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# Marine drilling riser disconnect and recoil analysis

Guttorm Grytoyr, Partha Sharma and Srinivas Vishnubotla, Det Norske Veritas (U.S.A.), Inc.

## Abstract

A methodology is presented for the dynamic analysis of marine drilling riser disconnect and recoil using general purpose riser FEA programs. The methodology includes the effects of mud column discharge, which is a governing effect in the first part of the transient phase, and the effects of pressure loss in the hydraulic lines for the riser tensioners. The global behavior of the riser due to, e.g. elasticity and inertia, is automatically accounted for by the riser analysis software.

The presented methodology is easy to use and can be applied to any riser system, both conventional wireline and direct acting tensioners. A typical case is selected and analyzed, with emphasis on lift height of the lower riser package and impulsive loading due to bottoming-out of the tensioners or the telescopic joint. The effect of tension setting is studied, covering a range of settings in order to select the optimum.

The methodology enables the riser system designers to reuse riser models from the design analysis. No additional riser model has to be built for the disconnect and recoil analysis. All major physical effects are taken into account by the methodology, including detailed cross sectional properties of the riser system, and the hydraulic and pneumatic response of the tensioner system.

## Introduction

State of the art of recoil analysis today is mainly based on 1D analysis with simplified riser models. See ref. 1, 2, 3, 4, 5 and 6. Some development has been presented recently, see ref. 7.

ISO TR 13624-2, ref. 8, includes a description of the requirements to a riser recoil analyses.

The methodology presented in this paper is partly based on the work presented in ref. 9 and 10.

The purpose of a riser recoil analysis is to establish an optimum riser tension level and a recoil valve control curve that will ensure that during an emergency disconnect

1. the LMRP is lifted clear of the subsea equipment;
2. the Telescopic Joint (TJ) does not bottom out

Both situations may give large impact loads, with possible damage to the subsea equipment near the bottom or to the drill floor equipment at the top.

A sketch of the system is presented in Figure 1 and Figure 2.

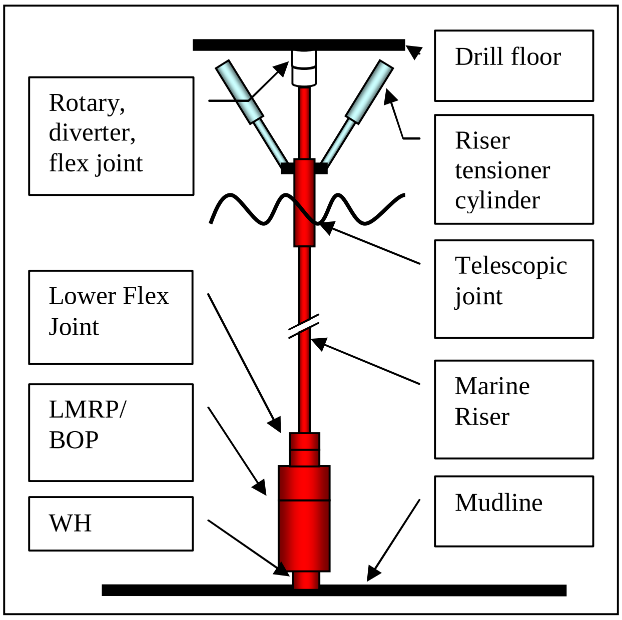

**Figure 1 Schematic of model of marine riser and riser system. Direct acting tensioner cylinders**

Following disconnect the following effects are observed

1. the elastic energy stored in the riser due to the overpull at the LMRP connector is released and travels along the length of the riser as an elastic pulse. This is usually not a dominating effect, but it is automatically accounted for by the riser software. Then the riser tensioners starts to pull the riser and lifts it up.
2. the column of drilling mud inside the marine riser will be discharged to the surrounding sea, see Figure 3. There may be a pressure pulse travelling through the mud column as the riser is disconnected and the the mud is exposed to the lower surrounding pressure. As with the elastic pulse in the riser itself this is usually not a dominating effect in the system, and is neglected

in the present methodology. This phase is also dominated by large friction forces from the outflow of mud. This is included in the present methodology. Hydrostatic equilibrium is re-established when there is balance between the riser contents and the seawater.

3. In the later stages of the discharge phase the riser tensioner will take over as the dominating force in the system, and the riser will accelerate upwards more quickly due to the reduced weight of the riser. In this phase the pressure losses in the hydraulic and pneumatic systems of the riser tensioners are an important aspect.

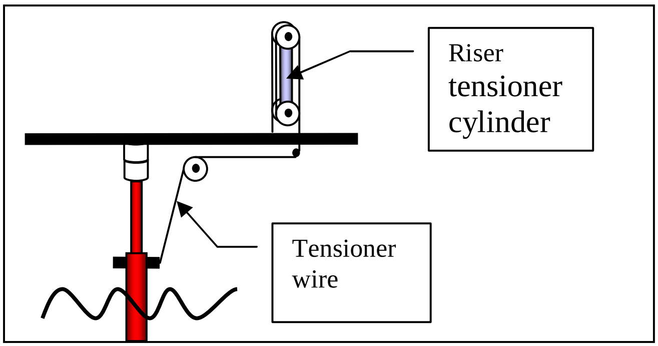

**Figure 2 Schematic of alternative model of marine riser and riser tensioner system. Conventional riser tensioners with rucker wires. Note that the wire model in the riser analysis is terminated at the sheave. The behavior of the cylinder is modeled as a non-linear characteristic of the wire**

## Analysis Methodology

A summary of the analysis methodology, including riser model, vessel motions, riser tensioner system and modeling of the mud column during the discharge phase, is given below.

### *Riser model*

The riser model will typically be reused from a previous global load response analysis, and so the details of the riser will be included in the existing model.

As a minimum, the model shall include the LMRP, lower Flex Joint, riser joints, Tension Ring, Telescopic Joint Outer and Inner Barrels, upper Flex Joint, and the riser tensioners.

The level of detail for the riser model should ensure that all physical effects are properly accounted for. Both the mass and stiffness distribution are important in order to get the correct response, especially if bottoming-out of the TJ is occurring, with subsequent high impact loads in the system.

The weight of the drilling mud is also a critical parameter, and this has to be modeled correctly. This is described in detail in section “Mud column weight and friction” below.

### *Boundary conditions*

The lower end of the LMRP is initially fixed to the top of the BOP, see Figure 1, and is then released at some instance.

The upper end of the riser model is usually the upper Flex Joint, or the RKB, depending on which parts have been included in the model. The upper end is fixed to the mobile drilling unit (MODU), and follows the motions of the MODU. The vessel motions are an important parameter, since they may be opposite to the upwards motion of the riser. If the riser tension is insufficient, the vessel motions may cause the LMRP to move downwards and impact with the subsea structure.

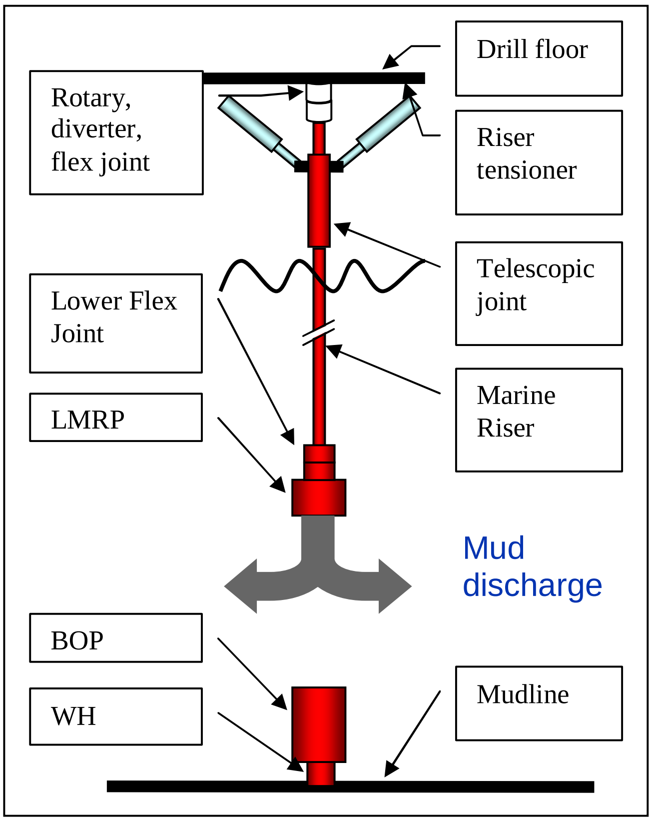

**Figure 3 Schematic of model of marine riser after disconnect, showing discharge of mud.**

### *Vessel motions*

The vessel motions are described by use of motion response amplitude operators (RAOs). These are usually established by a separate analysis of the vessel response in waves, using boundary element methods. Alternatively they can be established by use of model tests.

The RAOs are given as a set of tables of the vessel motion response as a function of wave frequency, and describes the amplitude of the vessel response relative to the wave amplitude, as well as the phase angle of the response relative to the wave crest, or trough.

A relatively small semi submersible drilling vessel has been selected for the sample cases presented below. A small vessel will in general have large motions. The selected vessel has a resonance heave period of about 20 seconds. The maximum heave response amplitude, at wave periods below the resonance period, is approximately 0.5 times the wave amplitude, at a wave period of approximately 15 seconds.

### ***Riser tensioners***

The applied top tension is designed to give a specified resulting tension at the LMRP connector. Typical values are in the range of 30 to 60 metric tonnes, or 60 to 120 kips, with some variation according to local company procedures, or special requirements from the recoil analysis.

A typical riser tensioner cylinder is connected to an accumulator with an interface between the hydraulic fluid and air, or nitrogen. The air, or nitrogen, is pressurized according to the tension requirements of the riser, and is stored in a large bank of high pressure vessels. The volume of the main bank should be as large as possible in order to reduce the pressure variation in the bank as the cylinder is stroking in and out.

The pressure variation in the main bank is calculated by use of the adiabatic gas equation, which relates the change of pressure, $P$, to the change of volume, $V$, through the following equation:

$$P \times V^{\gamma} = C$$

Where $\gamma$ is the adiabatic constant. For dry air this is 1.395. The constant, $C$, in this equation is determined by using the initial pressure and volume in the system. The pressure at later time steps in the dynamic analysis is calculated through the instantaneous volume, $V(t)$, which is related to the cylinder position.

One could also have selected the isotherm gas equation, or any other relation between volume and pressure. The selection should be based on the specific details of the system that is being studied.

There will be a pressure drop in the piping between the cylinder and the piston due to the flow of the fluid. This pressure drop is described by the Darcy-Weisbach formula :

$$\Delta P = \frac{\rho U^2 f L}{2D}$$

Where $\rho$ is the density of the hydraulic fluid, $U^2$ is the square of the fluid velocity in the piping, $f$ is the dimensionless friction factor, $L$ is the length of the piping, and $D$ is the diameter of the pipe.

The friction coefficient, $f$, is found from a Moody diagram for the hydraulic fluid in question.

The velocity of the fluid is directly proportional to the velocity of the cylinder piston. This means that the pressure drop can be written as a function of the square of the rate of change of length of the element that is used to model the cylinder.

A new damper model was added to RIFLEX in connection with the work presented in ref. 10. This allows for the inclusion of a damping force in beam elements, proportional to the strain rate, i.e. rate of change of length of the element. The damping force model can use any power of the strain rate. Hence, one may include the pressure loss described above by selecting a power of 2.

This damping model is not yet available through the standard release of RIFLEX, but according to MARINTEK this will be included in the next main release.

#### Conventional riser tensioner system

If the tensioner system consists of conventional riser tensioner wires, see Figure 4, then each of these wires is modeled as two connector elements in series. The upper element is given a force-elongation characteristic that varies according to the change of pressure in the main compressed air banks. The air pressure is assumed to vary adiabatically. The lower element is axially stiff in elongation, but can be compressed, and can hence model the situation when the tensioner wires go slack. The cylinder force is acting on a wire running in a double loop over two blocks, one at each end of the cylinder. This means that the wire stroke is four times the piston stroke, and the wire tension is one fourth of the piston force. This is accounted for in the model.

In addition to the force variation due to compression of the air in the banks, the connector elements have a damping force component that is proportional to the square of the rate of change of length of the elements. This represents the pressure loss due to flow of hydraulic oil through the systems, and is included as described above.

#### Direct acting tensioner cylinders

If direct acting tensioner cylinders are used, see Figure 5, these are modeled directly in the riser model. The characteristics are given in a similar manner as for the conventional tensioner system, while accounting for the mechanical differences between the two systems.

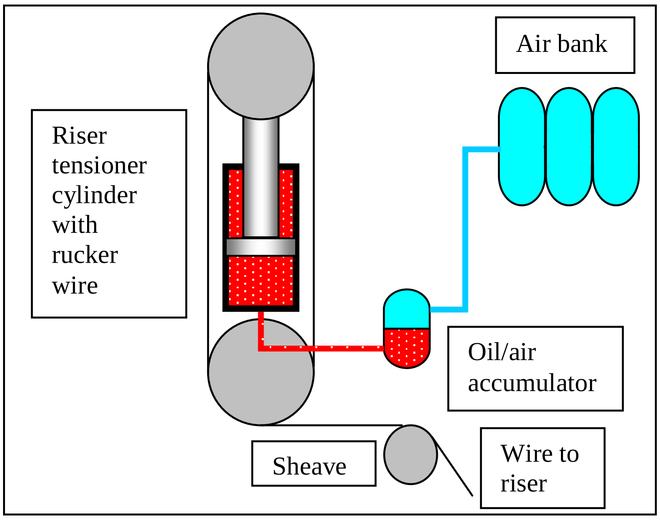

**Figure 4 Sketch of conventional riser tensioner cylinder**

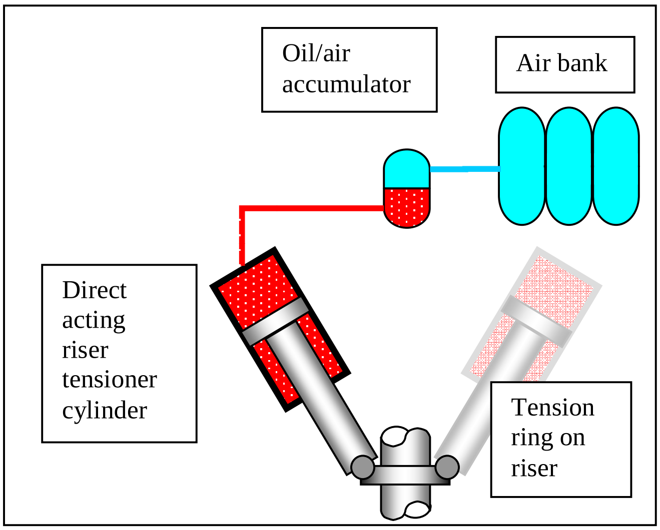

**Figure 5 Sketch of direct acting tensioner cylinder**

### *Anti-recoil system*

The anti-recoil system is designed to avoid hard impact loads during bottoming-out of the telescopic joint or the tensioner cylinders.

This is straightforward to include in the present methodology, as long as it is acting in a way that can be described by a set of equations, like e.g. a control-curve specifying a CV value as a function of cylinder stroke.

On the other hand, if the anti-recoil valve has a control system that involves e.g. time-delays or manual reset of the anti-recoil valve, it is not straightforward to include with the present method.

Note that for this analysis, the effects of the anti-recoil valve have been neglected. This is a vessel specific component, and has to be modeled on a project specific basis.

### *Mud column weight and friction*

The mud column plays an important role for the recoil analysis. It adds to the total weight of the riser in the pre-disconnect, or connected mode. During discharge in the post-disconnect phase it reduces the riser weight but more importantly imposes large friction loads on the riser.

The mud column has been modeled in two steps.

1. The mass of the mud column is included by using the concept of slug loads in the riser model. The slug is defined to have a length that matches the length of the riser. The velocity of the slug is controlled in a manner that reproduces the mass loss during discharge. Details are found below.
2. The friction loads from the mud column are established by a separate analysis, and the loads are applied to the riser elements as a set of user-specified time varying loads. Details are found below.

The combination of these two steps allows for introduction of the transient loads from the mud discharge to the dynamic riser analysis.

As the mud is flowing out of the riser, water is being let in at the refill valve. Hence, the mud is being replaced at the upper end by water. This continues until all the mud in the riser has been replaced. Large friction forces are created by the downward flow of mud and refill water.

The friction forces created by an unsteady flow represent a complex topic in itself. A few analytical solutions of unsteady flow exists, including the case with oscillating flow and the case with constant accelerating flow, see e.g. ref. 11, but none for the type of flow seen here with a non-trivial variation of acceleration.

A simplified approach is utilized for the analysis presented in this paper. The friction force is calculated using a friction coefficient from a Moody diagram. It is assumed that using a Moody diagram for steady state flow is adequately representing the flow.

The mud column velocities are calculated separately beforehand, based on the friction coefficient mentioned above. A rigid body analysis is conducted on the mud column, based on a differential equation that utilizes dynamic equilibrium between the weight of the mud column inside the riser, the friction forces between the mud column and the riser, and the hydrostatic pressure at the lower end of the riser. This gives a time table with the length and velocity of the mud column inside the riser. Figure 6 presents a typical curve. The mud discharge analysis predicts a slight overshoot, i.e. that the velocity of the mud and water column inside the riser is non-zero when all the mud is discharged. This is due to the momentum of the water column. Friction forces will eventually cause this motion to stop. However, after all the mud is released there is no net change of weight of the riser, and the friction loads due to the motion of the water are relatively small since they are proportional to the square of the velocity. Hence, it has been decided to assume that the loads from the water column are insignificant after all the mud is discharged.

The slug force model is in general not designed to account for discharge of mud. Hence, some simplifications have to be made. First of all, the slug velocity can not be defined in a manner that matches exactly the calculated velocity profile of the mud column as it is released. A best fit has to be made. It has been concluded that a constant velocity is giving the best possible fit to the expected velocity variation. A comparison is shown in Figure 7. The figure shows the length of the mud column as a function of time. This is equivalent to the weight of the mud column. It can be seen that the selected slug model will give an adequate description of the variation of mass of the riser system during the discharge phase.

It should also be noted that the slug model is not used to describe the friction forces from the mud. These are added as user-specified, time varying forces, to each individual element in the riser system. Hence, the friction forces will be as predicted by the flow analysis described above.

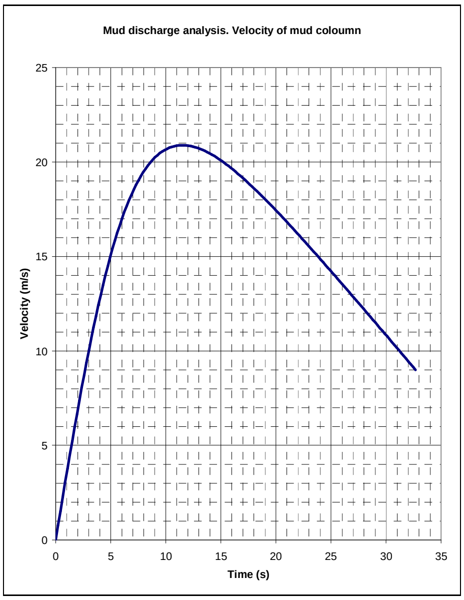

**Figure 6 Typical variation of mud column velocity during disconnect. 500 m water depth. Mud s.g. 1.6, assuming refill rate of water matches the discharge rate of mud.**

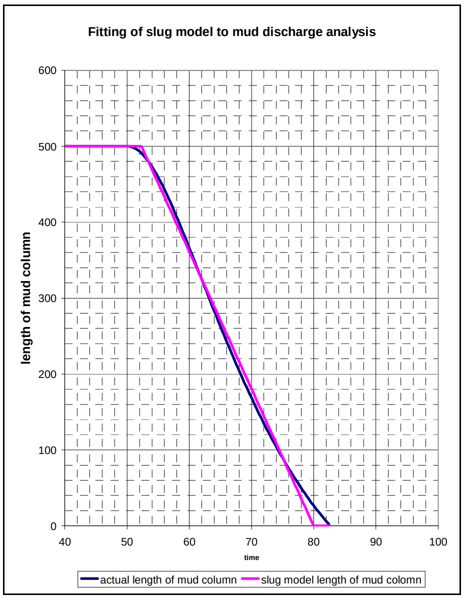

**Figure 7 Comparison of actual length of mud column to slug model representation. This is directly proportional to the mass of the mud inside the riser.**

### *Hydrodynamic loads*

The riser is subject to hydrodynamic loads from the waves and current. This is where the strength of the riser analysis tools come to use. The hydrodynamic loads are described by use of Morison's equation, and this is a standard part of all riser analysis tools.

The following hydrodynamic coefficients have been used:

**Table 1 Hydrodynamic coefficients. Typical values**

| Component | Tangential drag | Transverse drag | Drag diameter |
|---|---|---|---|
| | $C_{dt}$ (-) | $C_d$ (-) | $D_d$ (m) |
| Slick riser joint | 0.1 | 1.0 | 0.75 |
| Buoyant riser joint | 0.1 | 1.0 | 1.0 |
| LMRP | 2.0 | 2.0 | 3.0 |

### *Assumptions and limitations*

- The slug analysis capability is not optimized for mud discharge analysis. Experience has shown that using a constant velocity gives the most reliable results, and reasonable accuracy of the time varying mass and inertia of the riser.
- The friction model is not depending on the limitations of the slug model in the software; instead it is applied as a user-defined, time-varying load applied to each relevant element of the riser model.
- The riser tensioner model was developed

previously, see ref. 9 and 10.

## Sample Case

A sample case has been run to demonstrate the capabilities and possibilities when doing a disconnect and recoil analysis in a fully non-linear 3D riser analysis tool.

The analysis has been run in RIFLEX, ref. 12, in this case, but the methodology may be used in any finite element analysis tool capable of running non-linear riser analysis.

Figure 8 presents snapshots of the surface part of the riser in connected mode, showing the telescopic joint and tensioner cylinders in action.

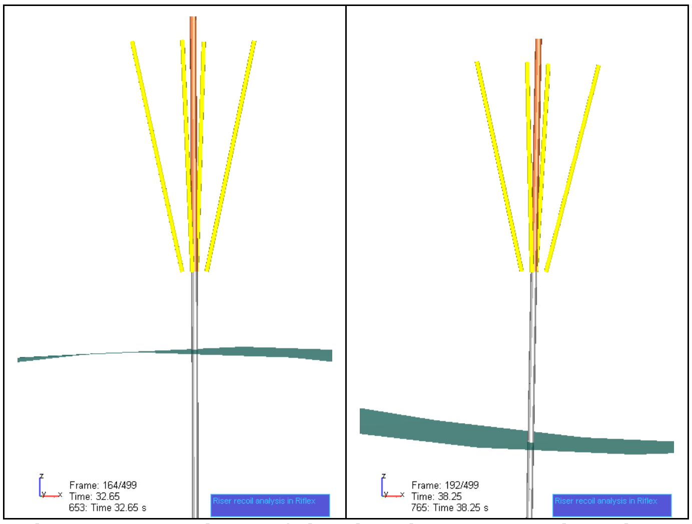

**Figure 8 Snapshots of the riser in connected mode, prior to disconnect. Vessel not shown. Heave up at left, heave down at right.**

Figure 9 presents snapshots of the riser during disconnect, showing the LMRP being lifted up and the cylinders and telescopic joint stroking in. The system was run intentionally with a high tension for these plots in order to provoke a violent impact. In the last plot in the figure it can be seen that the riser is temporarily buckled. This is a short duration event.

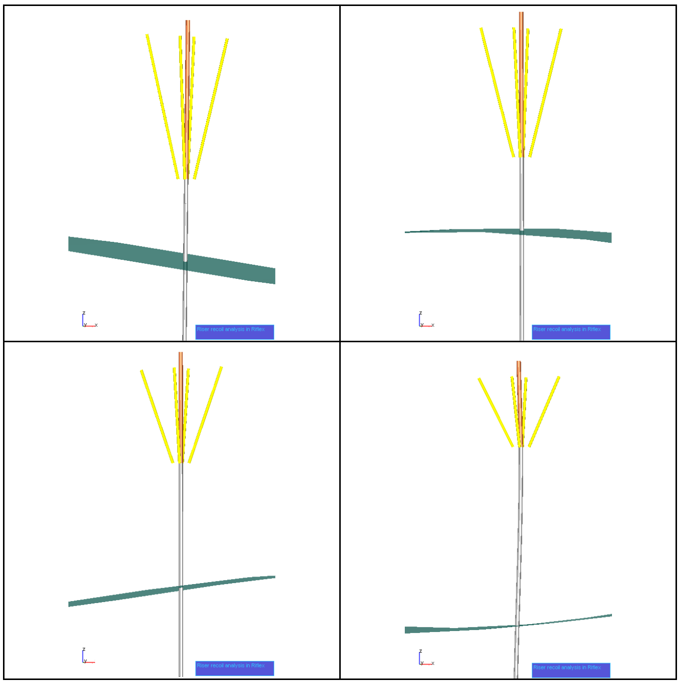

**Figure 9 Snapshots of the riser during disconnect. Vessel not shown. Note buckling of riser in last plot. Case run intentionally with high tension to get large impact loads at bottom-out.**

Figure 10 shows a plot of the elevation of the LMRP following disconnect in a wave with 10 sec period. The disconnect has been performed at 8 different phases of the wave profile.

The tension in the riser just below the tension ring is plotted in Figure 11. It can be clearly seen that large impact loads are expected in this case. Depending on the phase angle of the wave at disconnect, one may also experience a second impact, and it would be beneficial to reduce top tension, and to include an anti-recoil valve to remedy this issue. However, the scope of this paper is solely to demonstrate the feasibility of standard riser analysis tools, and no attempt is made to optimize the system.

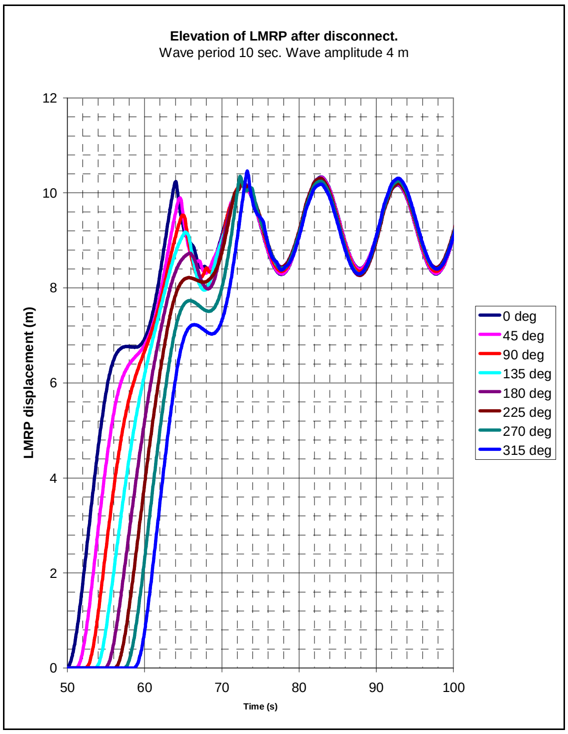

**Figure 10 Riser disconnect in 500 m water depth. Elevation of LMRP after disconnect. Wave period 10 sec. Wave height 8 m.**

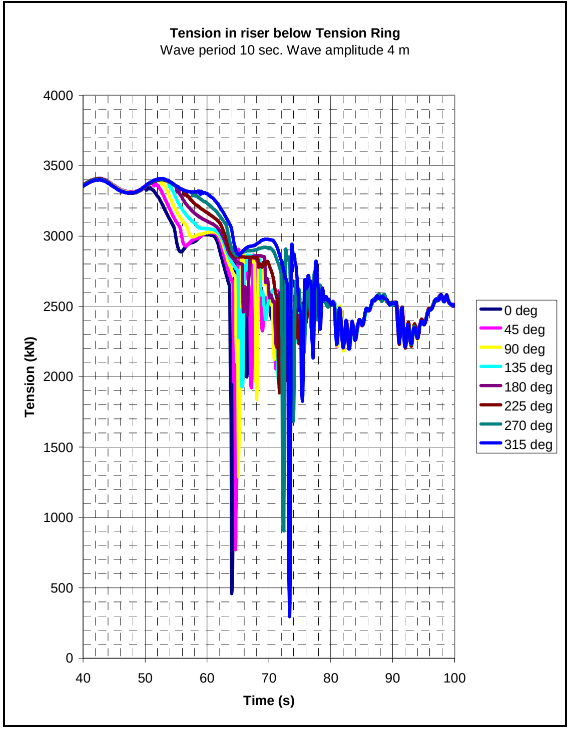

**Figure 11 Riser disconnect in 500 m water depth. Tension below tension ring during disconnect. Wave period 10 seconds. Note spikes with impact loads from bottom-out of the cylinders**

The elevation of the LMRP after disconnect is sensitive to the wave period and the wave elevation, due to the vessel motions. Figure 12 presents the elevation of the LMRP in a wave with period 15 seconds and height 8 m. Hence, the only difference to Figure 10 is the wave period. It can be seen that the responses are very different. The reason is the vessel heave RAO has a maximum close to a wave period of 15 seconds, but is very small at a period of 10 seconds. That is why the vessel heave is seen to be approximately 2 m (±1 m) in Figure 10, and approximately 4 m (±2 m) in Figure 12.

The sensitivity to vessel motions is also evident in Figure 13, which presents the tension in the riser just below the tension ring. When comparing to Figure 11, one can see that the impact loads are significantly increased due to the increased vessel motions.

This means that the recoil analysis has to cover a range of wave periods in order to capture the worst response, both with regards to LMRP elevation, and to impact loads during bottom-out of the tensioners or the telescopic joint.

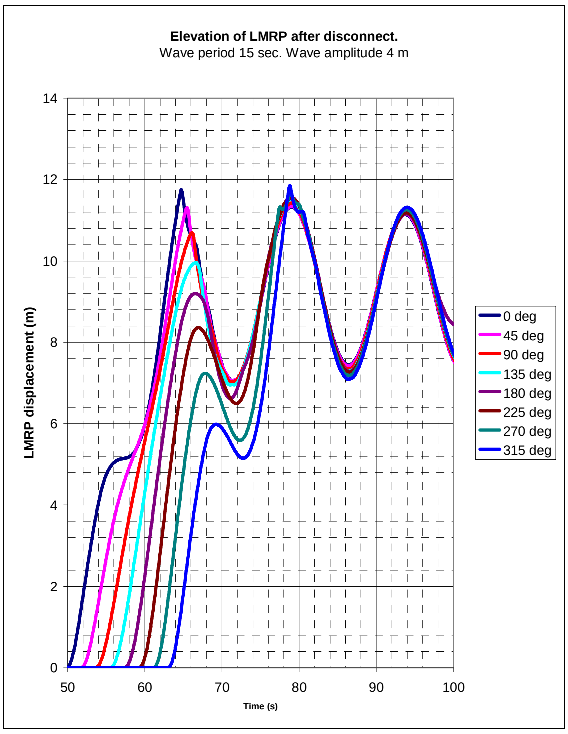

**Figure 12 Riser disconnect in 500 m water depth. Elevation of LMRP after disconnect. Wave period 15 sec. Wave height 8 m.**

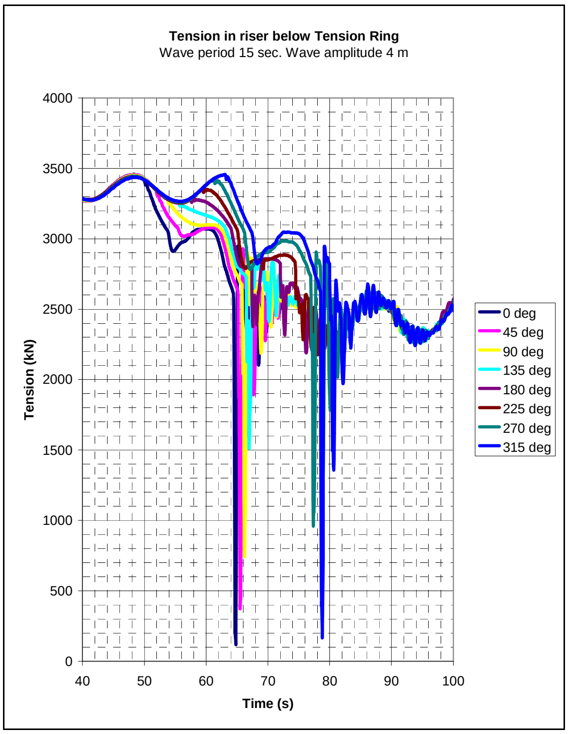

**Figure 13 Riser disconnect in 500 m water depth. Tension below tension ring during disconnect. Wave period 15 seconds.**

Another important issue is the space out of the telescopic joint. In this case it has been assumed to be placed at mid-stroke, which means that the LMRP is lifted almost 9 m up. It is more likely that the telescopic joint will be collapsed somewhat, especially in deep water, in order to allow for some vessel offset, which leads to riser set-down. Again, this is an issue that is of great importance when determining the optimal riser tension level. However, it does not pose any changes of principle, and is hence not discussed any further in this paper.

When using a fully non-linear, 3D, riser analysis tool it is also straightforward to include the effect of e.g. ocean currents, or vessel offset.

Figure 14 presents the trajectory of the lower end of the LMRP during disconnect when the vessel has been given a 2% offset, relative to water depth, i.e. 10 meters, from the nominal position. It is clearly seen that the LMRP is quickly pulled off location, which reduces the possibility of impacting with the subsea structure. This is the kind of operational procedures that can be fully utilized when using a fully non-linear 3D riser analysis tool.

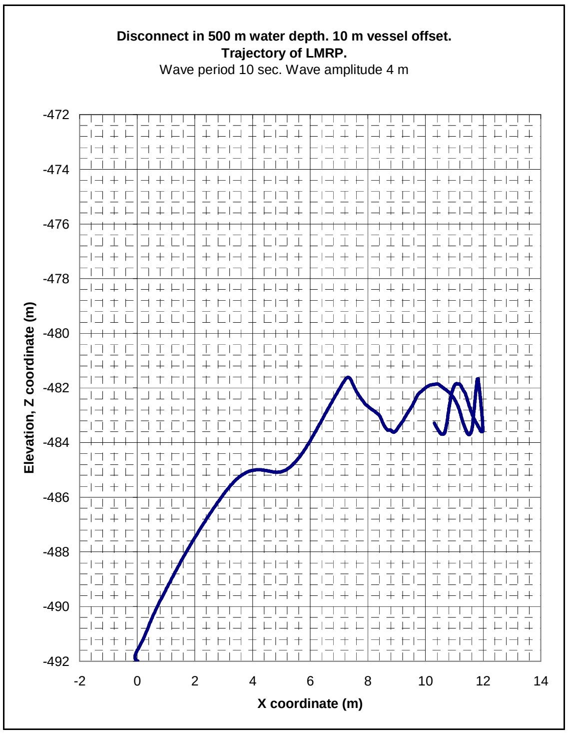

**Figure 14 Riser disconnect in 500 m water depth. Vessel offset 2% of water depth, i.e. 10 m. Trajectory of LMRP during disconnect. No current.**

## Proposed further work

The analysis presented in this paper has been run without an optimal anti-recoil valve and its control-curve included. This paper has been focused on the methodology of the analysis itself. The effect of the anti-recoil valve is a very important aspect of the process of selecting the right top tension for a specific riser system, but does not affect the general methodology as such.

For the analyses presented in this paper, a simplified version of the anti-recoil valve has been used, but clearly it has not been optimized for the operations assumed here.

There is a limitation to how complex control systems that can be adequately described without including a specialized tool for modeling of the control loops. However, an anti-recoil valve with a passive control system that changes the CV value of the valve according to cylinder stroke can easily be included since it gives a one-to-one relation between cylinder stroke and damping force coefficients in the valve.

## Conclusions

The methodology presented in this paper is capable of modeling all the important physical effects in the riser system and tensioner system during disconnect and recoil.

The following conclusions are made

- The overall physical behavior of the riser system

during disconnect and recoil can be adequately modeled and simulated by use of standard riser analysis tools.
    - The mud discharge phase can be modeled by use of the slug load capability that is included in most riser analysis tools. This models the change of mass of the riser.
    - The pneumatic stiffness of the main air banks are modeled as an element with non-linear axial stiffness characteristics.
    - The pressure loss due to friction loads in the hydraulic lines can be modeled as a dampening load in the element that models the riser tensioner. This requires that the riser analysis tool has this capability included.
    - The friction loads during the mud discharge phase are modeled as user-defined loads on each element. This requires some pre-processing before running the analysis.
- Using a general riser analysis tool allows for utilization of the possibilities with operational procedures, like moving the rig off location, etc.
- There is a limitation to how complex control systems that can be adequately described without including a specialized tool for modeling of the control loops. However, an anti-recoil valve with a passive control system that changes the CV value of the valve according to cylinder stroke can easily be included since it gives a one-to-one relation between cylinder stroke and damping force coefficients in the valve.

## Nomenclature

*BOP* = *Blow Out Preventer*
*CV* = *Flow Coefficient*
*CWO* = *Completion and WorkOver*
*FJ* = *Flex Joint*
*kips* = *kilo pounds*
*LMRP* = *Lower Marine Riser Package*
*MODU* = *Mobile Offshore Drilling Unit*
*RAO* = *Response Amplitude Operator*
*RKB* = *Rotary Kelly Bushing*
*TJ* = *Telescopic Joint*
*WH* = *Well Head*

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