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Stochastic Modelling of Trajectories of Dropped Cylindrical Objects in Offshore Operations

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Agenda

1. Background and Current Industry Practice

2. Methodologies
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2.3 Monte Carlo (MC) Method
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3.2 A Small-scaled Drill Pipe

4. Conclusions

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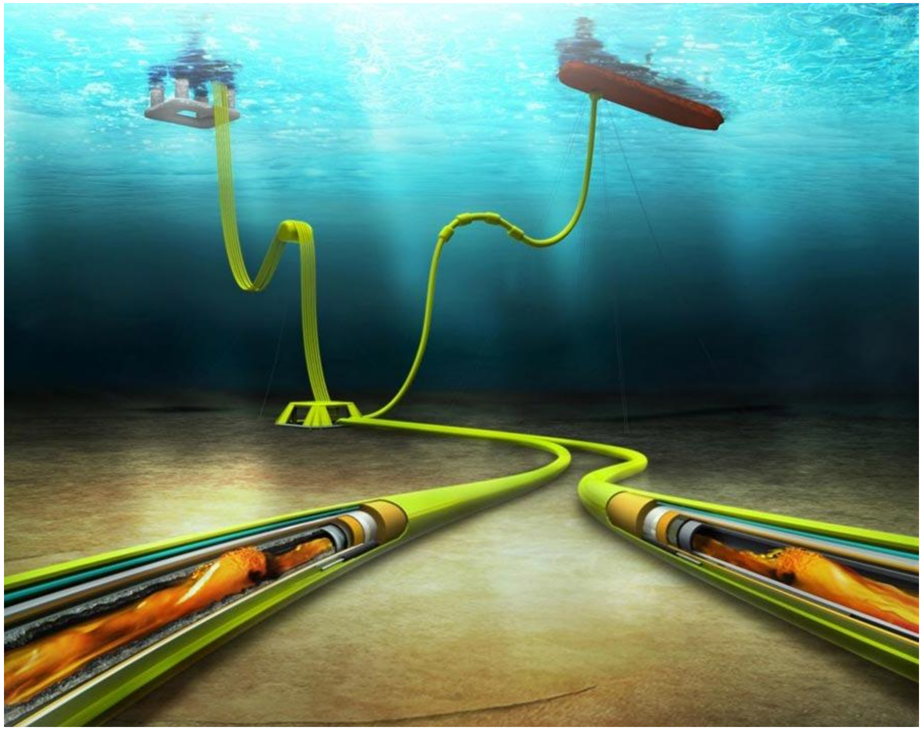
1.1 Background: Different Dropped Objects in Offshore Operations

- Dropped objects are one of the principal causes of accidents in the oil and gas industry and increase the total risk level for offshore and onshore facilities.
- Dropped objects like drill pipe, container and BOP will damage the subsea equipment like pipeline, manifold, Christmas tree and even wellhead. A damaged equipment may not only influence the whole oil production process but also harm the environments suck as oil leaking from a damaged pipeline.



Objects falling from vessels are likely to hit Pipelines

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1.2 Background: Risk and Frequency of Dropped Objects in Offshore Operations

- As recorded by the UK department of energy, during the period 1980—1986 (DNV, 1996), 81 incidents with dropped objects and 825 crane years are reported. The dropped object frequency is about 2.2·10-5 per lift. The total frequency is further divided into two kinds: 70 % chance to fall onto deck and 30 % chance to fall into the sea.
- Frequency of the dropped object into the sea is dependent on the lift type. Lifts operated by the drilling derrick are assumed to fall only in the sea.

Frequencies for dropped objects into the sea (DNV, 2010)

Type of lift	Frequency of the dropped object into the sea (per lift)
Ordinary lift to/from supply vessel with platform crane< 20tonnes	1.2×10^{-5}
Heavy lift to/from supply vessel with the platform crane > 20 tonnes	1.6×10^{-5}
Handling of load < 100 tonnes with the lifting system in the drilling derrick	2.2×10^{-5}
Handling of BOP/load > 100 tonnes with the lifting system in the drilling derrick	1.5×10^{-5}

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1.3 Background: Classification Guidance about Dropped Objects

- In ABS (2013) - Guidance Notes on Accidental Load Analysis and Design for Offshore Structures: "While the risk exposure to deeper water structures (either fixed jackets or hull systems) and subsea equipment may have the potential for significant facility, health and safety, or environmental release, this class of dropped objects will not be addressed herein. Proper study of these events requires specialized techniques to address the dropped object trajectory and subsequent likelihood of striking additional structure and equipment as well as predicting the consequences of such subsequent impacts."

- ABS Guide for Dropped Object Prevention on Offshore Units and Installations (2017) specifies the ABS requirements for an onboard dropped object prevention program to be implemented on an offshore asset.

- DNV (2010) proposed specific rules about the risk assessment of pipeline protection based on the assumption that landing points on the seabed follow normal distribution. The only factor influencing the distribution is mass of the dropped objects.

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1.4 Background: DNV's Simplified Method

Table 10 Angular deviation of object category.

no	*Description*	*Weight (tonnes)*	*Angular deviation (α) (deg)*
1	Flat/long shaped	< 2	15
2		2 – 8	9
3		> 8	5
4	Box/round shaped[1]	< 2	10
5		2 – 8	5
6		> 8	3
7	Box/round shaped	>> 8	2

1 A spread on the surface before the objects sinks is included.

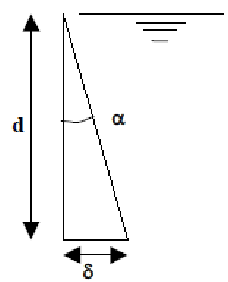

Figure 8 Symbols used in eq. (9).

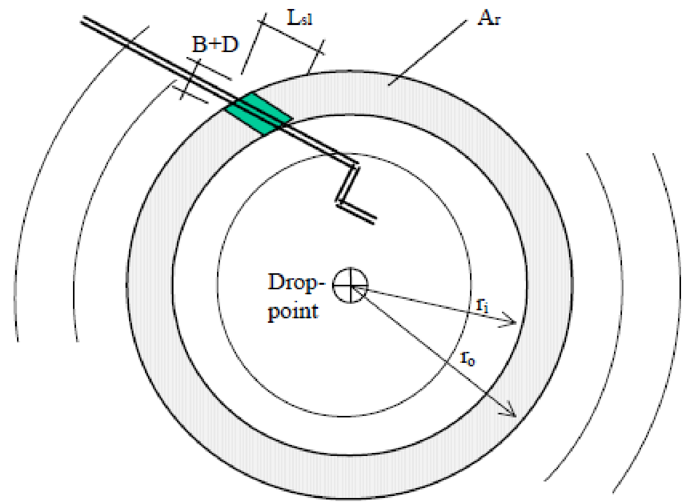

Figure 9 Probability of hit within a ring, defined by inner radius, r_i, and outer radius, r_o, from the drop point.

- However, DNV's simplified method ignores the hydrodynamics of objects.
- **Therefore, we need to numerically and experimentally investigate *Motion Simulation and Hazard Assessment of Dropped Objects in Offshore Operations*!**

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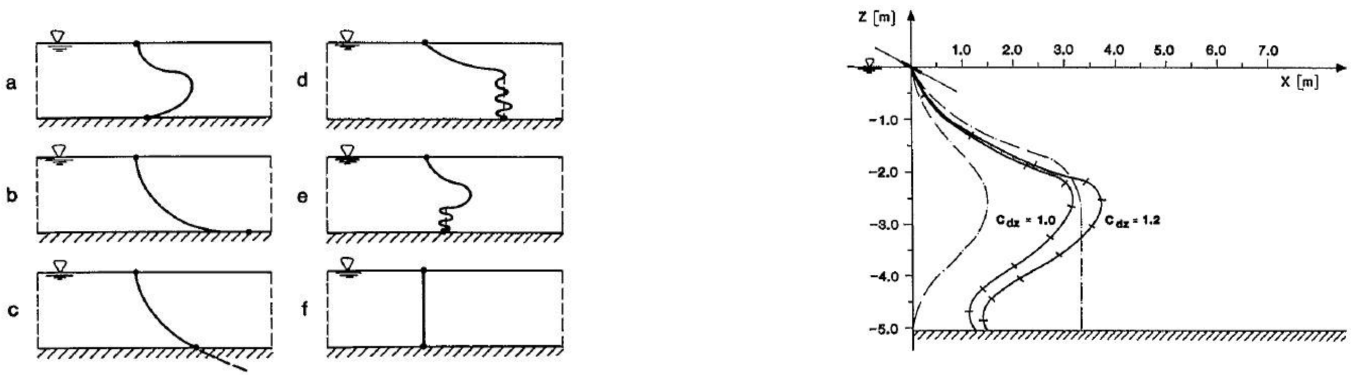
1.5: Numerical and Experimental Investigation of Dropped Objects (Aasnesland, 1987)

- A drilling pipe model is used to study the trajectory of dropped cylinder :

Table Property of the Cylinder

Parameters	Unit	Full Scale	Model Scale (1:20.32)
Length (L)	m	9.95	0.450
Mass density (ρ_c)	kg/m	225	0.548
Diameter (D)	m	0.203	0.010



Left - Observed trajectories; Right -simulated trajectory with drop angle at 30 degree compared with experimental envelope

- Aasnesland, (1987) found out that neglect of axial rotation will cause some errors in simulating the trajectory in real experiments.

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1.6 Experimental Investigation of Dropped Pipes and Containers in Awotahegn (2015)

Awotahegn (2015) focused on the experimental investigation of accidentally falling drill pipes and containers in order to see the distribution on the sea bed and observe the trajectory for different drop angles. Some findings are as following:

- The present recommended methodology for use of calculation by DNV is generally conservative and in some case's not conservative at all.
- The simplified method gives the initial estimate since it's based on a general category rather than a specific object hydrodynamics.
- Application of numerical tools in combination with experimental data promotes further development in preventing potential dropped/ falling objects.

Table 10 Angular deviation of object category.

no	*Description*	*Weight (tonnes)*	*Angular deviation (α) (deg)*
1	Flat/long shaped	< 2	15
2		2 – 8	9
3		> 8	5
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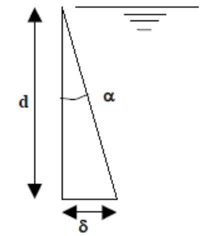

Figure 8 Symbols used in eq. (9).

DNV(2010)

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2.1: Our Previous Research Work – 2D Theory

$$(m - \rho\nabla)g\sin(\beta) + F_{dx} = m\dot{U}_1 \quad (1)$$

$$-(m - \rho\nabla)g\cos(\beta) + F_{dz} = \{U_1 m_t U_3 - U_1(x_t m_t)\Omega_2 + m_{33}\dot{U}_3\} + m(\dot{U}_3 - U_1\Omega_2) \quad (2)$$

$$M_{dy} = \{-U_1(m_{33} + x_t m_t)U_3 + U_1 {x_t}^2 m_t \Omega_2 + m_{55}\dot{\Omega}_2\} + M_{55}\dot{\Omega}_2 \quad (3)$$

where, the parameters are defined as following:

β : the instantaneous rotational angle between x-axis and X-axis;

m: the mass of the cylinder.

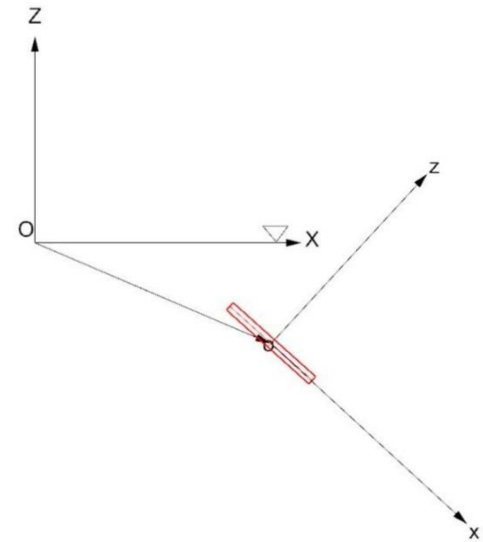
M_{55}: moment of inertia in pitch direction;

m_{33}: added mass for heave motion based on the strip theory

m_{55}: added mass for pitch motion based on the strip theory

m_t: 2D added mass coefficient along heave direction at the trailing edge

x_t: longitudinal position of effective



2D Coordinate system

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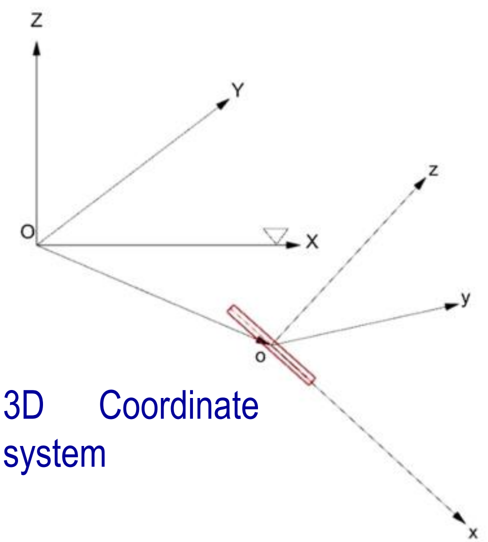
2.2: Our Previous Research Work – 3D Theory

- Extended the 2D thoery to 3D theory as follows (Xiang et al, 2016):

$$(m-\rho\nabla)g\sin(\theta)+F_{dx}=m(\dot{U}_1+U_3\Omega_2-U_2\Omega_3) \quad (13)$$

$$-(m-\rho\nabla)g\cos(\theta)\sin(\Phi)+F_{Ly}+F_{dy}=\{m_{22}\dot{U}_2+U_1m_{t2}U_2-U_1(x_tm_{t2})\Omega_3\}+m\left(\dot{U}_2+U_1\Omega_3-U_3\Omega_1\right) \quad (14)$$

$$-(m-\rho\nabla)g\cos(\theta)\cos(\Phi)+F_{Lz}+F_{dz}=\{m_{33}\dot{U}_3+U_1m_{t3}U_3-U_1(x_tm_{t3})\Omega_2\}+m\left(\dot{U}_3+U_2\Omega_1-U_1\Omega_2\right) \quad (15)$$



3D Coordinate system

$$\dot{\Omega}_1=0 \quad (16)$$

$$M_{Ly}+M_{dy}=\{-U_1(m_{33}+x_tm_{t3})U_3+U_1{x_t}^2m_{t3}\Omega_2+m_{55}\dot{\Omega}_2\}$$
$$+M_{55}\dot{\Omega}_2+(M_{44}-M_{66})\Omega_1\Omega_3 \quad (17)$$

$$M_{Lz}+M_{dz}=\{-U_1(m_{22}+x_tm_{t2})U_2+U_1{x_t}^2m_{t2}\Omega_3+m_{66}\dot{\Omega}_3\}$$
$$+M_{66}\dot{\Omega}_3+(M_{55}-M_{44})\Omega_1\Omega_2 \quad (18)$$

- Therefore, a simulation tool – DROBS (Dropped Objects Simulator) has been developed based on 2D and 3D theory.

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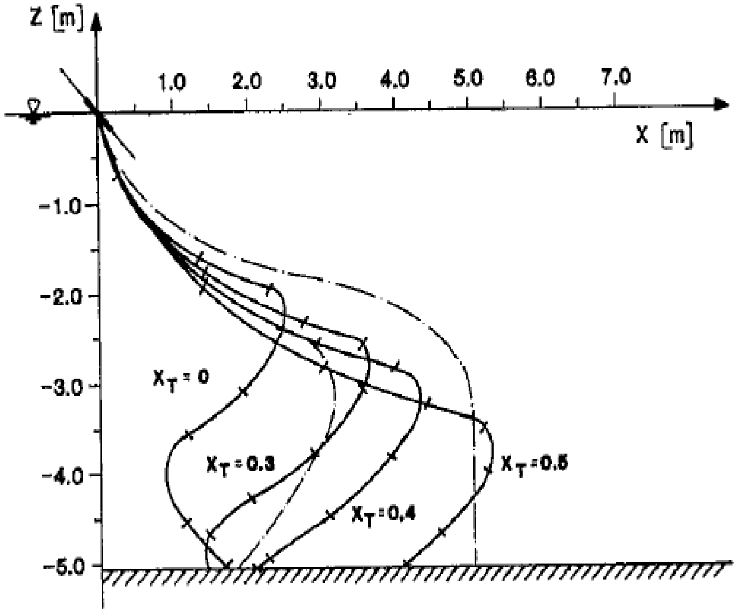
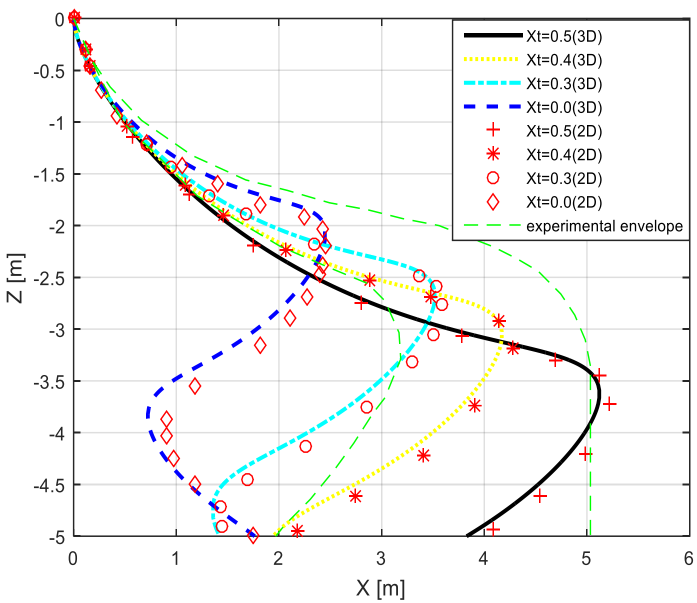
2.3 Validation of 2D & 3D Code



Left – results from Aanesland (1987)



Right – results from DROBS for comparison and validation

Comparison of current simulated trajectories at drop angle 45^o with Aanesland (1987)

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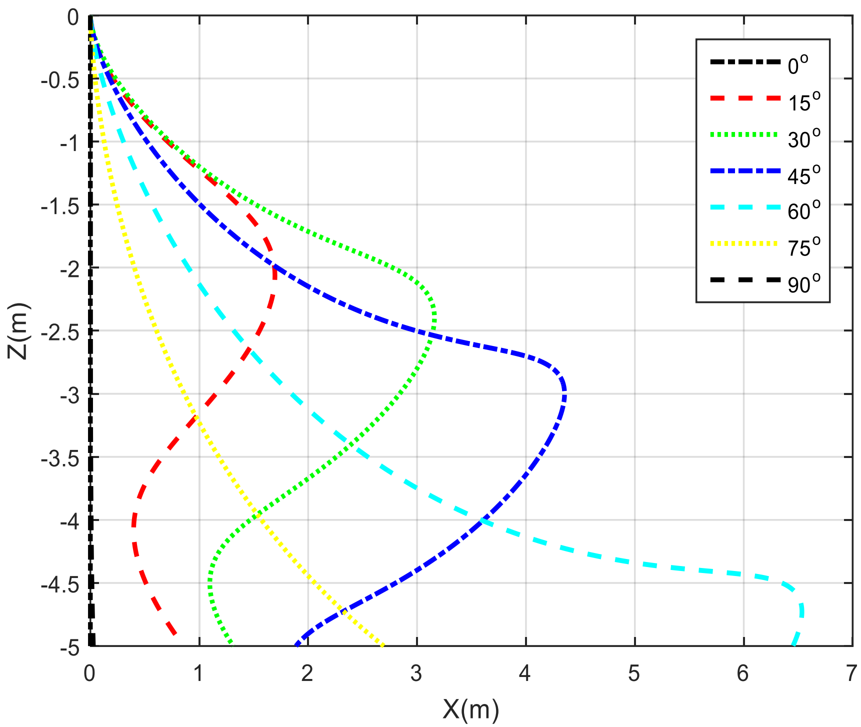
2.4: Simulated Motions @ 0-90deg

- The initial drop angle is from 0^o to 90^o with a uniform increment 15^o. Some parameters are unchanged: C_{dy}=1.0, C_{dz}=1.0 and Vroll=0.01 rad/s.

- As shown in Fig., we observed obvious Bifurcation Phenomena which usually occurred in nonlinear system. X is increasing when drop angle increases from 0^o to 60^o. However, for drop angle from 60^o to 90^o, X tends to decrease.



Simulated trajectory at X-Z plane with drop angle from 0 to 90 degree

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2.5: State-space Model in 2D

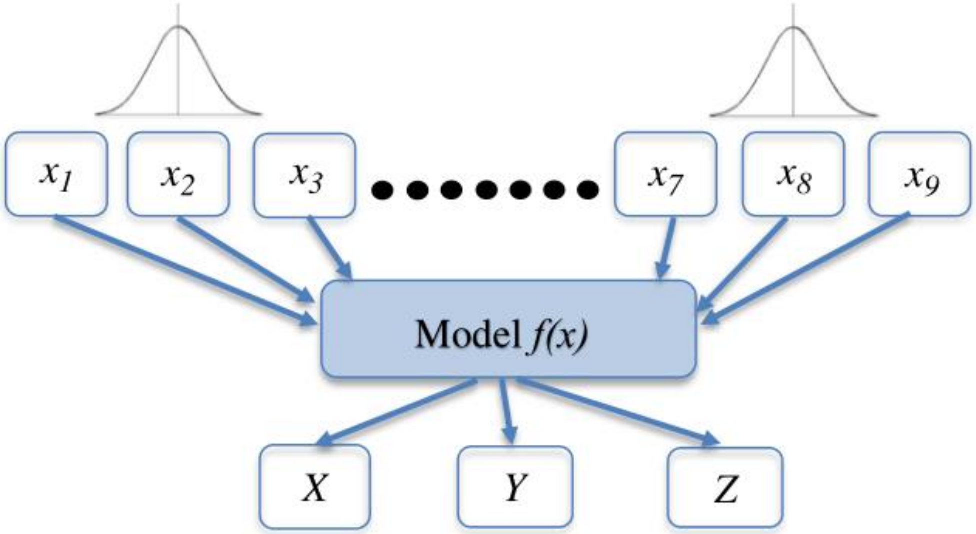
The state-based nonlinear dynamic system can formulate the equations of the motion of the dropped cylinder in two-dimensions above. The model of this system can be written as

$$\dot{x}_k = f_k(x_k) =$$

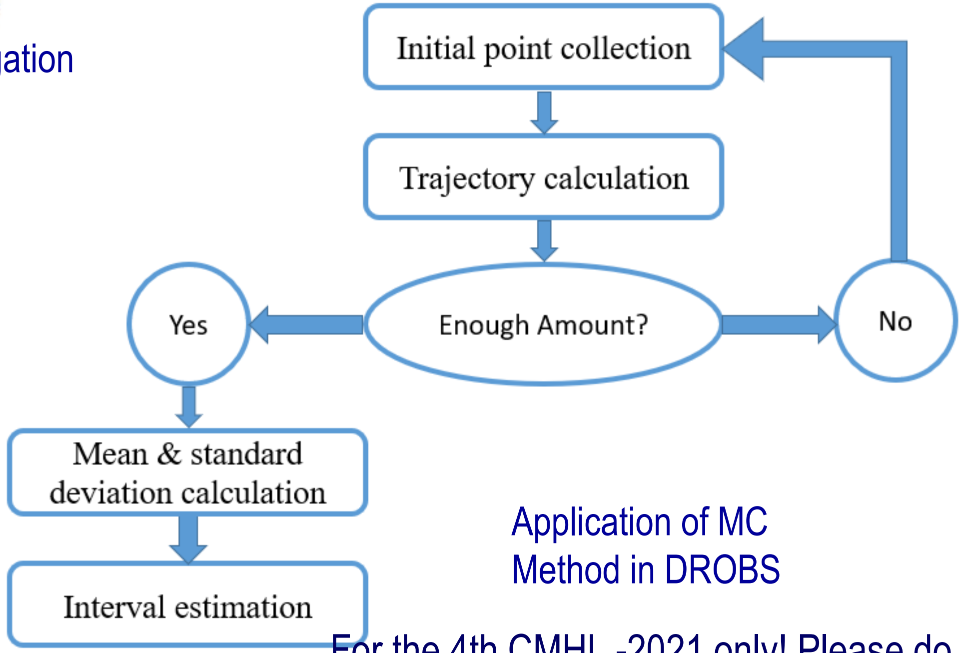
$$\begin{bmatrix} \frac{1}{m}(m-\rho\nabla)g\sin x_{4,k} - \frac{0.664}{m}\pi\sqrt{v\rho^2 L}x_{1,k}\sqrt{|x_{1,k}|} - \frac{1}{8m}\rho\pi C_{dx}D^2 x_{1,k}|x_{1,k}| \\ \frac{1}{m_{33}+m}\left[-(m-\rho\nabla)g\cos x_{4,k} + F_{dz} - m_t x_{1,k}x_{2,k} + x_t m_t x_{1,k}x_{3,k} + m x_{1,k}x_{3,k}\right] \\ \frac{1}{m_{55}+M_{55}}\left[M_{dy} + (m_{33}+x_t m_t)x_{1,k}x_{2,k} - {x_t}^2 m_t x_{1,k}x_{3,k}\right] \\ \dot{x}_{3,k} \end{bmatrix}$$

where $x_k = \left[x_{1,k}, x_{2,k}, x_{3,k}, x_{4,k}\right]' = \left[U_{1,k}, U_{3,k}, \Omega_{2,k}, \beta_k\right]'$.

2.6: Monte Carlo (MC) Method



Principle of stochastic uncertainty propagation



Application of MC Method in DROBS

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2.7: Unscented Transformation (UT) Method

One of the ways to construct the set of sigma points ς is following

$$\begin{cases} X^{(0)} = \bar{x} & W^{(0)} = w^{(0)} \\ X^{(i)} = \bar{x} + \left(\sqrt{\frac{n_x}{1-W^{(0)}} P_x}\right)_i & W^{(0)} = \frac{1-w^{(0)}}{2n_x} \\ X^{(i+n_x)} = \bar{x} - \left(\sqrt{\frac{n_x}{1-W^{(0)}} P_x}\right)_i & W^{(i+n_x)} = \frac{1-w^{(0)}}{2n_x} \end{cases}$$

The estimate of $\tilde{y}(\bar{y}, P_y)$ is as follows,

$$\begin{cases} Y^{(j)} = h(X^{(j)}) \\ \bar{y} = \sum_{j=0}^{2n_x} W^{(j)} \cdot Y^{(j)} \\ P_y = \sum_{j=0}^{2n_x} W^{(j)} \cdot (Y^{(j)} - \bar{y}) \cdot (Y^{(j)} - \bar{y})' \end{cases}$$

The operator $\sqrt{\cdot}$ is the Cholesky decomposition and $(\sqrt{\cdot})_i$ represents the i-th column of the decomposed matrix, i $= 1, 2, \dots, n_x$.

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3.1.1: A Dropped Model Rocket

	Full Scale	Model
L	40.7 m	51.1 cm
D	3.66 m	4.83 cm
Δ	411000 kg	0.997 kg

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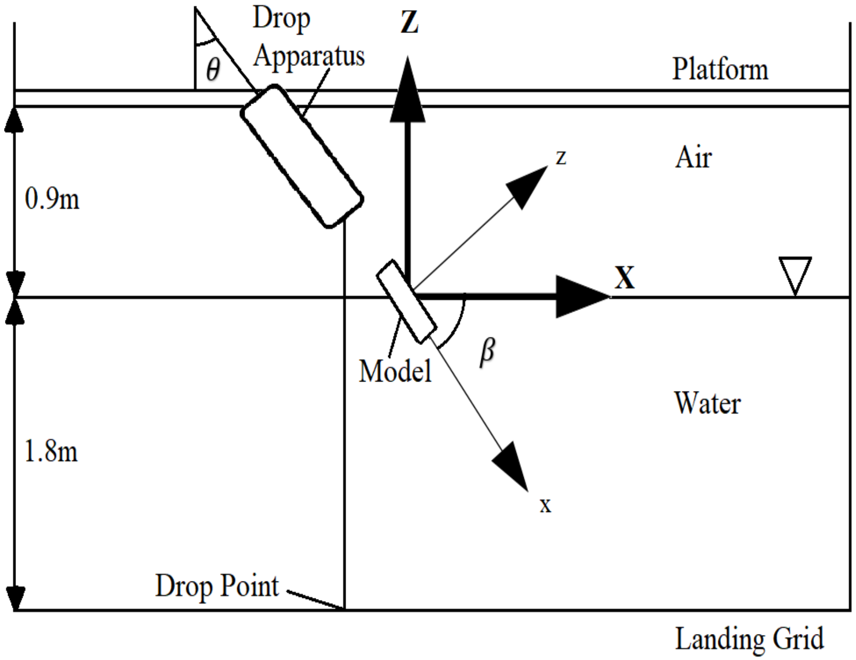
3.1.2: Experiment Setup

A view of dropped apparatus and landing grid



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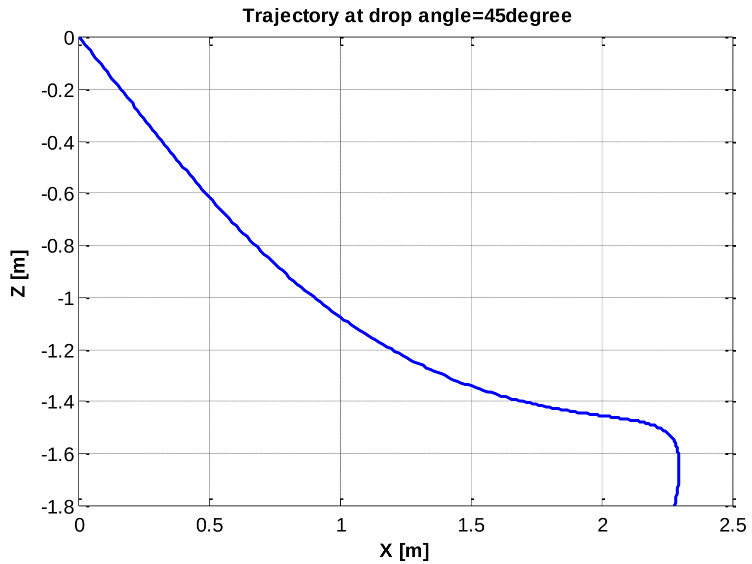
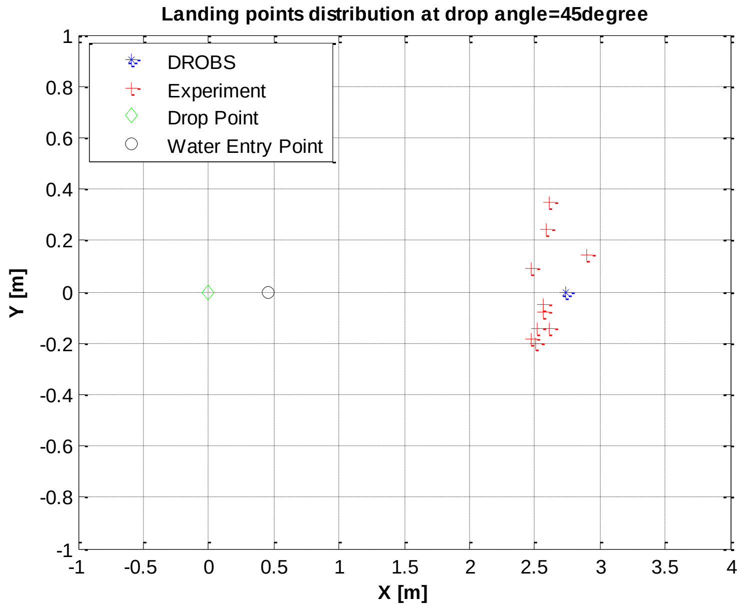
3.1.3: Deterministic Model





Left – the predicted trajectory from DROBS

Right- the predicted landing point from deterministic model vs. experimental landing points

Table 3: Comparison of Theoretical to Mean Experimental Landing Distribution

Drop Angle	Theoretical (cm)	Mean Experimental (cm)	Percent Difference
0	0	39.0	N/A
15	72.4	84.2	14.0%
30	204.4	207.7	1.6%
45	212.5	258.9	17.9%
60	296.4	275.1	-7.7%
75	173.7	235.6	26.3%
90	0	48.0	N/A

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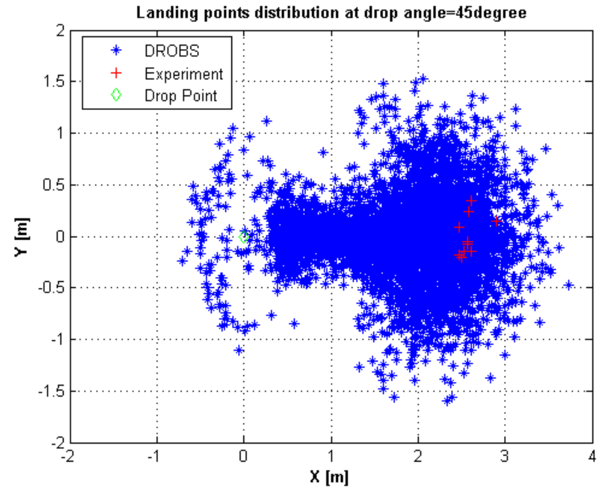
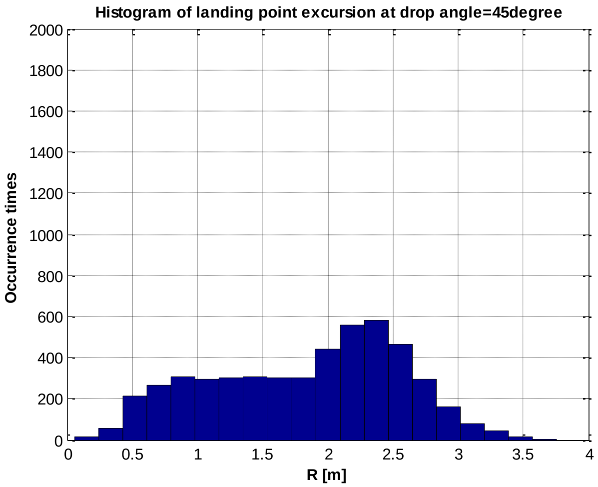
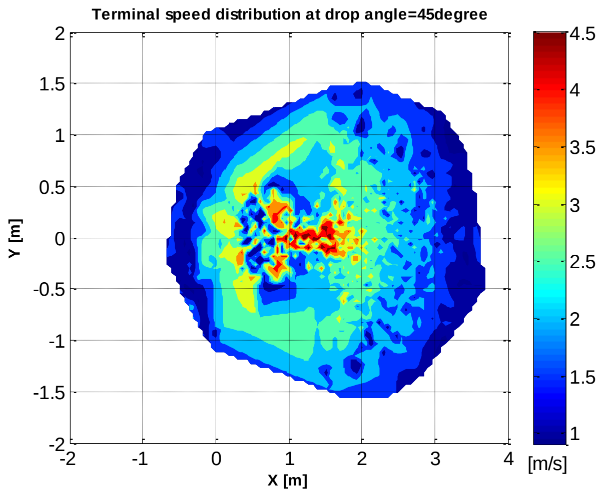
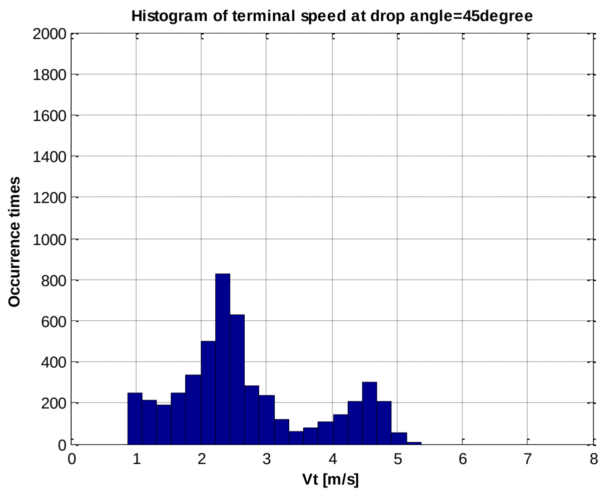
3.1.4: Stochastic Modelling using MC Method (45 deg)









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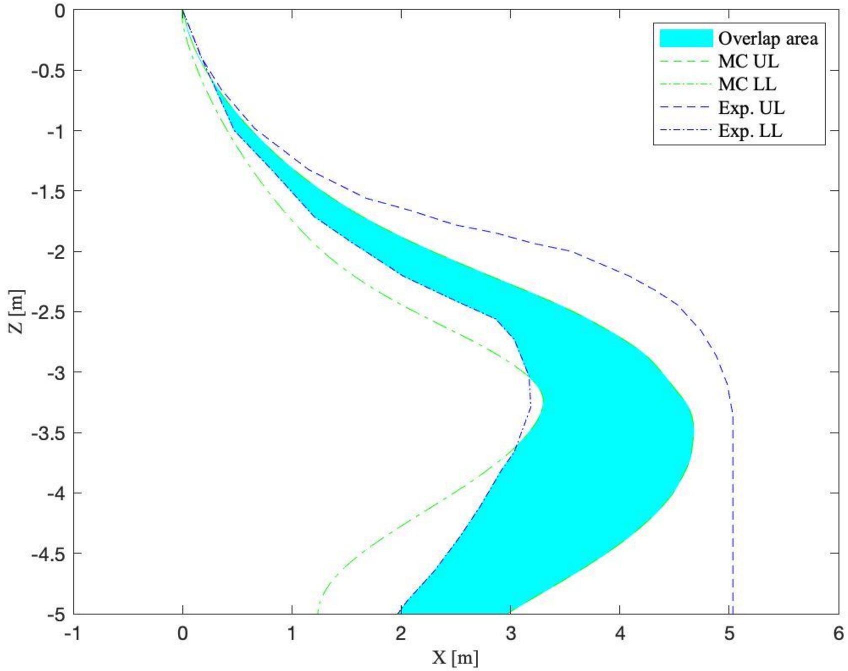
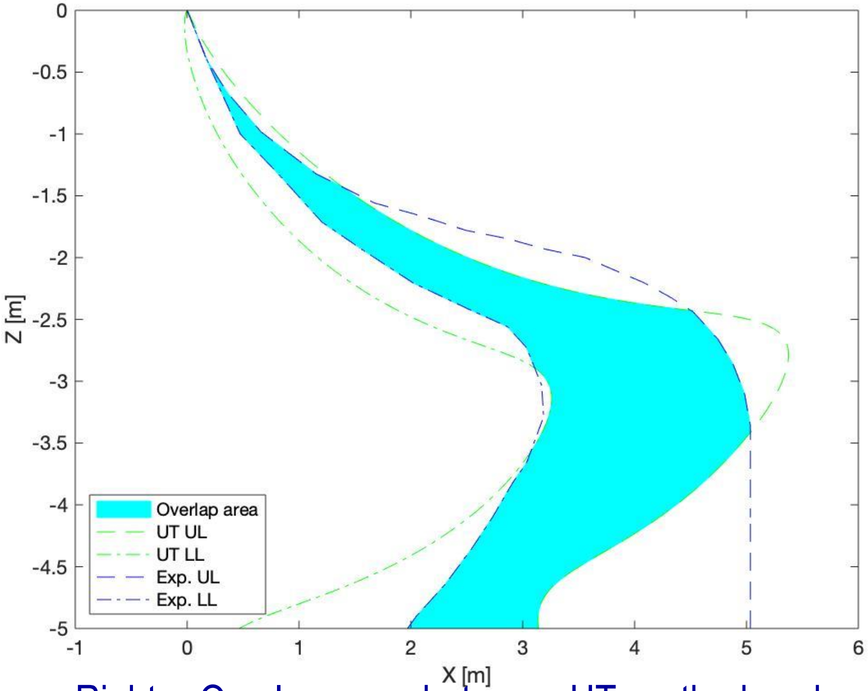
3.2.1: A Dropped Scaled Drill Pipe

Here, two new performance parameters are proposed,

(1) $R_A = \frac{A_{olp}}{A_{ee}}$; (2) $R_L = \frac{L_{olp}}{L_{ee}}$



Left - Overlap area between MC method and experimental envelope with the drop angle 45°(Samples =256, sigma range =1)



Right - Overlap area between UT method and experimental envelope with the drop angle 45°(Probability=0.6826)

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3.2.2: Comparison of MC Method and UT Method

Prediction results derived from MC method at drop angle=45°

Samples	Time(s)	R_A	R_L
$2^4 = 16$	2.089	0.518	0.145
$3^4 = 81$	10.326	0.566	0.323
$4^4 = 256$	49.843	0.572	0.326
$5^4 = 625$	123.078	0.565	0.319
$6^4 = 1296$	241.204	0.579	0.348
$7^4 = 2401$	433.816	0.579	0.345
$8^4 = 4096$	526.301	0.581	0.355
$9^4 = 6561$	856.669	0.584	0.359

Prediction results derived from these two methods under the same conditions at drop angle= 45°

Method	P	Sigma range	Time(s)	R_A	R_L
MC(Samples=256)	0.6826	1	49.843	0.572	0.326
UT	0.6826	1	1.737	0.693	0.382

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4. Conclusions

- The equations of motions of dropped cylindrical objects in 2D and 3D have been firstly established, and they can be transformed into state-space model. An in-house tool – DROBS has been successfully developed.
- The stochastic behavior of the cylinders falling into water has been investigated by two different statistical methods, i.e., MC method and UT method.
- In general, MC method is reliable under the premise of many samples. The results obtained by the UT method behaves in a similar way with MC method with reasonable sample size. However, the UT method can produce the trajectory envelop in a very short time and it ensure the possible real-time monitoring in the real offshore operations.
- DROBS can be merged into DNV's guidance (2010) and it can provide an optimal pipeline layout design by considering the hydrodynamic coefficients in a more accurate way.
- Besides, DROBs has been also applied to simulate the trajectory of a dropped model rocket, and it may help to track, recover and salvage the missing rocket.

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Q & A

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