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Aerodynamic response of articulated towers: state-of-the-art

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Abstract. Wind and wave loadings have a predominant role in the design of offshore structures in general, and articulated tower in particular for a successful service and survival during normal and extreme environmental conditions. Such towers are very sensitive to the dynamic effects of wind and wind generated waves. The exposed superstructure is subjected to aerodynamic loads while the submerged substructure is subjected to hydrodynamic loads. Articulated towers are designed such that their fundamental frequency is well below the wave frequency to avoid dynamic amplification. Dynamic interaction of these towers with environmental loads (wind, waves and currents) acts to impart a lesser overall shear and overturning moment due to compliance to such forces. This compliancy introduces geometric nonlinearity due to large displacements, which becomes an important consideration in the analysis of articulated towers. Prediction of the nonlinear behaviour of these towers in the harsh ocean environment is difficult. However, simplified realistic mathematical models are employed to gain an important insight into the problem and to explore the dynamic behaviour. In this paper, various modeling approaches and solution methods for articulated towers adopted by past researchers are reviewed. Besides, reliability of articulation system, the paper also discussed the design, installation and performance of articulated towers around the world oceans.

Keywords: dynamic behaviour; compliant tower; environmental loads; articulation system; wind induced waves; tankers mooring.

1. Introduction

Wind and wave loadings have a predominant role in the design of an offshore structure for a successful service and survival in harsh sea conditions. The flexibility of the new generation, compliant structures (articulated tower, guyed tower and tension leg platforms) give rise to natural periods ranging from 1 to 100 seconds. Such structures comply in the direction of environmental loads and results in an increase in their sensitivity to the dynamic effects of wind. Fixed structures will respond them in virtually static fashion. For fixed platforms, contribution of lateral wind loads for the design is only 10% of the global loads. While in case of compliant platforms, it increases to 25%. As articulated towers are more sensitive to wind fluctuations and varying wave drift loads, therefore, design of such structures must require an understanding of the environmental load effects

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and must develop an enhance response prediction method. Dynamic response studies are required to resolve these issues.

An articulated tower as shown in Fig. 1 consists of buoyant shaft connected to the sea bed through a universal joint which permits the tower to undergo limited pivoting about the base. A ballast chamber is usually provided near the bottom; and a deck is provided on the top of the shaft for various platform operations. Large diameter buoyancy chambers are provided just below the sea water level. The basic principle of articulated tower is that its weight is almost equal to buoyancy force which helps in tower restoration against the external disturbing environmental forces. The tower may have either a single articulated joint suitable for shallow water; or more than one such joint for deeper water conditions.

The resulting configurations are commonly known as single, double or multi hinged articulated tower as shown in Fig. 2 Further, various single and double hinged articulated towers around the world oceans are presented in Table 1 for a handy reference.

For many decades, articulated towers are used as portable offshore systems for the storage and loading of oil into assistant tankers moored to the tower. Such configuration is particularly suitable for fields that have a limited production capability, or are too far-off from refining to justify the laying of a pipe line. Reid U.S. Patent No. 4,010,500 discloses the use of a cardan type universal

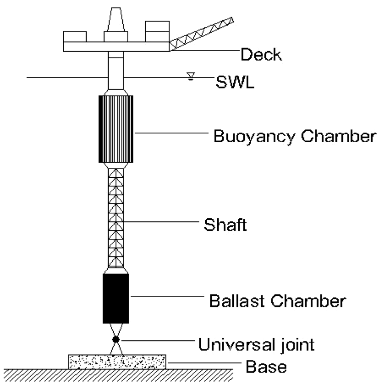

Fig. 1 Articulated tower

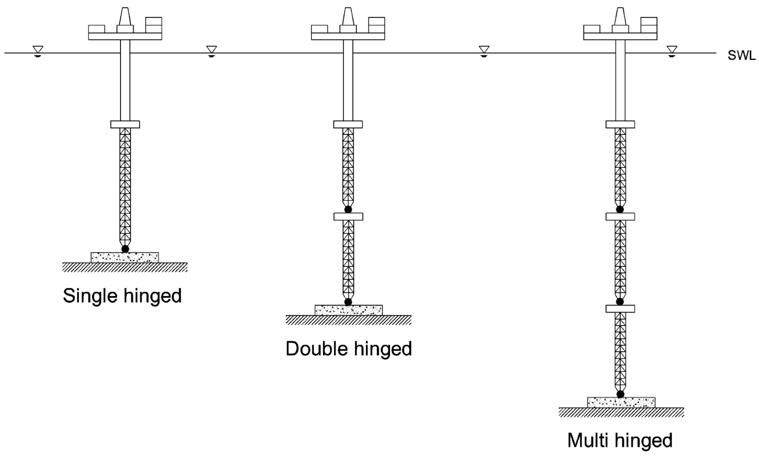

Fig. 2 Types of articulated towers

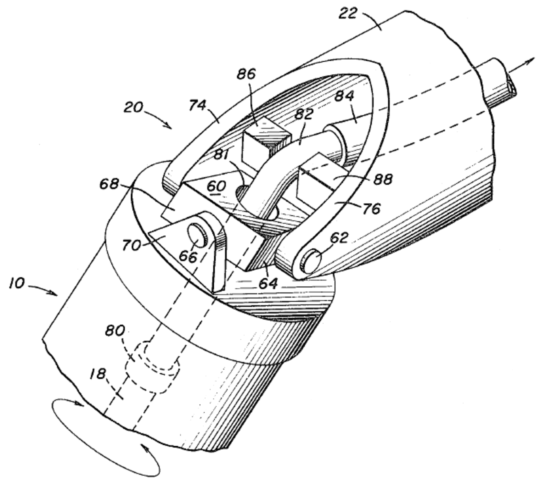

Fig. 3 Isometric view of an articulated joint

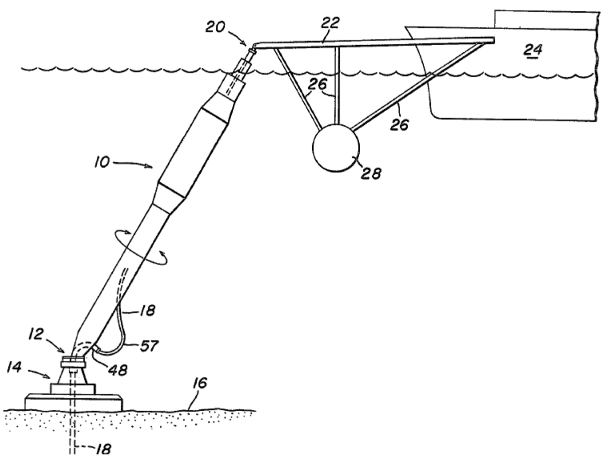

Fig. 4 Schematic of a mooring tower

joint (Fig. 3) at the top and bottom of an offshore mooring tower (Fig. 4), Invented by Andrepont (1980). Also, such structures are advantageously used as a flaring tower for a parent structure to safeguard against fire hazards on the production platform. Another distinguishing advantage of this tower is that it is re-usable. Once an oil reservoir is depleted, it can be easily relocated by simply detaching it from the universal joint and towed it to other oil field at minimal cost. This feature gives a major financial advantage to the operator, as the capital cost of the tower and its facilities can be allocated to several projects. Further, it greatly augments the economics of marginal oil fields.

Aerodynamic response of articulated towers has been a rather unexplored area for research and development. Therefore, the main objective of this state-of-the-art review is to understand the complex dynamic response of single and double hinged articulated towers, and to explore the superiority of multi hinged articulated tower for higher water depths over single hinged configuration. Emphasis is placed on modeling approaches and their solution techniques.

2. Design, installation and performance

The early use of articulated tower was limited to shallow water depths (100m) for marginal applications in oil industry. For this purpose single hinged articulated towers (SHAT) were used. In 1963, first articulated tower was designed by Enterprise de Mecanique et Hydraulique (EHM Inc.) for a water depth of 100 m. In 1968, it was installed in the Bay of Biscay (Atlantic Ocean) and remained onsite for three years during which various measurements were taken for a wide range of ocean conditions. Since then, only few authors discussed the design, installation and performance aspects of articulated towers and are briefly discussed herein.

Chassy, *et al*. (1971) presented the construction, installation and operation of the first articulated tower (ELFOCEAN), installed in the Bay of Biscay. It was a 110 m vertical cylindrical shaft of 7.0 m diameter. A universal joint that connects the shaft to a rectangular shaped gravity base of size 21 m × 24 m was provided. Restoring forces were provided by six buoyancy chambers attached to the cylindrical shaft. Installation of the base was carried out in six days, which required three tugboats, one trawler and one driver support vessel. Subsequently, installation phase of the tower started,

Table 1 Articulated towers around the world oceans

Field	Type	Installation date	Water depth (m)	Operator	Platform function
		SINGLE HINGED			
Sabah Malaysia	Single anchor leg mooring (SALM)	1974	117	Inter Moor	Tanker's mooring
Beryl	Articulated loading tower (ALT)	1975	117	Ben C. Gerwick, Inc.	Loading tower
Statfjord	Articulated tower	1978	145	EHM	Loading and mooring
Maureen	Gravity articulated tower	1982	490	Howard Doris Ltd.	Drilling and production
Beryl (UK)	Single point mooring (SPM)	1982	117	Shell Brent	Tanker's mooring
Fulmar	Single anchor leg storage system (SALS)	1982	83	Shell	Loading/offloading and Tanker's mooring
Maureen	Articulated loading column (ALC)	1982	93	Howard Doris Ltd.	Loading system
Hondo (USA)	Single Anchor Leg Mooring	1981	150	Exxon Co.	Tanker's mooring, oil & gas production
North East Frigg.	SHAT	1983	150	Total E&P UK Ltd.	Field control station & gas Prod
Brazil	SPM	1984	122	CBI	Tanker's mooring
Gulfaks	ALT	1986	133	Shell	Loading and mooring
Jabiru	Turret riser SPM	1990	120	SBM	Tanker's mooring
Garden Banks	Compliant articulated tower (CAT) tower	1998	501	Amerada Hess Corp.	Drilling and production
Angola	Compliant piled Tower (CPT)	2006	390	Chevron	Drilling and production
		DOUBLE HINGED			
Thistle(USA)	Double hinged SALM	1977	162	BP	Tanker's mooring
Bouri (Libya)	Bi-articulated SALM	1987	167	EHM	Tanker's mooring

CBI – Chicago Bridge Iron Co. Inc., Illinois, USA
SBM – Single buoy mooring Inc.
EMH – Enterprise de Mecanique et. Hydraulique Inc.

which required the same period and equipments. This phase consisted of: towing the column to the site; ballasting and tilting; positioning over the base; connecting to the guide cables; immersion in water by ballasting and counterweight in column; connecting and locking to the base. This installed experimental prototype was remained at site for two years to collect data. A 160,000 DWT (dead weight in tons) tanker was also moored to the tower for oil storage. The tower was used for oil production without any complexity. Further, platform configurations were modified depending upon the tower functions and in all the cases, its behaviour was found satisfactory under various applications. Burns and D'Amorim (1977) described the development, design and construction of two articulated buoyant steel towers at Groupa field (offshore Brazil) that provide mooring facilities. In another study, Gruy and Kiley (1977) described the design features of ARAMCOJU Aymah Single Anchor Leg Mooring (SALM) platform. It was the world's largest single point mooring export system, located in the Arabian Sea. The design feature of the tower included the design of a dual product fluid swivel for segregating the two fluids and a provision of energy sealing system. Due to this provision, maintenance requirements were minimized, and the panic shut down due to leakage in the fluid swivel was avoided.

Performance of Beryl Articulated Loading Platform (ALP) was evaluated by Hays, *et al*. (1979). The ALP was an unmanned offshore loading facility, located in the North Sea at a water depth of 122 m. The tower consisted of rotating head through which tankers were moored. Simplicity of design, superior under water reliability and favourable motion characteristics were the selecting drivers of this concept. After two years of operational experience, its performance was evaluated. Its efficiency was estimated to be 99.4%. The distinguished performance of the system is that it bears 18 to 30 percent lesser production losses of annual capacity. The concept and construction techniques of first buoyant concrete ALP installed in the Maureen field (North Sea) was described by Granville and Fisher (1983). In another study, Noblanc and Sehnader (1983) described the installation and construction of Statfjord B articulated loading platform designed for use as single point mooring system. Built in West Germany, the platform was towed to the site and installed adjacent to sea bed valve station and previously laid sea line in 1982. The SPM was maneuvered into position by three tugboats. Later on, Alexis and Jenin (1988) discussed the installation and construction details of multi hinged articulated tower in Bouri field in Mediterranean Sea. The tower was designed for a permanent mooring of 250,000 DWT storage tankers at a water depth of 167 m.

Will (1999) described the design and installation of Baldpate compliant piled tower (CPT) installed in the Gulf of Mexico in 1998, (Fig. 5). The tower is the first free-standing, non-guyed compliant tower, and has sway period of 32 seconds. The platform measures 635 m from its flare tip to the sea bottom. The tower has 19 slots, and one-rig drilling/production platform set over a 9-slot drilling template. The tower configuration consists of an articulated tower which has four basic structural components; the foundation piles, jacket base section (JBS), jacket tower section (JTS) and deck. The JTS basically respond as a compliant tower, while JBS as a rigid and fixed structure which transmit shear and overturning forces to the foundation. Flex-element (axial tubes) was utilized to stabilize the tower section against overturning forces. To facilitate the jacket portion of the JTS to rotate relative to the rigid base section, an articulated joint was provided. Dynamic wind studies of the tower were carried out for a service life of 20 years under extreme and long term fatigue environment. Wind gust factors and wind spectra taken from API RP2A were used to generate random wind simulations. Based on dynamic response analysis, the 20 minute sustained wind speed was adopted for design against wind load.

Baldpate tower comprises of 12,400-ton skirt piles (three per base leg) that were driven to a depth of 145 m. Following the base setting, the tower was towed by launch barge and launched end-on to them upright itself and is lowered by a derrick barge. The underside of each tower leg had a docking pin that stabbed into the receiving cones of the structure base. Once positioned, connections were grouted. Thereafter, the deck was transported to the site and installed by the derrick barge in a single lift. Subsequently, the main deck including the living quarters was lifted and set on the deck. Following hookup of flow lines and facilities, first oil production was achieved in September 1998.

Design and installation of another compliant piled tower (CPT), called Benguela – Belize CPT was presented by McNeilly and Will (2006). The platform was designed to support 40 wells, and 16 risers. This tower is located in offshore Angola, in 390 m of water depth. The tower configuration consists of a slender, four legged space frame with a 110 ft by 110 ft square footprint that supports the topsides, wells and risers. The space frame structure was supported by 12 flex-legs attached tubular steel sections that transmitted the environmental loads to the foundation piles. The flex-leg's uppermost portion was connected rigidly to the tower legs 134 m below the water surface. This provision facilitates shear to be transmitted from the tower to the foundation piles and provided a satisfactory sway period for the tower system. The design also included a series of slip-joints along

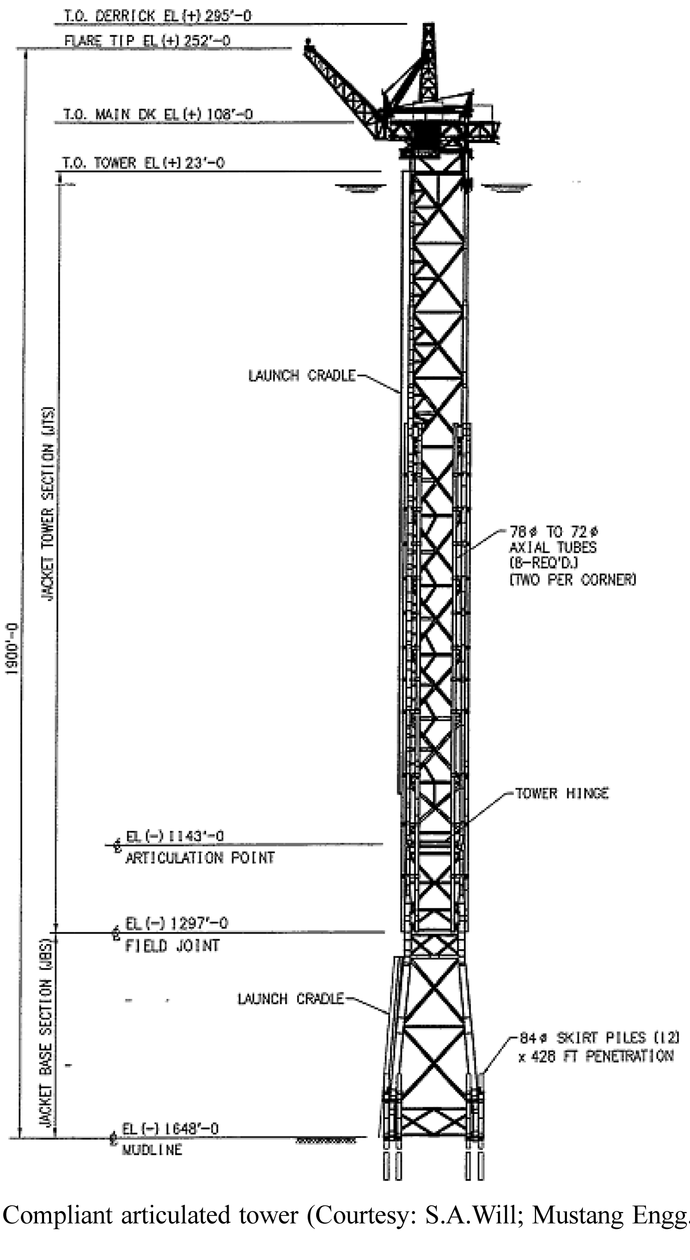

Fig. 5 Compliant articulated tower (Courtesy: S.A.Will; Mustang Engg. Inc.)

the flex-legs between the upper connection and the foundation piles. As the oil fields were developed from a single hub, the tower was engineered to support more than twice the payload of the CPT towers in the Gulf of Mexico. Installation of the tower took place in December 2004, with the tower base template was set along with the 12 main foundation piles measuring 180 to 190 m in length. The remaining tower sections were set in two pieces in April 2005. First oil was produced on January 22, 2006.

3. Reliability of articulation system

Articulated towers are continuously subjected to oscillatory environmental loads. Metal fatigue in the articulated joint caused by these oscillatory stresses is a possible mode of failure. Further, concentration of shear and axial forces at the hinge(s) makes it more susceptible to such failure. Therefore, its reliability assessment is one of the most important design aspects. Useful work has been done by many researchers to design the articulated joint. Chassy, *et al*. (1971) gave the details of the universal joint for the ELFOCEAN tower. The study was carried out considering the wear, tear and risk of the collapse of pipe walls passing through the joint. Sedillot, *et al*. (1982) designed a ball type universal joint (Fig. 6) for C.G. Dorris gravity type articulated tower. Field investigations for fatigue life were performed for few years. Based on tests, the minimum life of the articulation system was estimated as 200 years. For offshore structures, fatigue reliability assessment was discussed in detail by Wirsching (1984). Fatigue and wear studies were also carried out on new generation, Baldpate compliant tower by Chen and Will (1999), which showed good fatigue characteristics. They concluded that the impact on the fatigue damage due to low frequency responses, particularly wind loads are significant and can not be ignored. They also presented an

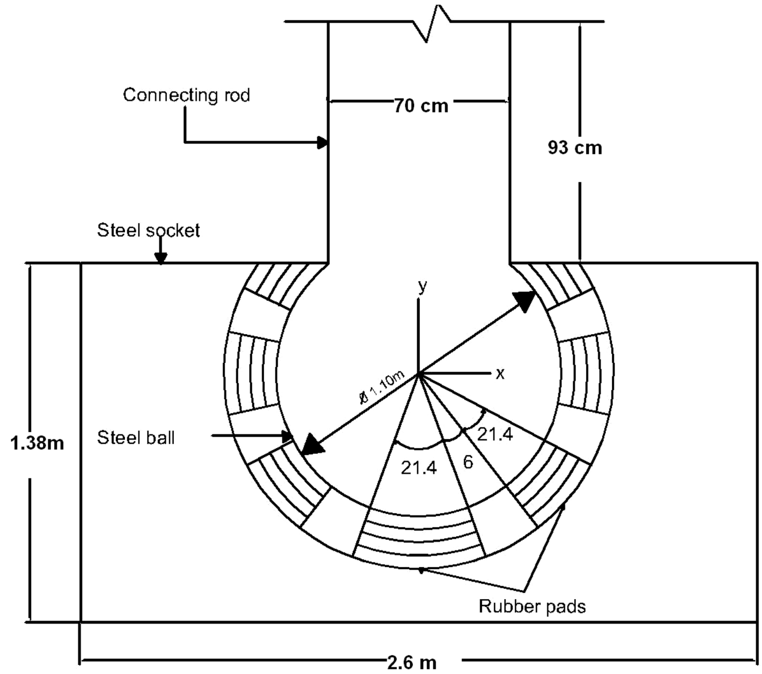

Fig. 6 Details of articulated joint

approach for predicting wear volumes at axial tube guides and conductor guides of the tower. Most recently, Islam and Ahmad (2007) carried out fatigue and fracture reliability assessment of articulated tower joint designed by Sedillot, *et al*. (1982) and as shown in Fig. 6 against randomly fluctuating shear stresses. Non-linear limit state functions were derived in terms of important random variables using S-N curve and fracture mechanics approaches. Advanced First Order Reliability Method (FORM) was used for reliability assessment of the joint. Fatigue life estimation was made using probabilistic approach. They observed that S-N curve approach yields a conservative estimate of probability of failure as compared to the fracture mechanics approach.

4. Dynamic response

Articulated towers comply with the environmental forces instead of resisting them fully. Therefore, for assessing the safety of the tower, it was necessary to investigate the nonlinear dynamic response under harsh ocean environment. Disturbing forces due to wind, waves and currents were considered to obtain the responses. Mathematical model for most of the studies considered it as an upright rigid pendulum having one or two angular degrees of freedom about an articulation point. Some authors idealized it as a beam element with a point mass at the free end. Morison's equation is widely used to evaluate hydrodynamic forces. Two common approaches available in literature are employed for predicting structural vibration of these towers:

- Frequency domain approach
- Time domain approach

In frequency domain approach, the forcing function is not needed; only their spectrum has to be known. Of course, the mechanical admittance function that transforms the load spectrum to the response spectrum must also be known. This type of analysis is basically suitable for linear systems or systems that can be linearized conveniently. Since articulated tower is a highly nonlinear structure; therefore, very few authors obtained the solution of equation of motions by this technique. Instead, time domain simulation is often used to determine the dynamic response of articulated tower systems. The nonlinearity may be due to large displacements, stiffness of the tower and the environmental forces. For this approach, time history of the load must be known. The differential equation is then solved numerically on a computer to get the response as a function of time. This analysis though computationally more expensive, yields reliable response estimates for highly nonlinear articulated tower system and therefore found favor. The review on the dynamic analyses carried out by various investigators has been presented under the two heads, namely single hinged and double hinged articulated towers.

4.1. Single hinged articulated tower

Single hinged articulated tower (SHAT) as investigated by most of the authors considered it as rigid and can rotate about one axis at its base in the plane of fluid loading. State-of-the-art suggests that in most of the cases, the analysis is based on the hydrodynamic behaviour only with small rotations. Combined behaviour under wind and waves has limited reporting.

Chakrabarti and Cotter (1978) developed a mathematical model to analyze the motions of a tower-tanker system. The tower was assumed to be rigid, pivoted at the sea bed and connected to a tanker via a spring. The steady and dynamic loads due to wind, waves and current were considered collinear. Initially, the static equilibrium state due to only wind and current were established. Then, small perturbations about the equilibrium position were assumed in the formulation of the equation of motion. The tanker motion was described by two degrees of freedom namely surge and pitch. Equations of motion for tower and tanker were derived and coupled through the linear spring connecting the tower to the tanker as:

$$I_t\ddot{\psi} + F_{Dt} + C_B\psi + F_r l\cos(\theta + \phi) = M_t e^{i(\varepsilon_1 - \sigma t)} \tag{1}$$

$$m\ddot{x} + F_{D1s} - F_r\cos\theta = F_t e^{i(\varepsilon_2 - \sigma t)} \tag{2}$$

$$I_s\ddot{\mu} + F_{D2s} + C_B\mu - F_r[H_s\cos\theta + (L/2)\sin\theta] = M_s e^{i(\varepsilon_3 - \sigma t)} \tag{3}$$

Where ψ, x, μ = tower's deflection angle, the tanker's surge and pitch respectively; F_r = spring force; C_B = buoyancy term; F_{Dt}, F_{D1s}, F_{D2s} = drag forces proportional to the square of the relative velocity between the fluid and the structure; and σ = wave frequency. The equations were solved numerically and the results were compared with experimental values. A wave tank test was performed on a model built to a scale of 1:48. A good correlation between the test results and theoretical predictions were found. However, model failed to foresee the drift force due to irregular waves caused by soft spring-mass system.

Olsen, *et al*. (1978) investigated the motion and loads acting on a single-point mooring system and the resulting response. The tower was modeled as a rigid body connected to the sea-floor via a universal joint. The equation of motions for the tower and the tanker were derived separately. For analytical calculations of the tower, it was divided into N elements, each having two degrees of freedom. Forces and displacements (horizontal and vertical) due to waves, current and wind were evaluated at each element. For N elements, $2N$ nonlinear differential equations in generalized form were established.

$$\sum_{i=1}^{N}[(\bar{r}_{iv} - z_o.k) \times \bar{F}_{iv} + \bar{r}_{iH} \times \bar{F}_{iH}] = 0 \tag{4}$$

Where $\bar{r}_{iv}$, $\bar{r}_{iH}$ = displacements of element i in the vertical and horizontal directions respectively; $\bar{F}_{iv}$, $\bar{F}_{iH}$ = environmental loads acting on element i in both directions; and $z_o.k$ = motion of the universal joint in the z-direction.

The tower tanker was considered as a split system, in which tanker was modeled as a rigid body having three transverse degrees of freedom. The equations are derived in the tanker coordinate system and transformed into the tower's coordinate system to yield

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = [F] \tag{5}$$

Where [M], [C], [K] = mass including added mass terms, damping and stiffness matrices of the tanker, [F] = force vector acting on the tanker, and $\{\ddot{x}\}$, $\{\dot{x}\}$, $\{x\}$ = acceleration, velocity and position vectors of the tanker. Due to coupling of the tower and tanker, a constant mooring force fm was added to the forcing function of Eqs. (4) and (5) at each time station. The solution of the governing equations gave the low frequency motion of the tanker as well as the tower's response. The responses ware compared with experimental results that showed a good correlation. The study concluded that the tower tanker system had a significant low response as compared to the tower alone. Influence of tanker on the water particle kinematics was also observed by the investigators. However, the effect was not included in the tower response analysis.

In a later study, Chakarbarti and Cotter (1979) analyzed the motion of an articulated tower on the same assumptions as outlined in earlier paper, Chakrabarti and Cotter (1978). The analysis was based on the linear wave theory, and the resulting equation of motion was

$$I\ddot{\psi} + B(\dot{\psi}) + D\dot{\psi} + C\psi = M_o e^{i(\alpha - \beta t)} \tag{6}$$

Where I = total moment of inertia including added mass; $B(\dot{\psi})$ = nonlinear drag term; $D\dot{\psi}$ = structural damping; $C\psi$ = restoring moment due to buoyancy; M_o = magnitude of the wave moment and α = corresponding phase angle with respect to the waves.

For closed form solution, the non-linear drag term was linearized with respect to time. The added mass of the tower and its damping coefficient were obtained from the forced sinusoidal oscillation analysis in still water. Then, oscillation of the tower and the horizontal reaction at the universal joint were obtained. A wave-tank test was performed using the model of an articulated tower and the data were compared with the mathematical results. In the analysis, the static displacement was kept separate from the dynamic oscillation and superimposed linearly. They concluded that a closed form solution for the motion of an articulated tower is obtained. But, the solution was not applicable to highly drag dominant systems. These results can, therefore, be applied in the design of articulated towers which are highly inertia dominant systems.

Dynamic analysis on a full-scale articulated loading platform (ALP) in North Sea was carried out by Spidsoe and Brathang (1983). It was shown how an ALP moves in response to the wind and wave environment considering nonlinear damping and buoyancy as restoring forces. The damping was modeled as $c|\dot{x}|^{\alpha-1}\{\dot{x}\}$ where, α is a constant having values 0, 1 and 2 for coulomb, linear and drag damping respectively. Drag damping gave the lower extreme response than the linear damping whereas the coulomb damping showed the opposite behaviour. The nonlinear restoring force was modeled as $K(x) = kx + kx^2$. The mathematical model for their study was same as given by Eq. (5).

Initially, the wind forces on offshore structures were not well established and a linearized version of Morison's equation was believed to be appropriate. In addition to the inertia and drag forces, non-linear forces caused by vortex shedding on the buoyancy tank and the steel chimney may be anticipated. If the structural system behaves in close proximity to linear, the forcing function are quite linear and both wind and wave induced responses are independent, then the spectral density of the platform displacements may be expressed as follows:

$$S_x(w) = H(w)F_a(w)H^*(w)S_u(w) + H(w)F_h(w)H^*(w)S_u(w) \tag{7}$$

The study concluded that the ALP was sensitive to turbulent wind and its response varied linearly with the aerodynamic loads. Non-linear interactions between low-frequency motions caused by wind and wave forces were indicated while the effect of vortex shedding was found to be insignificant.

Thompson, *et al*. (1984) investigated the motion of an articulated mooring tower. They modeled the structure as a bilinear oscillator, which consists of two linear oscillator having different stiffnesses for each cycle. As expected, harmonic and subharmonic resonances appeared in the response. A comparison between the responses and experimental results of a reduced scale model showed good agreement between the two.

In a later study, Chakarbarti and Cotter (1989) developed an efficient method of analysis for a moored floating structure. The analysis was carried out in time domain assuming rigid body motion and the solution is generated by a forward integration scheme. The adopted approach permits nonlinear line and fender forces to be incorporated readily into the analysis. Forces due to wind, waves and currents were considered. All six degrees of freedom motion for the floating vessel namely surge, heave, sway, roll, pitch, and yaw were considered in the analysis. The tower is free to respond in two degrees of freedom. The motion of the mooring system was described by the coordinates x, y, z, ϕ, ψ and θ, plus Ω and ε when a tower is present. The resulting equations of motion were obtained as

$$I_t\ddot{\Omega} - (I_t - I_1)\dot{\varepsilon}^2 \sin\Omega \; \text{in}\Omega \, c = M_\Omega \tag{8}$$

$$(I_t \sin^2\Omega + I_1 \cos^2\Omega)\ddot{\varepsilon} + (I_t - I_1)\dot{\Omega}\dot{\varepsilon}\sin 2\Omega = M_\varepsilon \tag{9}$$

In which I_t and I_1 = the moment of inertia of the tower about its transverse, Ω, and lengthwise, 1, axes, respectively and M_Ω, M_ε are the moments on the tower in the Ω and ε coordinate directions.

Analytical results were compared with model tests. Satisfactory correlations have been obtained which demonstrate the versatility of the analysis.

Jain and Datta (1987) and Datta and Jain (1990) investigated the response of an articulated tower to random wave and wind forces. They treat the system as single degree of freedom. The tower was discretized into n elements having appropriate masses, volumes and areas lumped at the nodes. The equation of motion of the tower was given by

$$I(1 + \beta(t))\ddot{\theta} + c\dot{\theta} + R(1 + v(t))\theta = F(t) \tag{10}$$

Where $I\beta(t)$ is the time varying added mass, $Rv(t)$ is the time varying buoyancy moment and $F(t)$ is the random force due to wind and wave. The equation of motion was solved in frequency domain. Davenport spectrum was used for the estimation of fluctuating wind velocity while Pierson-Moskowitz spectrum was assumed for the wave height. From the solution they concluded that the random wind responses were higher than the wave responses; non linearities due to drag force and large displacements do not affect the response when only wind force is considered; the root mean square value of the tower response varied linearly with mean wind velocity.

In another study, Jain and Datta (1991) studied the behaviour of an articulated tower to low frequency drift forces in random sea using a simulation procedure. The tower was idealized as a single two-dimensional column structure undergoing motion in the plane of fluid loading. Time history of viscous drift forces arising due to the interaction of current velocity, mass transport, velocity of waves and wave-structure relative motion was generated by a wave superposition technique. The tower response was determined by numerical integration of equation of motion; derived in terms of the instantaneous heel angle θ as given below.

$$I_0\ddot{\theta} + 2\xi' I_0 \omega\dot{\theta} + R_0\theta = F(t) - R_0 v(t)\theta - I(t)\ddot{\theta} \tag{11}$$

In which, I_0 is the mass moment inertia of the tower; R_0 is the rotational stiffness; ω is the natural frequency of the tower; ξ' is the structural damping ratio; $R_0v(t)$ is the time varying rotational stiffness and $I(t)$ is the time varying added mass moment of inertia; $F(t)$ is the moment of the dynamic forces; $\dot{\theta}$ and $\ddot{\theta}$ are, respectively, the angular velocity and acceleration. Non linearities due to variable buoyancy and variable added mass effects were considered in the analysis. The results were analyzed for characterizing the random behaviour of both the exciting force and the response. The outcome of the analysis showed importance of the tower response excited by the viscous drift forces when comparing it with the response produced by first-order wave forces.

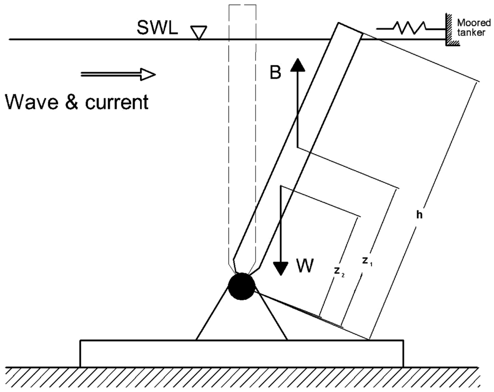

Fig. 7 Articulated tower with moored tanker

Choi and Lou (1993) investigated the slow drift motions of a tanker moored to an articulated loading platform as shown in Fig. 7.

The ALP was considered a rigid tower free to pitch. The tower tanker system was modeled as a nonlinear oscillator with different stiffnesses for positive and negative displacement. In earlier paper (Choi and Lou 1991), the moored ship was assumed to be fixed due to the massive inertia while the tower was oscillating in waves. In this study, they included surge motion of the ship in order to investigate the dynamic coupling between the ship and the tower. However, they have not included unstable motions and stability analysis. The mooring line between the ALP and tanker was represented by an unsymmetric, piecewise-nonlinear restoring function. The highly nonlinear characteristics, including multiple solution, subharmonics, and bifurcations were considered.

The two DOF system equations were derived as

$$I_v\ddot{V} + C\dot{V} + g_a = M_o\cos\omega t \tag{12}$$

$$(M+\mu_{11})\ddot{x} + \lambda_{11}\dot{x} + g_t = F_{DX} + F_{WC} \tag{13}$$

where $$g_a = \begin{Bmatrix} k_1\sin v, \\ k_1\sin v - \mathrm{h}\cos v(F_{WC} + k_{11}\delta I + k_{13}\delta I^3) \end{Bmatrix}, \quad if\ \delta f \le 0;\ \text{Otherwise} \tag{14}$$

$$g_t \begin{Bmatrix} 0, \\ F_{WC} + k_{11}\delta I + k_{13}\delta I^3, \end{Bmatrix} \quad if\ \delta f \le 0;\ \text{Otherwise} \tag{15}$$

$$\delta I = |\mathrm{h}\sin v - x| \tag{16}$$

$$F_{WC} = F_W + F_C \tag{17}$$

v is the angular displacement of the tower; I_v is the virtual moment of inertia of the ALP; C is the linear damping coefficient; g_a the piecewise-nonlinear restoring function of the tower; k_1 the restoring moment coefficient; k_{11}, k_{13} the linear and nonlinear spring coefficients of the mooring line; and M_o the amplitude of moments due to inertia dominant forces of the wave; F_{DX} is the wave force; F_{WC} the combined force due to wind and current on the tanker. Modified Morison's equation was used to evaluate the wave load on the ALP which includes fluid/structure interaction effects. The hydrodynamic load on the tanker was calculated based on the diffraction theory. For numerical calculations of the ALP-tanker system, direct numerical integration using the fourth-order Runga-Kutta method was used. They concluded that for the piecewise-nonlinear 2-DOF system, only the low order subharmonic responses were observed. The effects of the various system parameters and possible bifurcations were examined. Results showed that as the amplitude of excitation increases or damping decreases in the system, the subharmonic oscillations with slowly varying amplitudes will occur. Further, the dynamic response is sensitive to the changes of system parameters as well as the initial conditions.

The study of Thompson, *et al*. (1984) was further extended by Gerber and Engelbrecht (1993). They investigated the response of an articulated mooring tower under random sea. The tower was modeled as a bilinear oscillator. The resulting equations of motion were same as developed by Thompson, *et al*. (1984). The solution was obtained for different cases: linear oscillator, bilinear oscillator, and an impact oscillator in which oscillations can occur only in one half of the cycle. The stiffness of the tower tanker connection was recommended as nonlinear for various models.

Ran and Kim (1995) investigated the slowly varying responses of an ALP in unidirectional irregular waves. The viscous drag forces were computed from the Morison's drag formula. First and second order wave diffraction problems were evaluated by the ring-source boundary integral equation method. They used two-term Volterra series to calculate the time series of nonlinear potential excitations in random seas. The governing equation of pitch motion of the platform was considered as

$$[I + I_a(\omega)]\ddot{\theta}(t) + C_w(\omega)\dot{\theta}(t) + K\theta(t) = M(t) \tag{18}$$

Where θ = pitch angle; I = moment of inertia of the structure; I_a = added moment of inertia; C_w = wave damping coefficient; K = restoring moment coefficient; and M = wave exciting pitch moment respectively. Solution was obtained by utilizing both frequency and time domain approaches. The linearized drag force model was used for the spectral analysis in the frequency domain, while a direct step-by-step integration method was used in the time domain to account for the nonlinearities in the system. The relative importance of various excitation and damping forces for different sizes of ALPs were discussed. They concluded that the second-order low-frequency potential excitations were greater than the drag induced low frequency forces; the low frequency responses were comparable to the wave frequency responses; hence, they need to be included for the reliable motion analysis of an ALP. On comparing these results with Sincock's experimental results, a good correlation was obtained.

Later, Bar-Avi and Benaroya (1996) carried out studies on the response of an articulated tower in the ocean subjected to deterministic and random wave loading. The tower was modeled as an upright rigid pendulum with a point mass at the top. It has single DOF about a hinge with Coulomb friction and viscous structural damping. The nonlinear time dependent differential equations of motion were

$$J_{eff}\ddot{\theta} + C\dot{\theta} = \int_0^L([\sum F_{fl}^x \sum F_{fl}^y][-\tan\theta a 1])x dx - M_{gb}^{\theta} - M_{fr}^{\theta} \tag{19}$$

Where $J_{eff} = \left(\frac{1}{3}ml^3 + Ml^2\right) + \frac{1}{3}C_A\rho\pi\frac{D^2}{4}L^3(1 + \tan^2\theta)$, represents the effective. M.I and (20)

$$M_{gb}^{\theta} = \rho g\pi\frac{D^2}{4}\left[\frac{D^2}{32}\tan^2\theta(2\cos\theta + \sin\theta) + \frac{1}{2}\left(\frac{d + \eta(y, t)}{\cos\theta}\right)^2\sin\theta\right] - \left(\frac{1}{2}ml + M\right)gl\sin\theta \tag{21}$$

denotes the moment due to gravity and buoyancy. The equation was numerically solved using 'ACSL'– Advanced continuous simulation language software. The results were analyzed using 'MATLAB'. The responses to random wave heights for different significant wave heights were investigated. The influence of Coulomb damping, current velocity and direction on the response was analyzed, and chaotic regimes of the behavior were identified. It was noticed that the equilibrium position depends on the current velocity and direction. Further, the tower response due to harmonic wave excitation at its 'natural frequency' and half and twice of its 'natural frequency' demonstrates beating.

A general purpose finite element program for the analysis of articulated tower was developed by Nagamani and Ganapathy (1996). They incorporated the nonlinear effects due to large displacement, large rotation and wave forces. The tower was treated as a 3-D beam element. Finite element analysis was performed in accordance with Bathe and Bolourchi (1979). Different solution approaches like Wilson-θ method, Newmark-β method and Newton-Raphson method were used to solve the nonlinear equations of motion. It was found that the updated Lagrangian formulation is computationally more effective than the total Lagrangian formulation for above mentioned solutions.

Bar-Avi and Benaroya (1997) investigated the stochastic response of two degrees of freedom articulated tower as shown in Fig. 8. In this paper, the tower was modeled as a spherical pendulum having two angular DOF. Forces due to waves, current and vortex shedding loads were considered in the analysis, including non-linearities due to geometry, coulomb damping, drag force, buoyancy, and added mass. The governing non-linear differential equations of motion were described as

$$J_{eff}^{\theta}\ddot{\theta} + C\dot{\theta} + I_g\dot{\phi}^2 + M_{gb}^{\theta} = \int_0^L (-F_{fl_x}\tan\theta + F_{fl_y}\cos\phi + F_{fl_z}\sin\phi)\,x\,dx - M_{fr}^{\theta} \tag{22}$$

$$J_{eff}^{\theta}\ddot{\theta} + C\dot{\phi} + I_g\dot{\phi}\dot{\theta} = \int_0^L (-F_{fl_y}\tan\theta\sin\phi + F_{fl_z}\tan\theta\cos\phi + F_{fl_z}\sin\phi)\,x\,dx - M_{fr}^{\phi} \tag{23}$$

Where J_{eff}^{θ} and J_{eff}^{ϕ} are the effective position dependent moment of inertia about z and x axis, respectively.

$$J_{eff}^{\theta} = \left(\frac{1}{3}\overline{m}l + M\right)l^2 + \frac{1}{12}C_A\rho\pi D^2L^3(1+\tan^2\theta) \tag{24}$$

$$J_{eff}^{\phi} = \left(\frac{l}{3}\overline{m}l + M\right)l^2\sin^2\theta + \frac{1}{4}(\overline{m}l + M)D^2\cos^2\theta + \frac{1}{12}C_A\rho\pi D^2L^3\tan^2\theta \tag{25}$$

I_g is a constant depending on system parameters,

$$I_g = \left(\frac{1^2}{2}\left(\frac{1}{3}\overline{m}l + M\right) - \frac{D^2}{8}(\overline{m}l + M)\right)\sin 2\theta \tag{26}$$

And M_{gb}^{θ} represents the moment due to gravity and buoyancy.

$$M_{gb}^{\theta} = \rho g\pi\frac{D^2}{4}\left[\frac{D^2}{32}\tan^2\theta(2\cos\theta + \sin\theta) + \frac{1}{2}\left(\frac{d+\eta(y,t)}{\cos\theta}\right)\sin\theta\right] - \left(\frac{1}{2}\overline{m}l + M\right)gl\sin\theta \tag{27}$$

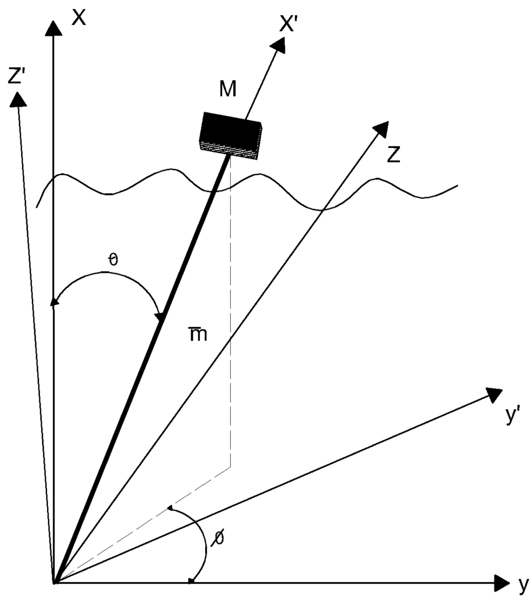

Fig. 8 Model and coordinate system of ALP

All forces/moments were evaluated at the instantaneous position of the tower. The resulting equations were numerically integrated and Monte-Carlo simulations were performed using 'ACSL' software to evaluate the tower response. Effects of several parameters such as fluid constants, significant wave heights, coulomb and structural damping coefficient and current direction were then investigated. Study revealed that the average equilibrium position of the tower depends on the drag coefficient, current velocity and direction; the tower deflects from its vertical position due to current, and then oscillates about the equilibrium position. Coulomb friction had a very small effect on the average steady state response, but a larger one on the transient response.

A method for active control of an articulated leg platform was presented by Suneja and Datta (1998) by combing feedforward and feedback (open-close loop) strategies. The tower was idealized as a SDOF system. Random sea state was considered. The controlled law was derived by minimizing the quadratic performance function of the controlled force. Obtained controlled responses were compared with conventional feedback (close loop) active control. It was found that depending upon a certain range of the weighing index (r), significant reduction in peak displacement response can be achieved with the present approach when compared with the conventional active control.

Han and Benaroya (2000a) analyzed the free response of a compliant structure in vacuum and water. In the performed analysis, both transverse and axial responses were nonlinearly coupled. Hamilton's principle was used to derive the equations of motion. The study revealed that the fundamental frequency of axial motion was twice to that of the corresponding value of transverse motion. It was also found that due to the nonlinear coupling between the axial and transverse displacements, the fundamental frequency of vibration varies with the initial condition. In another paper, Han and Benaroya (2000b) analyzed the forced response of the same structure.

Nagamani and Ganapathy, again in (2000) presented analytical treatment and an experimental program for a three-leg articulated tower. The effect of mass distributions on the variations of the bending moment and the deck accelerations were considered. The model was tested in a 2 m wave flume under regular waves for various wave frequencies and wave heights. The tower was also analyzed using a computer program, and comparisons were made. The test results showed reasonable agreement with the theoretical results. They concluded that

- The maximum bending moment along the legs increases with the wave frequency and decreases with the natural frequency of the tower.
- The bending moment increases with wave height for all three legs.
- The deck acceleration increases with wave height and decreases with the natural frequency of the tower.

Ramesh, *et al*. (2001) investigated the dynamic behaviour of a single hinged articulated tower under first and second order wave forces considering diffraction effects. Wave forces on large diameter tower cylinder were determined in a regular sea using the method proposed by Eatock Taylor and Hung. The equation of motion was established by idealizing the tower as an inverted pendulum using the Lagrangian approach. The dynamic response of the tower with and without diffraction effects was studied and envelops of bending moment and shear force distributions were plotted. The results of the study showed that the dynamic response of the tower based on Morison's approach was larger as compared to the diffraction approach. It was also noticed that buoyancy forces were significantly enhanced in case of diffraction approach causing reduced displacement from mean sea level position.

A parametric study on a vertical member of a compliant offshore tower was conducted by Han and Benaroya (2002). The member (shaft of an articulated tower or one leg of a TLP) was modeled as a beam as shown in Fig. 9 with a point mass as an axial load at free end, undergoing both bending and extension. The main aim of the study was to compare the free and forced responses obtained by the linear transverse model and the nonlinear coupled model. The equations of motion for the axial and transverse displacements were nonlinear and coupled. The responses were obtained numerically for both the models.

A Quarter of the International Ship and Offshore Structures Congress (ISSC) tension leg platform model was used as a numerical example. It was observed that the transverse displacements for both the models are similar under the given boundary conditions. The responses showed irregular beating phenomenon, but when the same random transverse force was applied with non zero initial conditions, the beating disappeared.

In another study, Kuchnicki and Benaroya (2002) studied a continuous elastic model of an articulated

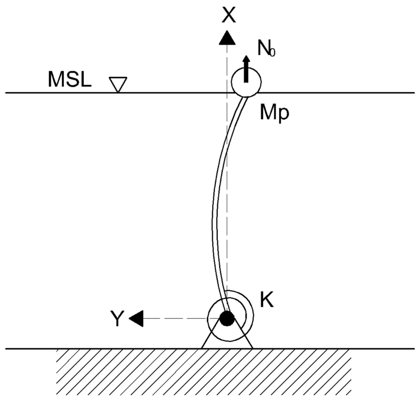

Fig. 9 Simplified model of a compliant tower

tower undergoing planar motion. The equations of motion were derived using Hamilton's Principle.

$$\rho A_o \ddot{u} - \frac{\partial}{\partial x}\left[EA_0\left(u' + \frac{1}{2}v'^2\right)\right] = f_u \qquad (28)$$

$$\rho A_o \ddot{v} - \frac{\partial}{\partial x}\left[EA_0\left(u' + \frac{1}{2}v'^2\right)v'\right] - \rho I_0 \ddot{v}'' + \frac{\partial^2}{\partial X^2}(EI_0 v'') = f_v \qquad (29)$$

Where A_0 is the cross sectional area of the shaft in the undeformed state. The force f_u is that due to gravity and buoyancy, and the force f_v is transverse vortex shedding load acting on the tower in the directions of u and v. These equations of motion were discretized using the finite difference method, and solved numerically. A parametric study on the tower system was performed by changing the characteristics of the wave profile (significant wave height), different tower material (aluminum) and by changing the inner diameter of the tower. On the basis of the parametric study, following conclusions were drawn:

- The maximum defection of the tower increases with increasing significant wave height.
- The material used in constructing the tower had an effect on the maximum defection, while no effect on the qualitative aspects of the tower response was observed.
- Increasing the inner diameter of a hollow tower causes an increase in maximum tower defection while the same had a small effect on the qualitative aspects of the response.
- Increasing the inner diameter of the tower decreases the maximum bending stress.

Clauss and Lee (2003) investigated the dynamic behavior of a compliant tower in harsh sea conditions. They used the finite element program ADINA for wave-structure interaction. The forcing function due to wave was determined using Morison's vector equation. Non-linear viscous forces were considered in terms of the relative velocity between fluid and the structure. Further, nonlinear characteristics of soil-structure interaction were also included in the analysis. Step-by-step implicit time integration scheme was used to determine nonlinear dynamic response of the tower. In the beginning, they investigated a monotower to validate the numerical program system with modal analysis. According to authors, the modal analysis and numerical ADINA simulations correlated reasonably well. Based on the validated program system, the Baldpate compliant tower was modeled using 3D beam models. The effect of dynamic pile-soil interaction was taken into account using non-linear dynamic p-y curves. Finally, the Baldpate tower was exposed to a real "freak" wave sequence (25.6 m) and the motions were investigated. They concluded that the validated ADINA program system proved to be a reliable tool for the design and optimization of compliant towers.

4.2. Double hinged articulated tower

Double hinged articulated towers (DHAT) have shown far better characteristics in deep water conditions when compared to other compliant structures. Such towers avoid concentration of high overturning moments due to hinge connections at the bottom and at the intermediate levels. Further, its response is optimized effectively without increasing the structural weight. Limited work reported in literature on these towers has been reviewed herein.

Jain and Kirk (1981) investigated the behaviour of double hinged articulated tower under regular waves with collinear and non-collinear current. They considered the tower as a double pendulum describing its motion by four degrees of freedom. Each tower possessed two degrees of freedom, namely meridian angle θ and circumferential angle ψ. The four equations of motion were derived through Lagrange's formulations and solved numerically via block integration for θ_1 and θ_2 to obtain the response.

$$I_1\ddot{\theta}_1 + I_3(k_1\ddot{\theta}_1 + k_3\ddot{\psi}_2) + I_1K_1 - I_1\sin\theta_1\cos\theta_1\dot{\psi}_1^2 - M_t^1 g\sin\theta_1 = M_v^1 \quad (30)$$

$$I_2\ddot{\theta}_2 + I_3(k_1\ddot{\theta}_1 + k_4\ddot{\psi}_2) + I_3K_2 - I_2\sin\theta_2\cos\theta_2\dot{\psi}_2^2 - M_t^2 g\sin\theta_2 = M_v^2 \quad (31)$$

$$I_1\sin^2\theta_1\dot{\psi}_1 + I_3(k_2\dot{\psi}_2 + k_4\ddot{\theta}_2) + I_3K_3 + 2I_1\sin\theta_1\cos\theta_1\dot{\theta}_1\dot{\psi}_1 = M_\psi^1 \quad (32)$$

$$I_2\sin^2\theta_2\dot{\psi}_2 + I_3(k_2\dot{\psi}_1 + k_3\ddot{\theta}_1) + I_3K_4 + 2I_2\sin\theta_2\cos\theta_2\dot{\theta}_2\dot{\psi}_2 = M_\psi^2 \quad (33)$$

Where K_1, K_2, K_3 and K_4 are nonlinear functions of the angular displacements and angular velocities. M_v^1, M_v^2 are the moments due to hydrodynamic forces about the instantaneous axes of rotation; while M_ψ^1, M_ψ^2 are corresponding moments about primary axes.

The hydrodynamic loading neglecting tangential component was estimated by Morison's equation. However, instantaneous inclined cylindrical effect was not incorporated in the analysis. The linearized equation of motion was solved for natural frequencies of the system. The study showed that the deck of the tower possess 3D complex whirling motion under waves with non-collinear currents.

Finite element analysis of multi-hinged articulated towers were carried out by Haverty, *et al.* (1982) and McNamara and Lane (1984). They considered two dimensional planer motion of the tower under waves and current. The tower was divided into 21 elements. A coordinate system attached to the tower rigid body motion was adopted besides the fixed coordinate system. Initially the elemental deformations were expressed in terms of system rotation; afterwards, it was transformed into the fixed coordinate system.

Random waves in time domain were obtained by the transformation of P-M spectrum through Borgman's method. The equation of motion was solved numerically by finite difference method introducing an artificial damping and also by Lagrangian approach. The response was found to be close to the results obtained by finite element analysis except for the few initial cycles. The study of McNamara and Lane (1984) therefore, shows that the rigid body approximation yield results, close to finite element analysis. Hence, simpler rigid body formulation was justified.

Leonard and Young (1985) verified the results of Kirk and Jain (1977) by conducting response analysis of the tower under waves and currents. They employed finite element formulation for the investigation. Considering 3D beam elements, equations of motion were established and solved numerically. The study concluded that the nonlinear formulation was computationally more efficient than that of linear formulation.

A new concept of Tension Restrained Articulated Platform (TRAP) was described by Hanna et.al (1988). Analytical studies conducted on a three-segment TRAP, designed for the Gulf of Mexico in 3000 foot of water depth were presented. The tower was subjected to wave, wind and current loads. The tower transmitted minimum reaction to the foundation by balancing the weight and buoyancy. Mathematical model consists of three rigid members with different lengths and masses. Each member has a single degree of freedom, and was interacted through rotational springs at hinges. The total height of the tower was 914.4 m. To analyze the dynamic response and the stresses, large rotations were considered. Nonlinearities due to geometry and drag forces were also considered in the analysis. Numerical solutions were obtained for regular and random waves using the P-M spectrum. Extreme values for tower deflections, shear and bending moments were determined. Study concluded that multiple articulated towers were an attractive option for deepwater applications. Further, authors also recommended the three dimensional response analyses of the tower and other similar compliant towers following the outlined procedure.

In another study, Helvacioglu and Incecik (1988) presented an analytical model to predict the dynamic behaviour of single and double hinged articulated towers subjected to wave and wind forces. Both the towers were idealized as simple oscillators, and the damping was subjected to harmonic forces. Motion of the tower was considered in one plane. Neglecting the fluid hydrodynamic drag forces, simple equations of motion were derived for both the models and solved numerically. Parametric studies were conducted to analyze the tower response due to varying position of buoyancy chamber, hinge location, and deck weight. The analytical results were then compared with experimental results. It was concluded that the responses of both the towers were comparable with the test results; natural frequency of the tower was significantly influenced by the position of buoyancy chamber.

A general mathematical model of multi hinged articulated tower as shown in Fig. 10 was presented by Sellers and Niedzweeki (1992). In this study, authors demonstrated its use for tri-articulated design of the tower. Role of significant tower parameters were identified by them in characterizing the tower natural periods. They modeled the tower as the up righting tri-pendulums interacted by linear rotational springs, undergoing a planer motion. Pendulum bodies were considered cylindrical and buoyant in nature. Each link of the tower was assumed to have different cross-section and mass density. Using Lagrangian approach, equations of motion were derived and solved by Wilson-θ and Newmark-β methods.

These equations were assembled to yield the matrix form as

$$M\ddot{\theta} + K\theta = Q$$

where
$$M = \begin{bmatrix} I_1 + m_{1t}L_{1G}^2 + m_{2t}L_1^2 + m_{3t}L_1^2 & m_{2t}L_1L_{2G} + m_{3t}L_1L_2 & m_{3t}L_1L_{3G} \\ m_{2t}L_1L_{2G} + m_{3t}L_1L_2 & I_2 + m_2L_{2G}^2 + m_{3t}L_2^2 & m_{3t}L_2L_{3G} \\ m_{3t}L_1L_{3G} & m_{3t}L_2L_{3G} & I_3m_{3t}L_{3G}^2 \end{bmatrix} \tag{34}$$

$$K = \begin{bmatrix} K_{11} & K_{12} & 0 \\ K_{21} & K_{22} & K_{23} \\ 0 & K_{32} & K_{33} \end{bmatrix} \tag{35}$$

$$\theta = \begin{Bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{Bmatrix} \tag{36}$$

and
$$\begin{aligned} K_{11} &= g[\Delta_1 L_{1B} + L_1(\Delta_2 + \Delta_3 - m_2 - m_3) - m_1 L_{1G}] + k_{\theta 1} + k_{\theta 2} \\ K_{12} &= K_{21} = -k_{\theta 2} \\ K_{22} &= g[\Delta_2 L_{2B} + L_{21}(\Delta_3 - m_3) - m_2 L_{2G}] + k_{\theta 2} + k_{\theta 3} \\ K_{23} &= K_{32} = -k_{\theta 3} \\ K_{33} &= g[\Delta_3 L_{3B} - m_3 L_{3G}] + k_{\theta 3} \end{aligned} \tag{37}$$

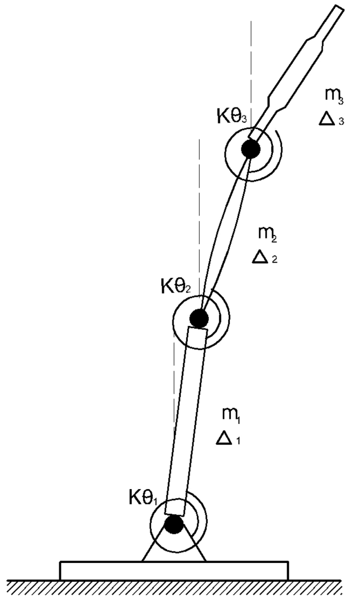

Fig. 10 Model of multi hinged articulated tower

The parametric study included the effect of link lengths, material density and spring stiffness on the natural frequency of the system. They concluded that the model was shown to be useful in changing the natural period of a simplified version of a structure prior to detailed member sizing and weight or buoyancy adjustments. Further, the generalities in the equations allow for inclusion of heavy deck weight, additional ballast and partially submerged members as applicable to specific designs.

Ahmad and Islam (2001a) compared the nonlinear dynamic behaviour of both single and double hinged articulated tower under long crested random sea. The mathematical model used by them is shown in Fig. 11. The nonlinearities due to time-wise variation of buoyancy, submergence, and added mass and instantaneous tower orientation were taken into account to get the equation of motion of single hinged articulated tower.

$$[I]\ddot{\theta}_1 - \left[\left(\sum_{i=1}^{np} m_{1i} r_i - \sum_{i=1}^{nsp} f_{bi} r_i + m_d I_c\right) g \cdot \frac{\sin\theta_1}{\theta_1}\right] = M_{\theta_1} \quad (38)$$

Where $[I]$ consists of the mass moment of inertia of all the elements including deck mass (m_d), about the hinge and $M_{\theta 1}$is the moment due to non-conservative forces. np and nsp are the total number of elements and number of submerged elements of the tower respectively.
For DHAT, two equations of motion were

$$(I_1^* + M_2^* l_1^2)\ddot{\theta}_1 + [M_2^* c_2 l_1 \dot{\theta}_2 \sin(\theta_2 - \theta_1)]\dot{\theta}_2 + \left[\{(F_1 b_1 - W_1 c_1) + (F_2 - W_2) l_1\}\frac{\sin\theta_1}{\theta_1}\right]\theta_1 = M\theta_1 \quad (39)$$

$$I_2^*\ddot{\theta}_2 + M_2^* c_2 l_1 \ddot{\theta}_2 \cos(\theta_2 - \theta_1) + M_2^* c_2 l_1 \dot{\theta}_1 \dot{\theta}_2 \sin(\theta_2 - \theta_1) + \left[(F_2 b_2 - W_2 c_2)\frac{\sin\theta_2}{\theta_2}\right]\theta_2 = M\theta_2 \quad (40)$$

Where 1, 2 denotes lower and upper tower respectively, I^* is the moment of inertia of the tower

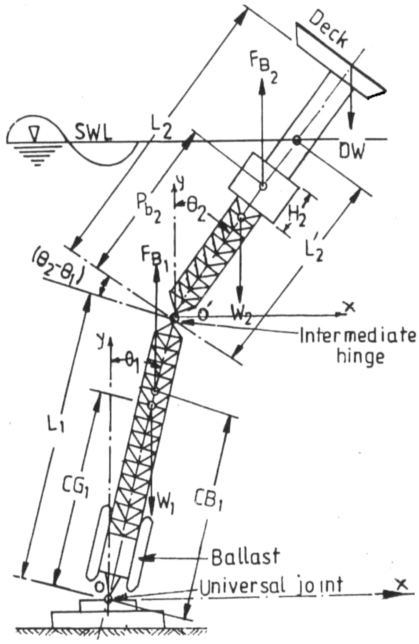

Fig. 11 Mathematical model of DHAT

including the added mass, θ, $\dot{\theta}$ and $\ddot{\theta}$ are the rotation, velocity and acceleration of the respective towers, F and W are the buoyancy force and weight respectively and M_θ is the moment due to non-conservative forces.

The non-linear equations of motion were solved by using Newmark-β integration method. Tower parameters, such as deck displacement, heel angle, base shear and bending moments for both the towers were compared and presented in the form of time histories and their respective power spectral density functions. Effect of current, significant wave height and zero-up crossing periods were also investigated.

Following observations were made in the study:

- Response spectrum of DHAT shows a concentration of closely spaced peaks along with prominent peaks. No evidence of low frequency response leading to subharmonic resonance was observed. However, super harmonic resonance sometime occurs due to high frequency content.
- Significant reduction in maximum bending moment was observed in case of DHAT as compared to SHAT.
- Time varying record of shear force at the hinges is an important input for the fatigue reliability analysis.

In another paper, Ahmad and Islam (2001b) studied the effect of directionality of waves on the responses of single and double hinged articulated towers. Sea state was specified by spread angle (α) = $\pm 15^\circ$, degree of directionality (S) = 1, principal direction of wave propagation $(\beta_0) = 0^\circ$. Two phase combination causing maximum response was considered. The governing nonlinear equations of motion were same as Eqs. (39) and (40). Direct time-stepping integration method was adopted to account for the nonlinearities present in the equation of motion. From the solution they concluded that directional phase distribution is an important parameter to achieve the maximum dynamic response; angular range $-\beta$ to $+\beta$ plays an important role in simulation of directional sea.

An appropriate range of angular limit should, therefore, be considered from $-\pi$ to $+\pi$ to achieve the quasi critical loading environment due to directional sea; and the tower response due to directional sea is significantly low than that due to long crested random sea.

Islam and Ahmad (2003) investigated the non-linear dynamic behavior of double pendulum articulated tower under long crested random sea. The non-linearities due to variable submergence, drag force, added mass, etc. were considered for modeling the forcing function of equation of motion. Effect of current and significant wave height were also studied. A long crested random sea was modeled by Monte-Carlo Simulation technique using P-M spectrum. It was concluded that the presence of mid hinge causes large variation in shear forces at the hinges. Further, tower response due to directional sea is significantly lower than due to long crested random sea.

5. Concluding remarks

The review presented here provides an essential input to the investigation of aerodynamic behaviour of articulated loading platforms. Some of the key issues that necessitate further investigations include the following:

1. More realistic models with multi degree of freedom system and having two or more dimensional motion in lieu of single degree of freedom models need to be analyzed.
2. Synthesis of this information for developing multi hinged tower models is more important. Only Sellers and Niedzweki have worked on tri articulated tower model. Further, as the oil industry goes into deeper water, therefore, such concept is one of the viable solutions.
3. Articulated towers are more sensitive to wind forces. Therefore, better modeling of wind forces is required. Most of the authors used Simiu spectrum for simulating wind loads. However, other spectra such as API-RP-2A, Kareem, Davenport, Ochi, Pond, etc. will help in better optimization of wind loads and therefore should be thoroughly investigated.
4. Bluff body configuration of the platform superstructure gives only approximate results. Hence, careful consideration of the interference and shielding effects; and influence of vortex shedding induced vibrations on deck structures warrant critical investigations.
5. Responses under various wind spectra with and without correlated waves have not been generally covered by the past investigators. Wind driven waves are more realistic, hence, analysis under combined effect of wind and waves with currents are important.
6. Pierson-Moskowitz spectrum is widely used for the determination of wave forces, while Jonswap spectrum has limited reporting. Therefore, it provides scope for further investigation.
7. The current force has an overriding influence on the dynamic response of the tower and should be carefully considered in the analysis (i.e. both its magnitude and variation).
8. A closer look into the literature indicates that there is a dearth in the fatigue reliability study of articulated joints, although its importance increases manifold due to its failure under fluctuating wind loads.
9. A general outcome is that, multi hinged articulated towers in deep water conditions are more economical as compared to single hinged towers due to reduced bending moment.

Turbulent wind-induced loads dominate deck structural loading and design. Therefore, design of articulated tower warrant the use of response based criteria, or the determination of the “100-year” response to fix environmental criteria; use of wind gust factors and API-RP-2A wind spectra to generate random wind simulations; impact of aerodynamic damping; use of higher averaging time, say 20 minutes wind to produce design force levels consistent with forces produced with dynamic wind analysis; and the use of reliability based design for the articulated joints. Because these joints are most vulnerable to fatigue, therefore, it is a promising area of research in the years to come. Further, stability analysis of articulated tower can be made use of in the design of mooring lines to avoid structural instabilities in the evolving offshore environment.

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