the fatigue critical weld between the LP housing and the top of the conductor considering both a D and F1 class weld fatigue detail with appropriate thickness correction factors applied. As can be seen from the results presented, substantial reductions in the fatigue damage rate can be achieved with increasing conductor size. The largest improvements can be obtained through increasing the conductor OD, which offers the greater increase in conductor stiffness than through an increase in wall thickness. This increase in stiffness reduces the deflection of the conductor under loading, and subsequently reduces the cyclical bending moments at the location of the critical weld. The most substantial improvements are obtained through the increase in conductor OD from 30in to 36in, which yields a reduction in fatigue damage rate of approximately 82%.
As discussed in the background section earlier in this paper, a key parameter in defining the fatigue damage rate of a system is the capacity of the system to withstand fatigue cycling. Hence to fully evaluate the fatigue response of the girth welds present between the LP wellhead housing and the top of the conductor it is necessary to select an appropriate fatigue capacity for this weld. Industry codes such as DNV-RP-C203 [2] can be used for guidance in this area, and this standard defines a range of fatigue design capacity data appropriate for welds. The data is generated from testing data recorded for a range of weld designs, and from this data S-N fatigue performance curves are defined.

For girth welds, DNV-RP-C203 defines a range of S-N performance curves which are applicable for differing weld designs and manufacturing processes. An SCF (stress concentration factor) is then also required to be applied to the curve to represent stress raisers at the weld location due to features such as pipe misalignment, ovality and geometrical tolerances.

The fatigue analysis is repeated to evaluate the effects of the use of the different S-N curves and a range of potential SCFs on the fatigue damage rates obtained for the welds considering otherwise identical input parameters for the equipment modelled and the environmental loading considered. This assessment considers a 30in conductor with 1.5in WT, and the fatigue damage rate at the critical weld between the LP housing and the top of the conductor is presented in Figure 6 for a variety of fatigue classifications.

From the results it can be clearly observed that there is a very large spread in the fatigue performance between the best and worst fatigue classifications with the best classifications demonstrating a fatigue capacity of 25 times greater than the worst capacity considered (C vs. F1) for the same SCF. While this is essentially a theoretical exercise, it highlights the importance of specifying well designed and fabricated welds in fatigue critical applications.
Practical Fatigue Design Enhancements

The analysis results presented in the previous section indicate that a significant spread of fatigue damage rates can be observed for a well drilled in one location, and that wellhead systems are sensitive to variations in input parameters such as environmental loading and rig type. To ensure that a wellhead system design is robust, it is therefore necessary to consider the design enhancements which can be reasonably implemented for wellhead systems to improve their fatigue capacity. Some potential enhancements that are considered practical to implement are listed below.

Weld enhancement:
One of the easiest factors to change is the weld design and welding procedures of the conductor housing joint. DNV RP-C203 provides guidelines for the construction of fatigue resistant welds. If the circumferential weld joint goes through a rigorous post-weld NDE inspection and post-weld machining (grinding) on the OD and ID, the weld classification can be greatly improved, thus reducing the damage caused by fatigue. In addition to the weld classification, a reduction in stress concentration factor (SCF) through improvement of weld design, and pipe tolerances also offers significant benefits.

The F-Class weld is essentially a single sided girth weld in the “as welded” condition, without post-weld machining or grinding. Any misalignment, weld under cuts, gaps in full penetration, can cause stress raisers in the conductor wall that can lead to crack propagation. By machining or grinding the weld to smooth out these imperfections, along with full non-destructive examination (NDE), the weld class can be improved potentially achieve a C-Class weld classification. This can be implemented during the manufacturing process, and the beneficial effects of this have been presented previously in the analysis results section.

Another consideration that is also of significance is appropriate qualification and testing of existing weld procedures to fully quantify the fatigue capacity of the weld. While the S-N curves provided in DNV-RP-C203 provide data that can be used, these are only based on a particular set of welds that have been historically tested. For large diameter welds in thick walled conductors the welding process can be complex, and hence specific fatigue testing the welding procedures used offers a much higher degree of certainly of the fatigue capacity of the weld that is actually produced.

Conductor Size Selection
A second factor can be determined early in the wellhead system design phase is the conductor OD and wall thickness. Many operators aim to reduce the conductor size to save on weight, but as shown in the analysis results above, the conductor...
becomes more susceptible to fatigue damage the smaller and lighter it gets. However this does not mean that to achieve a robust fatigue performance the entire conductor string must be heavy wall and large OD. Depending on the soil conditions, only the top joint, or top two joints, may need to be of fatigue resisting size, while the lower joints could be of a thinner wall thickness and smaller OD. By replacing the top two 40 foot joints of a 320 foot long 30" conductor string with 36" joints, it is possible to achieve a significant increase in the fatigue life, while only adding approximately 5.5% to the conductor string weight.

**Location of Welds and Stress Concentrations**

A consideration that can often be overlooked is the location of critical fatigue sections in the wellhead and conductor string. The bending moment profile along the top section of the wellhead and conductor can vary significantly, and is dependent on a number of factors including soil support conditions, wellhead stick-up and the stiffness of the actual conductor itself. However in some cases it can be possible to optimise the location of critical fatigue hotspots such as welds and regions of high stress concentrations (i.e. threaded connectors) by placing them in regions away from the peak bending moments. A plot of the fatigue life over the upper section of a sample wellhead and conductor system is presented in Fig 6. Also marked on the plot are the typical location of welds and connectors which are the most fatigue sensitive sections of the system. As can be seen from the plot, the fatigue damage rate varies along the length in a curved profile, and a clear peak can be observed. It should be noted that the actual location of this peak will vary and is based on specific field parameters, however by optimising the location of the welds and connectors in the wellhead and conductor string such that they are as far away from the peak as practically possible can give significant fatigue resistance enhancements. This could take the form of avoiding the use of welds for extension joints or swages directly below the wellhead, or the use of longer conductor joints in soft soil conditions to move the location of the first conductor connector deeper below the seabed.

![Typical Fatigue Damage Distribution Along Conductor Length](image)

**Figure 6 – Typical Fatigue Damage Distribution Along Length of Conductor**

**External Support**

In situations where very high fatigue damage rates occur, the use of providing external support to the conductor can also be considered. This may take the form of a seabed conductor guide support or template. The stiffness of the external support guide is required to be sufficient to allow a significant proportion of load transfer from the wellhead to the support structure to occur, and in doing so this reduces the magnitude of the fatigue cycles experienced in the conductor. However, if relying on such a system to reduce fatigue loading and extend fatigue life, it is necessary to ensure that the connectivity between the conductor and the seabed support is robust and reliable to ensure that system can provide the necessary performance. This can add complexity to the system design, particularly if the system is required to be post installed.

**Operation Planning**

As discussed with the results of the seasonal fatigue assessments, a significant variation in the fatigue damage rates can be observed for drilling operations which occur at different times of the year. In addition, a significant variability can also be
observed when using different drilling rigs on the same wellhead. While it is recognised that a high level of flexibility is desirable by operators to allow rig contracts to be secured on favourable terms, where circumstances allow, effective operational planning can be used to maximise wellhead fatigue life by avoiding well operations under unfavourable conditions where high fatigue damage rates may be anticipated. An example of this might be to schedule a potentially long duration, high risk well operation for a period where benign weather conditions might be predicted, and when a rig which might be expected to produce a lower fatigue damage rate would be available. This would reduce the risk of excessive fatigue damage being incurred in the wellhead or conductor in the event that the drilling duration has to be increased, and allow for greater contingency should difficulties be encountered with the well program.

Another area where planning can be of benefit is to identify as accurately as possible the potential full operational life cycle for a well during the initial wellhead design phase. This should include allowances for the planned/expected drilling, completion, workover and abandonment operations for the well. While it is appreciated that in many cases specific values may not be possible to be defined for these operations, reasonable allowances for each stage should be evaluated at the initial design stages so the wellhead and conductor system can be specified to meet a specific operational target. This can be of particular concern where operators may plan to convert a well that was initially intend as an exploration well into a long term production well, only to discover that this cannot be achieved due to a lack of fatigue life.

Accuracy of Design Data

When assessing whether a wellhead has an acceptable fatigue capacity for a proposed application, the use of accurate data in the assessment is essential. If data is not accurate, or, as is more common, not available, then conservative parameter assumptions are required to be made, which can often lead to significant over-predictions of fatigue damage. In cases where wells are planned to be drilled in frontier regions, where existing knowledge of environmental conditions and seabed properties are limited, this can present a significant difficulty for operators, and in these cases drilling operations may have to proceed without a complete understanding of the structural suitability of the wellhead and conductor.

In these scenarios, and cases where high fatigue damage rates are of concern, it is recommended that further data be gathered during the drilling campaign to allow retrospective assessments of the actual system performance to be evaluated, and to determine the acceptability for further use of the wellhead system. This data gathering should include regular measurements of environmental conditions such as waves and currents, together with drilling logs recording riser tensions and mud weights etc. This information can then be used to develop an accurate understanding of the actual fatigue damage incurred in the system from the operations conducted to date, and enable more accurate predictions of the system fatigue life for other wells to also be determined. Alternatively, the use of drilling riser monitoring systems can also be considered to allow measurement of actual riser motions and deflections to be established, and this data can then be used to confirm loading on the wellhead.

Conclusions

This paper aims to demonstrate the sensitivity of wellhead and conductor system fatigue response to changes in input parameters in order to highlight the extent of the variability that may be expected in the system fatigue response when similar equipment is used in different applications. The fatigue analysis results shown highlight how what may be considered as an acceptable fatigue design for one application may not necessarily be suitable for another. As wells are drilled in more remote regions, where environmental data (i.e. weather and seabed conditions) are less defined, and using larger, higher specification drilling equipment such as 15ksi BOP systems, the fatigue loading on wellhead system can quickly become significantly greater than that for other applications.

Historically limited guidance has been available regarding the methodology for assessing wellhead fatigue [3], however increasing sophistication of analytical modelling is now being recommended [4], with more extensive analyses required to establish performance acceptability. This is helpful to improve the ultimate accuracy of fatigue life predictions, however before starting on an extensive analytical exercise it remains important to first understand the key mechanisms and drivers of the fatigue process so that the appropriate analytical assessments can be made. It is only from having a sound understanding of the main drivers of the fatigue response that the results of an analytical study can be fully evaluated, and that practical design and operational guidance can be obtained. Using the information available from such a study, the benefits of the potential fatigue design enhancements presented earlier in this paper can be established, and appropriate improvements can be selected and implemented as necessary for a specific well campaign.

The purpose of this paper is to show that if proper planning, design and analysis criteria, and updated manufacturing requirements are identified early in the project, then the fatigue damage imparted on the wellhead system during the drilling and completion phase can be managed, allowing sufficient life in the wellhead system for workover or abandonment operations years in the future. Planning of the drilling and completion operations during favourable seasonal weather, designing and analyzing the conductor string to fully understand its structural capabilities and the use of manufacturing
processes to make the best welds possible with NDE processes to verify the manufacturing, will produce a wellhead system that will give many years of trouble free service. If this is addressed at the appropriate stage in a project life cycle, these measures can be relatively straight forward to implement, and have a limited impact on the operators ability to drill and produce from the well. However, once a project proceeds further along the project cycle, design changes become increasingly difficult to implement and ultimately significantly less effective.

**Limitations of Work**

The work presented in this paper is not intended to provide a thorough analysis of a specific well, or wellhead system. The intention of this is work solely to provide a comparative assessment to demonstrate the sensitivity of wellhead fatigue response to fatigue loading. The fatigue mechanism considered is wave induced first order fatigue, and a rigidly locked-down wellhead system in normal drilling mode is considered. Effects such as Vortex Induced Vibration (VIV) are not considered, and non-lockdown wellhead systems or other modes of drilling operation are not analysed. However from experience of other assessments the sensitivity of the wellhead fatigue response to parameters variations for these other scenarios is also broadly similar to those presented earlier in this paper. This further highlights the importance for specific fatigue assessments to be undertaken for specific well operations, to ensure that the fatigue performance of the equipment used in each different application is appropriately understood.

**Nomenclature**

- **BOP** – Blow Out Preventer
- **HP** – High Pressure
- **LMRP** – Lower Marine Riser Package
- **LP** – Low Pressure
- **MODU** – Mobile Offshore Drilling Unit
- **NDE** – Non-Destructive Examination
- **OD** – Outer Diameter
- **RAO** – Response Amplitude Operator
- **SCF** – Stress Concentration Factor
- **VIV** – Vortex Induced Vibration
- **WT** – Wall Thickness

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