Numerical Modeling of Launching Offshore Jackets from Transportation Barge & the Significance of Water Entry Forces on Horizontal Jacket Members

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Abstract

Development of a numerical model which describes launching of offshore jackets from barge is presented in this paper. In this model, in addition to capabilities of commercial softwares, water entry forces on jacket members and an implicit Newmark solution technique are included. The results are in general agreement with other numerical software's available (SACS). Fluid forces acting on jacket and the importance of each one is discussed. It is observed that water entry forces on horizontal jacket members are very significant and may locally govern the design of these members. This force is more important for horizontal slender members near the mud-line, which do not experience significant environmental loading in operating conditions. Therefore the water entry impact force with large magnitude can cause over-stress and/or ovalling of near mud-line members. It is also observed that taking water entry forces in account modifies the jacket trajectory only in a little extent.

Keywords: Launch - Offshore Jacket - Hydrodynamic Force - Water Entry Force – Newmark - SACS
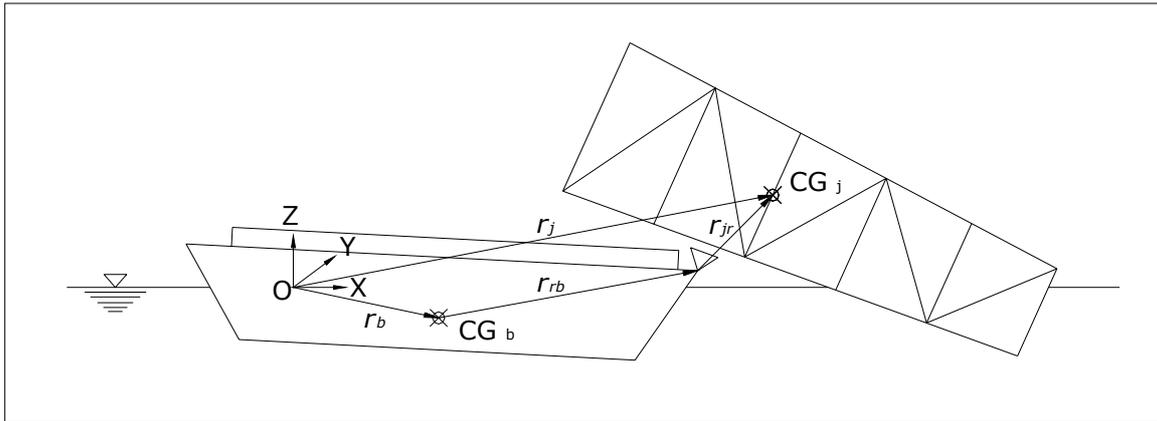
Introduction

In most relatively shallow waters, fixed platforms are the optimum economical choice. One of the important aspects of offshore fixed platform design is their installation procedure. Among the several conditions during installation, launching is probably the most critical. This operation has to be modeled and examined carefully in order to insure safe separation of jacket from barge.

As the platforms get heavier, launching technique for placing the steel template jacket from transportation barge onto its location is preferred, rather than lifting it directly by means of crane barges. This operation, besides the preparations, takes only a few minutes, which shows the operations dynamic and critical nature. A complete time-history launch analysis is generally required for three reasons: a) checking the jacket will not hit mud-line, b) checking that jacket members (launch truss) can resist the reaction forces exerted by rocker arm and c) checking that members can resist the hydrodynamic forces experienced during plunging in sea.

Vasicek and Lu [1] presented a numerical model of jacket launching. They used an iterative finite difference scheme to solve the governing equations of motions. Sphaier et al. [2] describe the theoretical backgrounds of a launch modeling software. In their work, the system of governing differential-algebraic equations is solved (algebraically) at the beginning of time step with accelerations and reaction forces as unknowns. These values are assumed constant through the time step and displacements at the end of time step are calculated. Nelson et al. [3] presents a numerical modeling of a similar case; lifeboat launching. Similar to [2], accelerations and reaction forces are calculated at the beginning of each time step. Reactions are considered constant through the step and the resulting system of differential equations is solved using the Runge-Kutta method.

In this paper a mathematical formulation of the problem accounting for water entry forces using experimental slam coefficients [4], on the launched body is presented. A numerical solution using the

Figure 1. Jacket rotating about rocker arm. Orientation of the global coordinate system and the relative positions of jacket and barge CG's.

Newmark linear acceleration method is used. Also, iteration is performed in each step to obtain solutions consistent with the constraint equations. The effect of each of the fluid forces acting on jacket during launching, including water entry are investigated.

Description of Problem

A calm sea/weather is required for launch. Jacket is transported on launch barge to installation site. Barge compartments are ballasted; trimming the vessel a large angle (2°-4°) and sea-fastenings are cut. This is the start point in a launch analysis. Jacket slides toward rocker arm located at barge aft. After passing the rocker arm it rotates and plunges in sea. After separation of barge and jacket they both oscillate a few times and come to rest [5], [6]. Depending on the relative motions of jacket and barge, five phases of motion are possible [7]:

Phase 1: Jacket is sliding on barge deck due to hydraulic jack pushing or winch pulling.

Phase 2: Jacket is sliding on barge deck under action of its own weight.

Phase 3: Jacket is only rotating about rocker arm pin.

Phase 4: Jacket is rotating about rocker arm pin and sliding on tilting beam (rocker arm) simultaneously.

Phase 5: Jacket and barge have separated.

If initial trim angle of barge is greater than dynamic friction coefficient angle, after cutting sea-fastenings, phase 2 will occur, however due to large friction at beginning, an initial pull/push by winch/jack is required. If not, phase 1 will occur and the jacket will slide on barge deck with the constant velocity of winch. There are two conditions necessary for the jacket to start rotating on rocker arm: 1) jacket CG (center of gravity) passes rocker arm pin and 2) reaction moment is negative. The necessity of condition 2) implies that jacket CG might slide a few meters past the pin and then start rotating.

If the two mentioned conditions occur while jacket is still in phase 1, phase 3 will occur. Jacket stops here and starts to only rotate about the pin. Rotation continues until angle of jacket exceeds static friction coefficient angle. From this point on, jacket rotates and slides simultaneously (phase 4). Therefore, Phase 3 can only occur after phase 1. Phase 4 can only occur after phase 2 or 3. Geometry of barge and jacket during phases 3 or 4 is shown in Fig. 1. A right-hand-sided coordinate system with its origin located at S.W.L. and above CG of barge is used to describe the problem. Positive Z axis is upward and X axis lies in water-plane with positive direction pointing toward barge aft (Fig. 1).

Equations governing the motion are Newton-Euler equations of motion. These

equations are the same for all phases. In addition to equations of motion, constraints are needed to describe the motion. These constraints vary in each phase. By assembling the motion and constraint equations, one gets a system of differential-algebraic equations, with accelerations and reaction forces as unknowns.

Equations of Motion

The Newton-Euler equations of motion state that rate of change of system momentum equals the forces acting on system. We consider jacket and barge as two separate systems, with the common reaction forces acting on both. In practice jacket is placed on barge deck such that their CG's lay in a vertical plane above each other, eliminating any yawing moments. Therefore launch is essentially a two dimensional problem. In this regards and by assuming jacket and barge as rigid bodies, position of each body can be represented by three components, namely X, Z and θ coordinates of their CG. Equations of motion for these six degrees of freedom are as follows:

$$m_j\,\ddot{X}_j = P_c^X + P_w^X + F_{F,j}^X$$

$$m_j\,\ddot{Z}_j = P_c^Z + P_w^Z + F_{F,j}^Z - W_j$$

$$I_j\,\ddot{\theta}_j = M_c^Y + M_{F,j}^Y + (P_c^X + P_w^X) \times (Z_c - Z_j)$$

$$-(P_c^Z + P_w^Z) \times (X_c - X_j)$$

$$m_b\,\ddot{X}_b = -P_c^X - P_w^X + F_{F,b}^X$$

$$m_b\,\ddot{Z}_b = -P_c^Z - P_w^Z + F_{F,b}^Z - W_b$$

$$I_b\,\ddot{\theta}_b = -M_c^Y + M_{F,b}^Y - (P_c^X + P_w^X) \times (Z_c - Z_b)$$

$$+(P_c^Z + P_w^Z) \times (X_c - X_b)$$

$$(1)$$

Where:
m: Mass
I: Moment of inertia about CG of body
X, Z, θ: Components of position vector.
P, F: Forces. *M*: Moment. *W*: Weight.
Subscripts *j*, *b* denote jacket and barge respectively
Subscripts *c*, *w*, *F* denote contact, winch and fluid (hydrodynamic and hydrostatic) forces respectively

Double dot denotes second derivative with respect to time.

Eleven unknowns appear in these six motion equations, namely six accelerations, three contact forces and two winch forces. Therefore one needs constraint equations to complete the system of equations.

Constraint Equations/Relations

Constraint equations are geometrical/force relationships that relate the motion of jacket and barge. These constraints are required in all phases except phase 5. In phase 5 the two bodies have separated and reaction forces are all zero, therefore only the six accelerations are unknown and the six equations of motion Eq. (1)-(6) suffice.

In phases 1 to 4 where the two bodies are connected, positions of their CG's are related. Differentiating this relation with respect to time yields the velocity relation and another differentiation results in the acceleration constraint of the system:

$$\vec{r}_j = \vec{r}_b + \vec{r}_{rb} + \vec{r}_{jr}$$

$$\vec{V}_j = \vec{V}_b + \vec{\dot{\theta}}_b \times \vec{r}_{rb} + \vec{\dot{\theta}}_j \times \vec{r}_{jr} + \dot{\vec{r}}_{jr}$$

$$\vec{a}_j = \vec{a}_b + \vec{\ddot{\theta}}_b \times \vec{r}_{rb} + \vec{\dot{\theta}}_b \times (\vec{\dot{\theta}}_b \times \vec{r}_{rb}) + \vec{\ddot{\theta}}_j \times \vec{r}_{jr}$$

$$+\vec{\dot{\theta}}_j \times (\vec{\dot{\theta}}_j \times \vec{r}_{jr}) + 2\vec{\dot{\theta}}_j \times \dot{\vec{r}}_{jr} + \ddot{\vec{r}}_{jr} \tag{2}$$

Where:
r : Position vector
V : Velocity   *a* : Acceleration
Dot denotes first derivative with respect to time and subscript *r* denotes rocker arm pin.

The vector form of acceleration constraint results in two constraints in scalar form:

$$\ddot{X}_j = \ddot{X}_b + (Z_r - Z_b)\ddot{\theta}_b - (X_r - X_b)\dot{\theta}_b^2$$

$$+(Z_j - Z_r)\ddot{\theta}_j - (X_j - X_r)\dot{\theta}_j^2$$

$$-2V_t\dot{\theta}_j Sin(\theta_j) + \dot{V}_t Cos(\theta_j)$$

$$\ddot{Z}_j = \ddot{Z}_b - (X_r - X_b)\ddot{\theta}_b - (Z_r - Z_b)\dot{\theta}_b^2$$

$$-(X_j - X_r)\ddot{\theta}_j - (Z_j - Z_r)\dot{\theta}_j^2 \tag{3}$$

$$-2V_t\dot{\theta}_j Cos(\theta_j) - \dot{V}_t Sin(\theta_j)$$

Where:

V_t: Jacket relative sliding velocity on launch skids/rocker arm.

$\dot{V}_t$: Jacket relative sliding acceleration on launch skids/rocker arm.

Equation (3) is valid throughout phases 1 to 4. As can be seen in Eq. (3) another unknown, Jacket relative sliding acceleration, is introduced in the constraint equations. Therefore in phases 1 to 4 there are a total of 12 unknowns. In addition to Eq. (3), four more equations are needed to construct a system of equations for the 12 unknowns. These additional equations vary for each phase.

Constraint Equations during Phase 1

During phase 1 jacket is sliding on barge deck due to winch pulling or hydraulic jack pushing, therefore relative velocity of jacket sliding on launch skids is constant and equal to velocity of winch. This implies that relative sliding acceleration is zero, resulting in the following relation:

$$\dot{V}_t = 0 \qquad (4)$$

The following equations result from these facts respectively: winch force is parallel to barge deck, contact forces result from normal reaction and friction force which are related by the dynamic friction coefficient, and finally, barge and jacket rotate together.

$$P_w^X \, Sin(\theta_j) + P_w^Z \, Cos(\theta_j) = 0 \qquad (5)$$

$$
\begin{aligned}
&P_c^X \times (Cos(\theta_j) + \mu_d \times Sin(\theta_j)) \\
&- P_c^Z \times (Sin(\theta_j) - \mu_d \times Cos(\theta_j)) = 0
\end{aligned} \qquad (6)
$$

$$\ddot{\theta}_b = \ddot{\theta}_j \qquad (7)$$

Where:

μ_d: Dynamic friction coefficient between jacket and launch skids.

Constraint Equations during Phase 2

In phase 2, jacket is sliding on barge deck under action of its self weight. Physically this means that angle of barge has exceeded angle of dynamic friction. This implies that relative sliding velocity exceeds winch velocity; so equation (4) is

not valid. Also winch force is zero. Rests of the equations are the same as phase 1.

$$P_w^X = 0$$

$$P_w^Z = 0 \qquad (8)$$

Constraint Equations during Phase 3

In phase 3, jacket is rotating about rocker arm pin without sliding. Therefore Eq. (4) is valid. Equation (8) is also valid. Note that because there is no sliding, friction force relation, Eq. (6), is not valid. In addition, rocker arm pin does not resist moments, therefore:

$$M_c^Y = 0 \qquad (9)$$

Constraint Equations during Phase 4

Additional constraints/relations in this phase are the same as phase 3, except that due to sliding, Eq. (6) is valid and equation (4) is not.

The 12 equations required in each of the first four phases to set up the system of differential-algebraic equations are summarized in Table (1).

Table 1. Summary of equations used in each phase.

Phase	Motion Equations	Constraints
1	(1)	(3), (4)-(7)
2	(1)	(3), (5)-(8)
3	(1)	(3), (4), (7)-(9)
4	(1)	(3), (6)-(9)
5	(1)	-

Fluid Forces Acting on Jacket

Since the jacket is made of tubular elements, fluid force acting on jacket is sum of fluid forces acting on individual tubular elements that are submerged. Therefore we derive the fluid forces acting on a typical submerged tubular element.

Buoyancy

Every element is buoyed up by the surrounding fluid with a force equal to weight of displaced fluid. This force passes through center of submerged volume. The calculation is straight forward, except for members partially submerged (near SWL).

These members are divided into strips for calculation of submerged volume.

$$F_B^Z = \rho_w g V_w$$

$$M_B^Y = -F_B^Z \times (X_m - X_j) \qquad (10)$$

Where:

X_m : X coordinate of element axis center

V_w : Volume of displaced water by element

ρ_w : Density of sea water

g : Gravitational acceleration

Added Mass

Acceleration of body disturbs the fluid and causes a pressure field. Resultant of these pressures on body is a force proportional to acceleration of body, known as added mass. Normal acceleration of a point p ($\vec{a}_{p,n}$), on axis of a submerged tubular element, is derived as:

$$\vec{a}_{CG,j} = \ddot{X}_j \vec{i} + \ddot{Z}_j \vec{k}$$

$$\vec{a}_p = \vec{a}_{CG,j} + \ddot{\theta}_j \vec{j} \times \vec{r}_{pj} + \dot{\theta}_j \vec{j} \times (\dot{\theta}_j \vec{j} \times \vec{r}_{pj})$$

$$\vec{a}_{p,n} = \vec{u} \times (\vec{a}_p \times \vec{u}) \qquad (11)$$

$\vec{u}$: Unit vector along element axis

$\vec{r}_{pj}$: Position vector from jacket CG to point p

Added mass force and moment of a submerged element due to this acceleration are as follows:

$$F_{A,j}^X = k_1 \int_0^L a_{p,n}^X \, dl$$

$$F_{A,j}^Z = k_1 \int_0^L a_{p,n}^Z \, dl$$

$$M_{A,j}^Y = k_1 \int_0^L (Z_p - Z_j) a_{p,n}^X \, dl$$

$$-k_1 \int_0^L (X_p - X_j) a_{p,n}^Z \, dl \qquad (12)$$

L : Length of submerged element

OD : Outside diameter of element

C_a : Added mass coefficient of element's section which theoretically equals 1

$$k_1 = -\rho_w C_a \pi \frac{OD^2}{4} L$$

Calculation of added mass forces and moments can be simplified by use of added mass matrix [8].

Drag

There are two sources for drag force: friction of fluid on body surface, known as friction or viscous drag and a force due to the unbalanced pressures on body, known as form drag. Drag is proportional to square of velocity. Drag forces experienced by tubular members of jackets during launching is mainly form drag, due to the high Reynolds number of the member. Therefore velocity of element perpendicular to its axis is considered. Because the motion of jacket during launching is not harmonic, drag force linearization schemes cannot be used. Velocity of point p perpendicular to element axis ($V_{p,n}$) is derived as:

$$\vec{V}_{CG,j} = \dot{X}_j \vec{i} + \dot{Z}_j \vec{k}$$

$$\vec{V}_p = \vec{V}_{CG,j} + \dot{\theta}_j \vec{j} \times \vec{r}_{jp}$$

$$\vec{V}_{p,n} = \vec{u} \times (\vec{V}_p \times \vec{u}) \qquad (13)$$

The three components of drag force are calculated as:

$$F_{D,j}^X = k_2 \int_0^L |\vec{V}_{p,n}| V_{p,n}^X \, dl$$

$$F_{D,j}^Z = k_2 \int_0^L |\vec{V}_{p,n}| V_{p,n}^Z \, dl$$

$$M_{D,j}^Y = k_2 \int_0^L (Z_p - Z_j) |\vec{V}_{p,n}| V_{p,n}^X \, dl$$

$$-k_2 \int_0^L (X_p - X_j) |\vec{V}_{p,n}| V_{p,n}^Z \, dl \qquad (14)$$

C_D : Drag Coefficient

$$k_2 = -\frac{1}{2} \rho_w C_D (OD)$$

The integrals are evaluated numerically using three point gauss quadrature.

Water Entry/Exit

When jacket members enter water, they experience forces similar to wave slam. These forces have very large magnitudes but affect the member for a very short interval. It is observed that considering them, modifies the jacket trajectory to a little extent. On the other hand they are important in local member design-checks. Mathematically this force is equal to rate of change of added mass

momentum, i.e., during water entry added mass of member is zero in air, an instant later when it is submerged, it has a large added mass. As shown in Ref. [9], excluding buoyancy and drag, the total force in Z direction acting on a tubular section during water entry is:

$$F_E = \frac{d}{dt}(m_a V) = \frac{d(m_a)}{dh}\frac{dh}{dt}V + m_a \frac{dV}{dt} =$$

$$\frac{d(m_a)}{dh}V^2 + m_a \frac{dV}{dt} = \frac{\rho_w}{2}C_s(OD)V^2 + m_a \frac{dV}{dt}$$

(15)

m_a : Added mass of section

h : Distance between bottom of tubular and SWL

C_s : Water entry (slam) coefficient

Theoretical value of C_s is π. But experimental results, [4], show that C_s is 5.15 at the instant of entry and after that it decays (Eq. 16.). Also, m_a is the time varying added mass during water entry, which reaches its asymptotic value m_w (mass of fluid displaced by tubular element), after complete submergence. It is assumed that water entry/exit forces act on any section while $0 < h/OD < 1$.

$$C_s = \frac{5.15}{1 + 17\dfrac{h}{OD}} + 0.55\frac{h}{OD}$$

(16)

The velocity considered in Eq. (15) is that component of $V_{p,n}$ lying in the u-Z plane. Three components of water entry/exit forces are:

$$F_{E,j}^X = k_3 \int_0^L |\vec{V}|\vec{V}^X\, dl$$

$$F_{E,j}^Z = k_3 \int_0^L |\vec{V}|\vec{V}^Z dl$$

$$M_{E,j}^Y = k_3 \int_0^L (Z_p - Z_j)|\vec{V}|V^X\, dl$$

$$-k_3 \int_0^L (X_p - X_j)|\vec{V}|V^Z\, dl$$

(17)

$$k_3 = -\frac{1}{2}\rho_w C_s(OD)$$

C_s is a function of h, therefore considering water entry/exit force as mentioned, needs high computation times and has prevented commercial softwares from using it.

Finally, the three components of fluid force acting on jacket are calculated by summing up the mentioned forces on all elements of jacket:

$$F_{F,j}^X = \sum_{elements}(F_{D,j}^X + F_{A,j}^X + F_{E,j}^X)$$

$$F_{F,j}^Z = \sum_{elements}(F_{B,j}^Z + F_{D,j}^Z + F_{A,j}^Z + F_{E,j}^Z)$$

$$M_{F,j}^Y = \sum_{elements}(M_{B,j}^Y + M_{D,j}^Y + M_{A,j}^Y + M_{E,j}^Y)$$

(18)

Fluid Forces Acting On Barge

Fluid forces acting on barge are the same as jacket, with the exemption of water entry/exit. Similar to jacket, barge is made up of a number of plates. The drag force formulation for each plate is identical to that of jacket element; considering velocities normal to plate and drag coefficient of plate. In lieu of a rigorous evaluation of barge added mass (for example numerical methods), one can use approximate values. Values given in CEM [10] are used: added mass for vertical motion is approximately equal to mass of displaced fluid; added mass for horizontal motion is approximately fifteen percent of mass of displaced fluid. Therefore barge added mass force is:

$$\begin{Bmatrix} F_{A,b}^X \\ F_{A,b}^Z \end{Bmatrix} = \begin{bmatrix} 0.15\rho_w V_w & 0 \\ 0 & \rho_w V_w \end{bmatrix}\begin{Bmatrix} \ddot{X}_b \\ \ddot{Z}_b \end{Bmatrix}$$

(19)

Accordingly, the total fluid force on barge is sum of buoyancy, drag and added mass forces.

Assembling System of Equations, Partitioning and Solving

In phases 1-4, motions of the two bodies are modeled by 12 equations and 12 unknowns. Due to the fact that some of these unknowns are accelerations and some reactions, the assembled system of equations is a differential-algebraic one. Therefore the system is partitioned with accelerations as unknowns. The result is a system 7 second order nonlinear differential equations, which can be solved using standard time integration techniques.

In phase 5, there are no additional constraints/relations and the equations of motion alone, describe the motions completely. Assembling Eq. (1) and the relevant constraints/relations (Table. 1) we get:

$$\begin{bmatrix} M_{aa} & M_{af} \\ M_{fa} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{q} \\ R \end{Bmatrix} = \begin{Bmatrix} F_a \\ F_f \end{Bmatrix} \qquad (20)$$

Where:

$$\ddot{q} = \begin{bmatrix} \ddot{X}_b & \ddot{Z}_b & \ddot{\theta}_b & \ddot{X}_j & \ddot{Z}_j & \ddot{\theta}_j & \dot{V}_t \end{bmatrix}^T$$

$$R = \begin{bmatrix} P_c^X & P_c^Z & M_c^Y & P_w^X & P_w^Z \end{bmatrix}^T$$

By partitioning Eq. (20) in terms of accelerations and reaction forces we obtain:

$$M_{aa} \times \ddot{q} + M_{af} \times R = F_a$$

$$[m]\{\ddot{q}\} = \{f\} \qquad (21)$$

Where:

$$m = M_{aa}; \qquad\qquad f = F_a - M_{af} \times R$$

Note that Eq. (20) is non-singular, which physically means that the system is not over-constrained [11]. We solve Eq. (21) by the Newmark time integration technique. By assuming linear acceleration variation during a time step dt, accelerations and velocities at time i+1 are expressed as [8], [12]:

$$\dot{q}_{i+1} = -\frac{dt}{2}\ddot{q}_i - 2\dot{q}_i + \frac{3}{dt}(q_{i+1} - q_i)$$

$$\ddot{q}_{i+1} = -2\ddot{q}_i - \frac{6}{dt}\dot{q}_i + \frac{6}{dt^2}(q_{i+1} - q_i) \qquad (22)$$

Upon writing Eq. (21) for two successive time instances i, i+1 and substituting the accelerations from Eq. (24) in them we get:

$$\frac{6}{dt^2}[m_{i+1}]\{q_{i+1}\} = \{f_{i+1}\} - \{f_i\} + \frac{6}{dt^2}[m_{i+1}]\{q_i\}$$

$$+ \frac{6}{dt}[m_{i+1}]\{\dot{q}_i\} + 2[m_{i+1}]\{\ddot{q}_i\} + [m_i]\{\ddot{q}_i\}$$

$$(23)$$

Equation (23) is solved as a system of algebraic equations for q_{i+1}. m_{i+1} is a function of state (positions, velocities, accelerations) of system at time i+1, and therefore unknown. f_{i+1} is calculated by solving Eq. (20) as a system of algebraic equations. Therefore, in order to calculate

m_{i+1} and f_{i+1}, a state must be assumed and iteration is required. Using m_{i+1} and f_{i+1}, state at time i+1 is obtained. If this new state is reasonably close to the state assumed for calculating m_{i+1} and f_{i+1}, iteration stops, otherwise the new state is used for calculating m_{i+1} and f_{i+1} in the next iteration. This procedure converges quite fast (less than 5 iterations).

A computer code has been developed which determines the motion phase, calculates fluid forces acting on barge and jacket and time integrates the relevant equations.
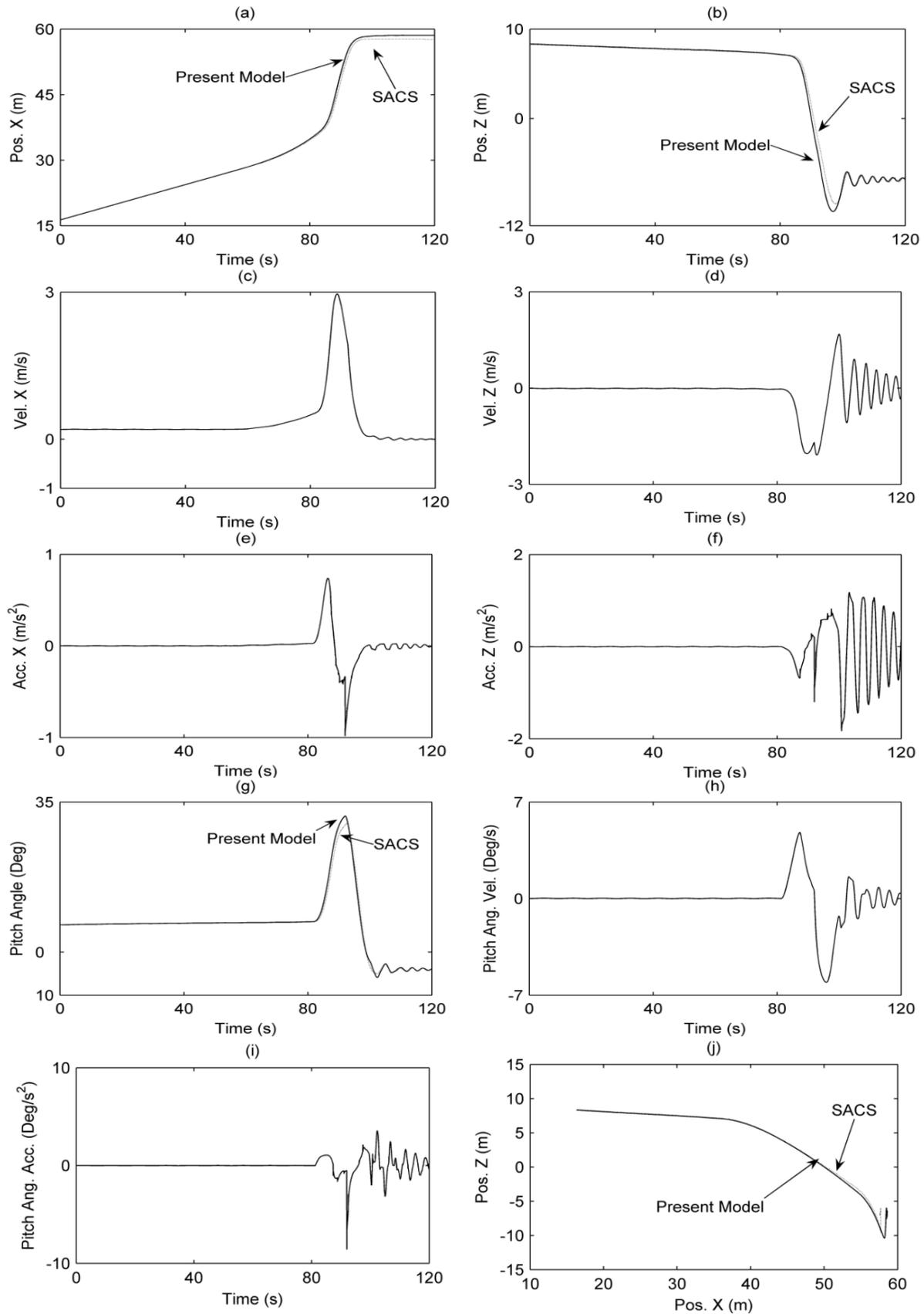
Verification and Discussion

A launch time history analysis has been carried out using the developed code, and the results are compared with that of a commercial well known software, namely SACS, and seen to be consistent. Barge and jacket properties are described in Table (2) Duration of analysis is 120 seconds with 0.02 s time steps.
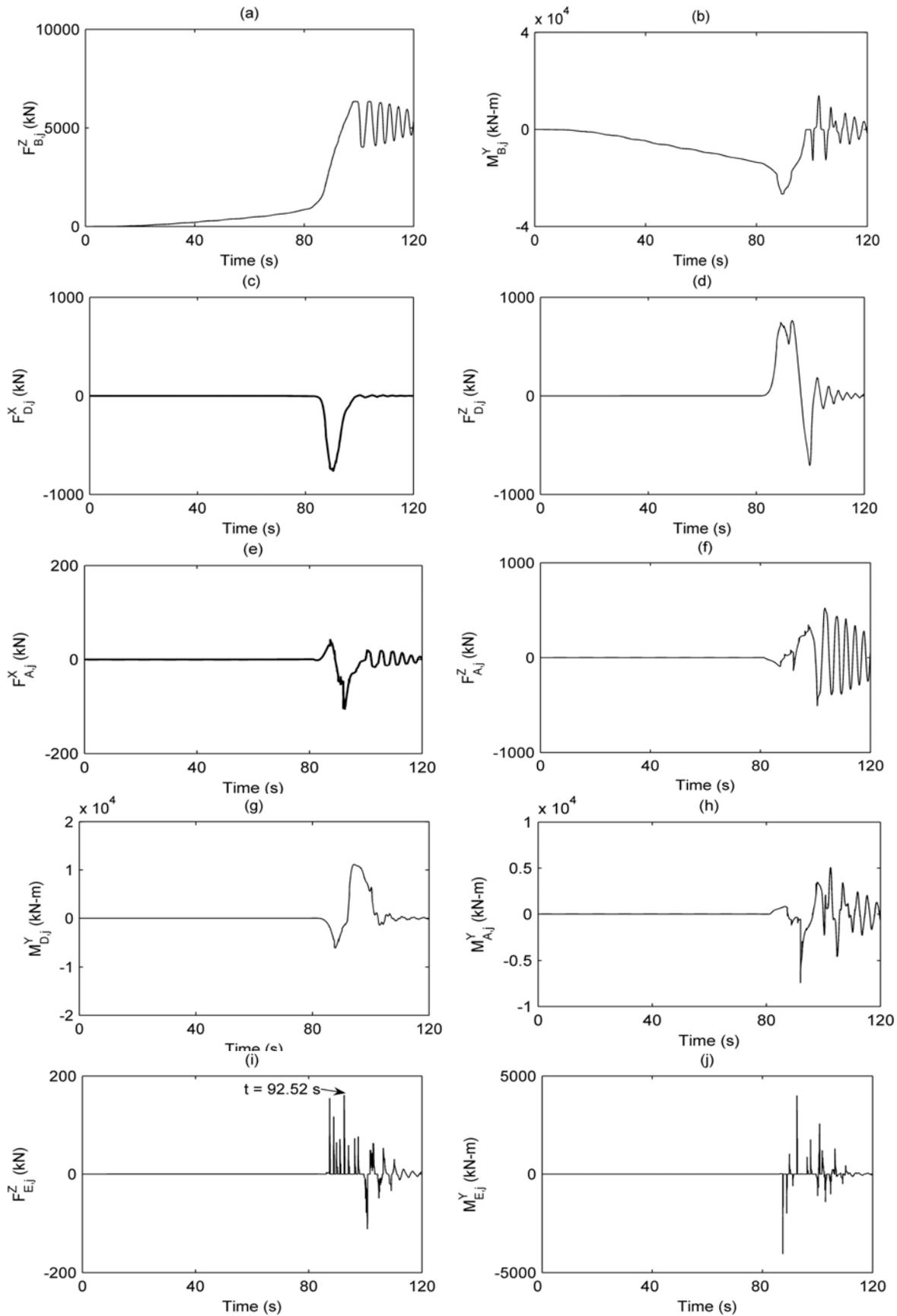
Table 2. Summary of barge and jacket properties used in example.

Barge	
Mass	5561 ton
Height	6 m
Width	20 m
Bottom Length	60 m
Initial Trim Angle	2.39 Deg
Drag Coefficient for Tubulars	1
Jacket	
Mass	537 ton
Total Buoyancy/Weight	120.2%
Height	50 m
Drag Coef. for Tubulars	0.65
Added Mass Coef. for Tubulars	1
μ_d	0.05

Figure (2) shows the position, velocity and acceleration time history of jacket CG. In addition, results from the same launch analysis carried out by SACS are presented with the displacement plots. Results agree quite well, which showcases the present model's reliability. It is seen that jacket's peak velocity and acceleration occur at rotation phase.

Figure 2. Position, velocity and acceleration time histories of jacket CG (Jacket CG positions are compared with SACS). (a) Position X (b) Position Z (c) Velocity X (d) Velocity Z (e) Acceleration X (f) Acceleration Z (g) Pitch Angle (h) Pitch angular velocity (i) Pitch angular acceleration (j) Trajectory of jacket CG .

Figure 3. Time histories of fluid forces/moments acting on jacket (Sum of forces acting on all jacket members). (a) Buoyancy force (b) Buoyancy moment (c) Drag Force X (d) Drag force Z (e) Added mass force X (f) Added mass force Z (g) Drag moment Y (h) Added mass moment Y (i) Water entry/exit force Z (j) Water entry/exit moment Y.

As can be seen in the third plot of Fig. 2, the maximum jacket rotation obtained from the two analyses differs by 1.75°:

$$\theta_{j,\max}^{presented} = 31.75^o \, , \qquad\qquad \theta_{j,\max}^{SACS} = 30^o$$

This difference is due to the water entry moments on jacket which we have considered. It should be noted that SACS does not account for water entry forces. Also because of this additional rotation, the jacket plunges more deeply in our model:

$$Z_{j,\min}^{presented} = -10.41m \, , \qquad Z_{j,\min}^{SACS} = -9.6m$$

In addition because of the differences mentioned and some other minor differences in fluid force formulation (namely that our model considers buoyancy of members as they enter waterline), the jacket's maximum horizontal displacement differ by 0.86 m in the two models:

$$X_{j,\max}^{presented} = 58.56m \, , \quad X_{j,\max}^{SACS} = 57.7m$$

Figure 3 shows the time history of fluid forces (buoyancy, drag, added mass, water entry/exit) acting on jacket. In general, buoyancy has the biggest magnitude among fluid forces. Drag force has a more pronounced effect than added mass force. Drag force stops horizontal motion of the jacket and its vertical oscillations. By comparison of Fig. (2) and

Fig. (3) it is observed that drag and added mass force have nearly the same trend as velocity and acceleration respectively (plot (c) has the same trend in both figures i.e. drag force in X direction has the same trend as velocity in X direction. The same is true for plots (d), (e) and (f) from Figures 2 and 3 respectively) although each force component is a function of all other motion components.

The time history of water entry/exit has several peaks. These peaks correspond to instances were a horizontal chord of the jacket is entering water. For instance, state of launch is shown graphically at time 92.52 s (when the largest peak occurs) in Fig. 4, and the chord member entering water is highlighted. An impact force of 161 kN is affecting the water entering member.

The reaction forces between jacket and barge are resisted by launch skids (N_{sk}) and rocker arm (N_{ra}), which can be calculated from static equilibrium of reaction forces. Figure (5) shows the normal forces acting on rocker arm and launch skids. It is seen that rocker arm normal force reaches its maximum when jacket starts rotating, at which instant the launch skid force drops to zero. Lesser normal reaction of rocker arm needs less
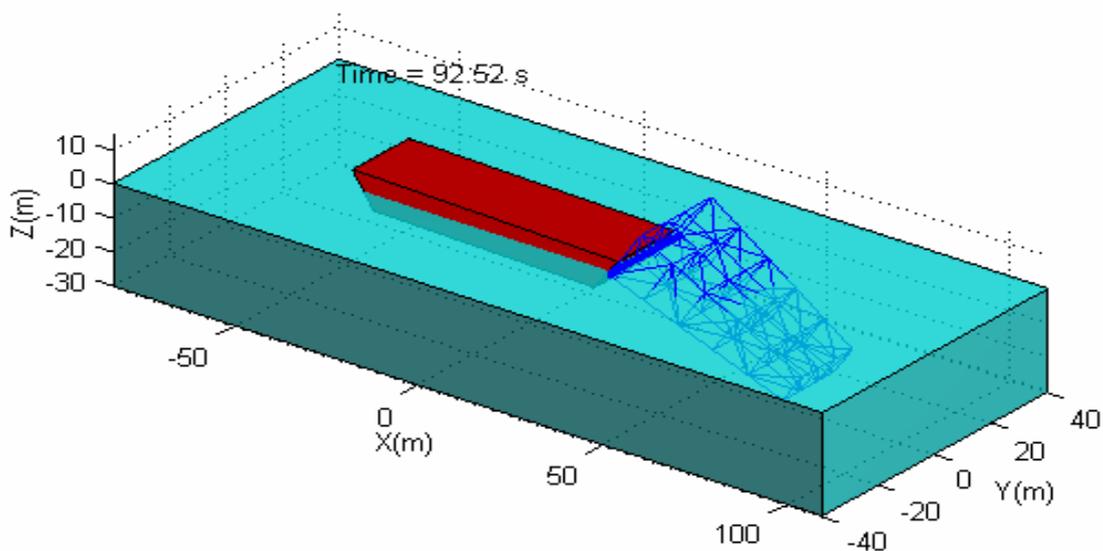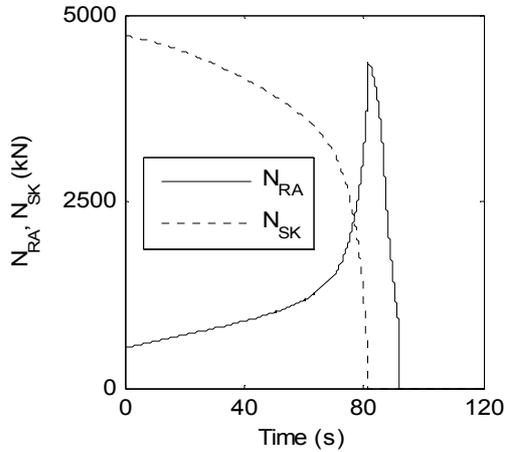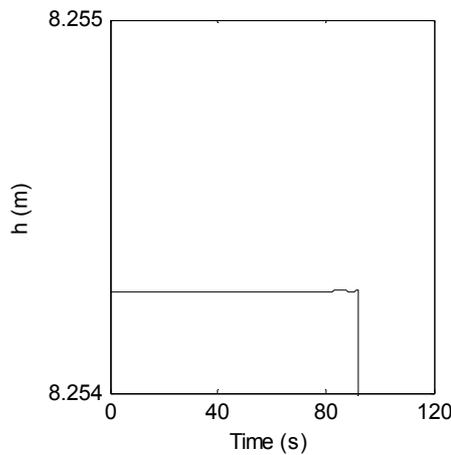

Figure 4. Graphical representation of jacket and barge at time 92.52 s and water entry of a jacket bottom chord. The water entering jacket chord is highlighted.

strengthening of launch truss. In this regards it is economical to use deeper drafts for barge so that buoyancy lessens the rocker arm normal force.

Figure 5. Time history of rocker arm and launch skid normal reaction force.

We note that if the acceleration constraint equations Eq. (3) are not satisfied accurately, displacements of jacket and barge are erroneous, that is, the jacket will either move away or interfere with launch skids, which is impossible. A descriptive output that indicates accuracy of solution is the perpendicular distance of jacket CG to rocker arm pin. This distance should remain constant throughout phases 1~4. Figure (6) shows this distance and it is seen that it is nearly constant until the end of phase 4.

Figure 6. Variation of perpendicular distance between jacket CG and rocker arm pin (*h*) during launch.

Conclusion

Equations governing the operation of launching a jacket from barge, including motion and constraints, are derived from principles of dynamics. Non-linear fluid forces acting on both bodies are also formulated, and the resulting system of equations is solved. Time histories of motions and forces are calculated. The following conclusions are drawn:

- Water entry forces are important regarding local member design, especially slender horizontal jacket chords. Jacket chords near mud-line (Figure 4) are examples of slender members which large water entry forces act upon them.
- Considering water entry forces and moments via Eq. 15 modifies the jacket trajectory to a little extent.
- Dominance of drag force among the hydrodynamic fluid forces, and its effect on limiting and damping jacket's motion.
- Very good accuracy in satisfying the acceleration constraint equations (Eq. 3) by using iteration.

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مدل‌سازی عددی به‌آب‌اندازی جاکت سکوهای فراساحل از روی بارج و اهمیت نیروی ورود به آب در مورد اعضای افقی جاکت

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چکیده

در این مقاله یک مدل‌سازی عددی از عملیات به‌آب‌اندازی جاکت سکوهای دریایی انجام گرفته است. در این راستا با استفاده از معادلات حرکت و معادلات قیدی هندسی، دستگاه معادلات دیفرانسیلی-جبری حاکم تشکیل شده و به کمک روش‌های عددی حل شده است. در این مدل‌سازی مواردی همچون در نظر گرفتن نیروی ورود به آب و حل معادلات حرکت به روش غیر صریح نیومارک، افزون بر نرم‌افزارهای رایج تجاری ارائه شده است. نتیجه این مدل‌سازی تاریخچه زمانی حرکات بارج و جاکت و نیروهای وارده به آنها می‌باشد. به منظور صحت‌سنجی، نتایج حاصل از مدل‌سازی ارائه شده با نتایج نرم‌افزار تجاری SACS مقایسه شده‌اند و تطابق نسبتاً خوبی بین نتایج ملاحظه شده است. نیروهای وارده از طرف آب بر جاکت مورد بررسی قرار گرفته و اهمیت و تأثیر هرکدام بر حرکات جاکت مشخص شده‌اند. همچنین ملاحظه شده است که نیروهای ضربه‌ای حین ورود به آب در مورد اعضای افقی جاکت جاکت مهم می‌باشد و ممکن است بر طراحی این اعضا حاکم شود. این نیرو می‌تواند در مورد اعضای افقی جاکت نزدیک کف دریا حائز بیشترین اهمیت باشد، چرا که به این اعضا بارهای محیطی بزرگی وارد نمی‌شود، اما نیروی ورود به آب بزرگی به آنها وارد می‌شود.

واژه های کلیدی: به آب اندازی سکو - سکوهای شابلونی - نیروی هیدرودینامیکی - نیروی ورود به آب – نیومارک - نـرم افزار SACS