Advances in Mooring Line Damping

by D. T. BROWN*, G. J. LYONS* and H. M. LIN*

Abstract
This paper discusses recent fundamental and applied work investigating the damping forces induced on floating vessels and in particular catenary mooring lines. A description of new tests being performed at University College London on large scale sections of mooring line to reveal damping contributions is also presented.

The contributions to damping from the morring lines is highly topical in that a number of floating production and storage units are currently being planned for hydrocarbon exploitation. Indeed a number of schemes are already in operation at North Sea sites. Design of the mooring system required to hold the vessel within a specified radius above the wellhead depends on an understanding of the imposed static and dynamic environmental loads. The low frequency excitation caused by the random waves, and, to a certain extent, wind loading results in resonant motion responses in the horizontal plane leading to high mooring line forces. Many of the loading mechanisms are well understood. However, until recently the fluid induced forces acting on the moorings were assumed to have little influence on the vessel dynamic response. Recent work has shown that the mooring system may under certain circumstances provide up to 80% of the total damping available thus significantly reducing the peak line tensions.

**Santa Fe Laboratory for Offshore Engineering, Department of Mechanical Engineering, University College London, Torrington Place, London WC1E 7JE, UK.*

1. Introduction

Offshore hydrocarbons have until recently been exploited using fixed platforms. These are restricted to relatively shallow waters, typically less than 200 m. With the advent of flexible pipe connections between the sea bed and water surface, floating production systems are now beginning to be utilised for a number of field developments, particularly in deeper water locations where there are often low levels of infrastructure support.

There are a number of key advantages to be gained by the use of floating units. These are principally their versatility to meet a variety of field parameters, together with ease of removal and adaptation to other fields. Furthermore floating facilities can often be implemented sooner than fixed installations with modest capital investment, enabling early return on investment. They usually require a lower productivity level and shorter field life to offset capital expenditure. Consequently there is increased demand for floating production systems as shown in Figure 1 using data derived from reference [1].

The decision to use ship-shaped or semisubmersible vessels (including tension leg platforms) depends on cost, load capacity, together with weather and system related operability. Rig availability is also a primary consideration. Semisubmersibles are relatively expensive to fabricate, have limited storage capability being space-framed type structures, and therefore field operability is dependent on the performance of the dedicated storage and off-loading system. Semisubmersibles are also restricted in space and weight

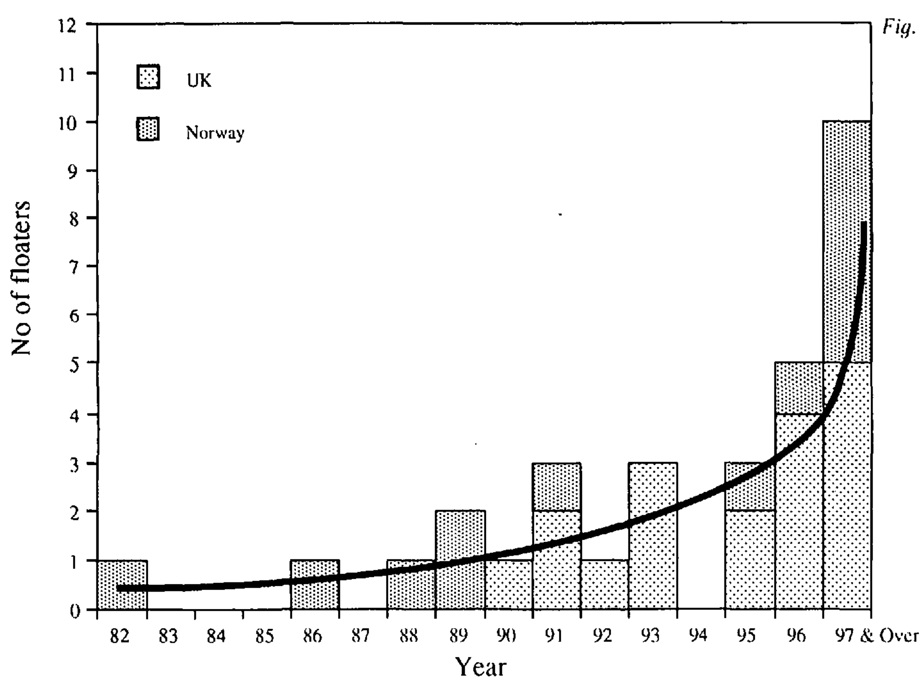


Fig. 1 Predicted floating production start-ups

capacities and thus there is less flexibility to install equipment at later stages of the field development to carry out activities such as re-injection. Monohulls, however, often have lower construction costs and offer high load capacities, but they can suffer from significant motions in adverse weather. These vessels are usually attached to the mooring system through a swivelling turret and weather-vane into the direction of the environmental forces, being effectively single-point moored.

Figure 2 indicates the primary external forcing mechanisms acting on a turret-moored vessel. The random loads result in the vessel undergoing small amplitude motions at wave frequencies and relatively large amplitude motions (particularly in surge) at low frequencies—often termed drift frequencies. The frequency of the slowly oscillating horizontal motions usually corresponds to the natural surge frequency of the mooring system. While the wave frequency motions are caused by the first order wave forces, the slowly oscillating motions result from the higher order drift forces. These phenomena are discussed further in Patel and Brown [2]. The damping associated with the resonant, low-frequency motions is relatively small and consequently high tensile loads are induced in the mooring lines. Accurate assessment of the individual damping levels is therefore critical to establishing peak mooring line loads.

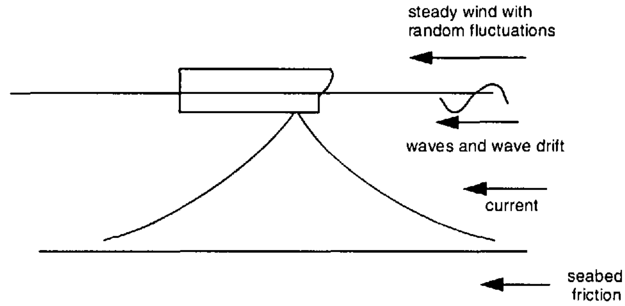


Fig. 2 Environmental forces acting on a moored vessel (not usually collinear)

The mooring lines themselves are made up of a number of components as shown in Figure 3. Lengths

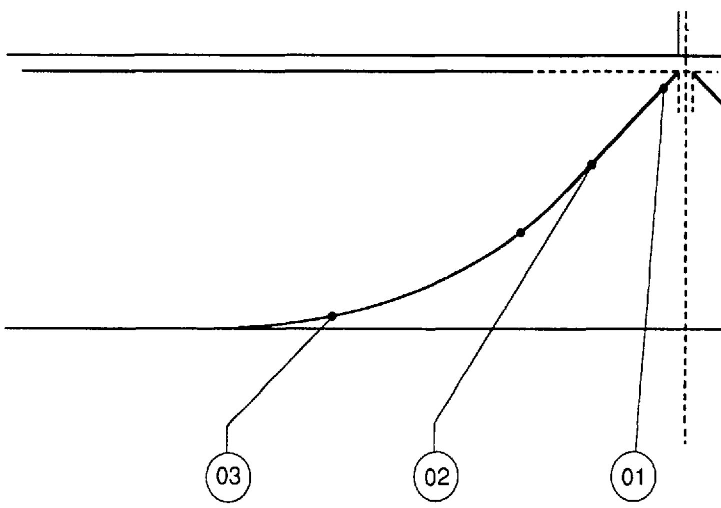
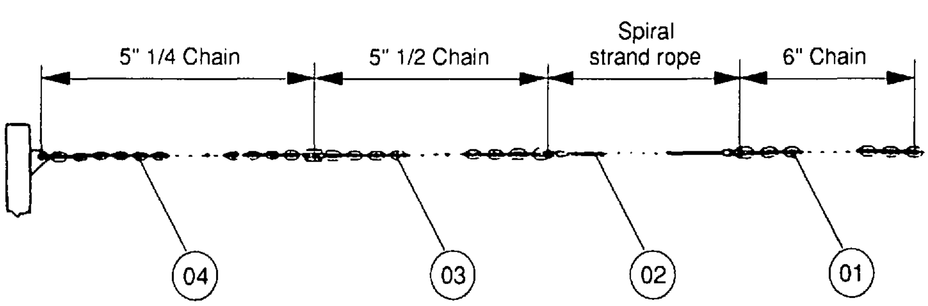


Fig. 3 Typical mooring line components (shackles not shown)

04	5" 1/4 Anchor Chain	L = 320m
03	5" 1/2 Anchor Chain	L = 300m
02	Spiral Strand Rope	L = 100m
01	6" Anchor Chain	L = 27.5m



of chain are used near the vessel and seabed end points. These are relatively easy to terminate and have good wear properties. The suspended section of line is often of wire rope construction with the advantage of being typically only 20% of the cost and weight of chain for a similar breaking strength requirement.

This paper outlines the major contributions to the damping forces experienced by a moored vessel and goes on to review some of the recent theoretical and experimental work being carried out on mooring line damping. An overview is also provided of large-scale tests being performed at University College London to provide a fuller understanding of the hydrodynamic forces acting on the lines.

2. Damping components

There are usually considered to be four primary components contributing to damping of a moored vessel. These have been investigated by a number of authors, for example Triantafyllou et al. [3] provide a good summary. The components are:

2.1 Current and viscous flow damping

The relative motion between hull and fluid caused by current together with the vessel's slowly varying motion gives rise to lift and drag forces. Both viscous drag and eddy making contribute. The magnitude of the damping increases with larger wave height.

2.2 Wind damping

Again the frictional drag between fluid (air) and vessel produces a damping force. As the wind force has a large steady component linearisation, procedures are often used to obtain the damping coefficient. It is noted however that the wind loading may also contribute to the resonant motions of the vessel in the horizontal plane because of its random nature. To the authors' knowledge little research work has been carried out in this area.

2.3 Wave drift damping

This is a potential effect associated with changes in drift force magnitude caused by drift velocity of the vessel—see for example [4], [5] and [6]. Within the framework of the theory the current velocity is often regarded as the structure slow drift velocity. It can be shown that when a vessel is moving slowly towards the waves, the mean drift force will be larger than when it is moving with the waves. The associated energy can be thought of as slow-drift motion damping.

2.4 Morring line damping

There are a number of contributions to the overall damping from the mooring system. These are:

- *Hydrodynamic drag damping.* This phenomenon is clearly understood by considering Figure 4, from Huse [7], showing a catenary mooring line subject to motion at the top end caused by vessel surge. Depending on the water depth, line pretension and weight, azimuth angle, etc., a relatively small surge motion can result in transverse motion over the centre section of the line that is many times larger than the surge amplitude itself. The corresponding tranverse drag force represents energy dissipation per oscillation cycle and thus can be used to quantify the line damping.

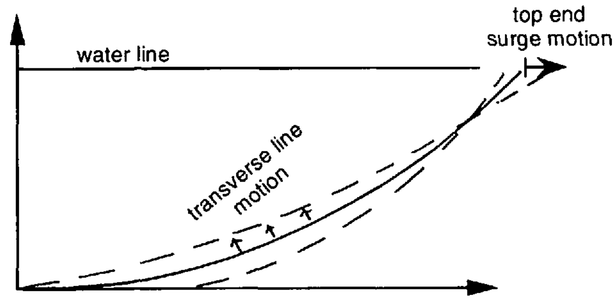


Fig. 4 Catenary line motion caused by vessel surge [7]

- *Vortex induced vibration.* Vortex formation behind bluff bodies placed in a flow gives rise to unsteady forces at a frequency close to the Strouhal frequency. The forces cause line resonant response in a transverse direction to the flow and the vortex formation can become synchronised along the length resulting in the shedding frequency 'locking-in' to the line natural frequency [8]. This can result in a significant increase of in-line drag. It is generally considered that the effect is important for wire lines whereas for chains it is assumed negligible.
- *Line internal damping.* Material damping caused by frictional forces between individual wires or chain links also contributes to the total damping. Little work has been performed here. Work is planned at University College London to subject a suspended line to cyclic loading (in air) and hence measure the motion decay.
- *Damping caused by sea-bed interaction.* Soil friction leads to reduced tension fluctuations in the grounded portion of line effectively increasing the line stiffness. Recent work [9] has shown that out of plane sea-bed friction and suction effects are negligible in deep water mooring situations whereas in-plane effects can significantly influence the peak tension values.

3. Relative magnitude of damping components

It is very difficult to make general statements on the relative magnitude of the damping components described above, because of the influence of water depth, environmental conditions, vessel type and mooring system. It is often considered that the dynamic contribution from wind is relatively small and line damping caused by internal friction and sea-bed interaction are usually assumed negligible.

Matsumoto [10] has attempted to quantify the relative contributions caused by hull viscous, wave drift and mooring line damping. The vessel considered was a 1:60 scale model of a ship-shaped floating production system in 120 m water depth. Results are given in Figure 5 indicating that the dominant effect is caused by mooring line damping, particularly for sea conditions corresponding to intermediate and high significant wave heights.

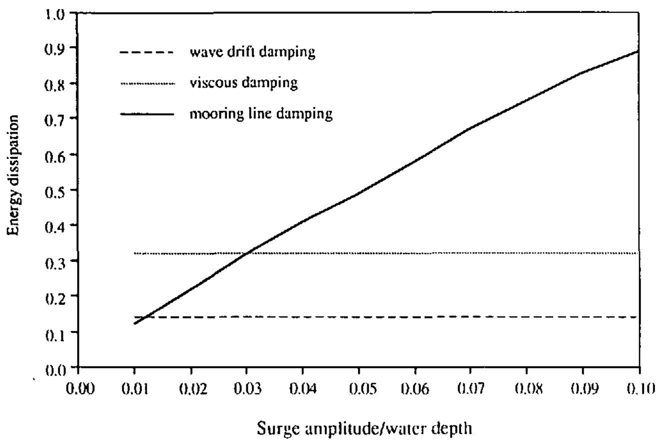


Fig. 5 Relative energy dissipation caused by surge damping contributions [10]

4. Line damping due to hydrodynamic loading

Although work has been carried out over a number of years investigating the dynamic response of floating systems to random forcing, it is only relatively recently that mooring line damping has been considered.

Early experimental work was carried out by Huse and Matsumoto [7, 10, 11 and 12]. Small scale model tests were performed on semisubmersible drilling rigs in 140 m and 160 m water depth and a 120,000 DWT tanker in 200 m depth. Two mooring systems were used; one with horizontal lines and springs replicating a linear system with low hydrodynamic damping; the second with a catenary mooring spread. For higher vessel motion amplitudes the latter system resulted in damping up to six times the levels of the linear spring system. The increased damping was caused by the significantly higher transverse response of the catenaries caused by top end motion as shown in Figure 5.

The studies also indicated that superimposing the wave frequency motions of the moored vessel with the low frequency motion led to a dramatic increase in the low frequency surge damping. Effectively this caused a drag coefficient amplification because of the quadratic variation in drag force with relative velocity between line and fluid. Consequently the slowly varying damping force varied in a non-linear manner with wave amplitude and frequency. For typical wave spectra this amplification resulted in increases of damping coefficient of between two and four. Measured results for the tanker indicated that, for the above tests, damping from the mooring system provided over 80% of the total with viscous and wave drift giving limited contributions in moderate and high seas as shown in Table 1.

Numerical methods to predict mooring line damping have also been developed in conjunction with the experimental work. A common way forward is to calculate the line energy dissipation in each low-frequency motion cycle and use linearisation methods to predict the damping. In early investigations [11 and 13] it was assumed that the line geometry was represented by the catenary equations. Both wave and low frequency effects were included. Mechanical elongation of the line was also considered using an energy balance argument. The approximations were considered valid for wire lines but for chain segments in deep water the results were questionable.

Table 1 Relative damping contributions for a 120,000 DWT tanker in 200 m water depth (from [7])

Significant wave height (m)	Peak period (s)	Damping contributions %		
		Mooring	Waves	Viscous
8.6	12.7	81	15	4
16.3	16.9	84	12	4

Work has also been carried out at Marin, in the Netherlands [14] on line damping for turret moored tankers. Again it was found that the damping levels were relatively large, particularly in greater water depths (250 m). For smaller depths (82 m) the line damping was relatively low. Furthermore, superimposing low frequency surge with wave frequency heave resulted in a large damping increase. This is of relevance as the heave amplitude may be relatively high for a bow mounted turret because of the pitch-induced vertical motion contribution. The experimental work was correlated with lumped mass, finite element modelling of the lines [15 and 16]. This method has the benefit that the change in line shape caused by fluid induced loading along the length is accounted for—that is a catenary shape is not assumed.

Other studies on turret-moored monohulls [17] and semisubmersibles [18] have arrived at similar conclusions to the work described above, tests again being based on model scale experiments. For example Fylling et al., [17], state that '... the damping due to the anchor system is strongly increased by the wave-induced motions in extreme conditions and the low-frequency motions cannot be modelled as Gaussian responses.'

Bompais et al. [19] present a simple design method to predict line damping by linearising the catenary equations. This has the advantage over finite element methods such as those described in [14] in that calculation times are relatively short. However, the method can only be used for preliminary design. Results are compared with experimental data and again conclusions drawn that mooring line damping is the dominant component. Furthermore, its magnitude is sensitive to line geometry and consequently time-domain modelling should consider the damping as a function of the instantaneous slow-drift motion.

Useful work carried out by Papazoglou et al. [20] investigating the dynamic behaviour of suspended elastic cables in water provides insight into physical modelling of cable systems. A rig was developed allowing harmonic oscillations of a 3 mm diameter suspended cable, attached at the lower end to the tank base using springs to reduce the elastic stiffness. Good agreement between measured results and theory was obtained. Without a spring the line had large elastic stiffness (as Young's modulus cannot be easily scaled

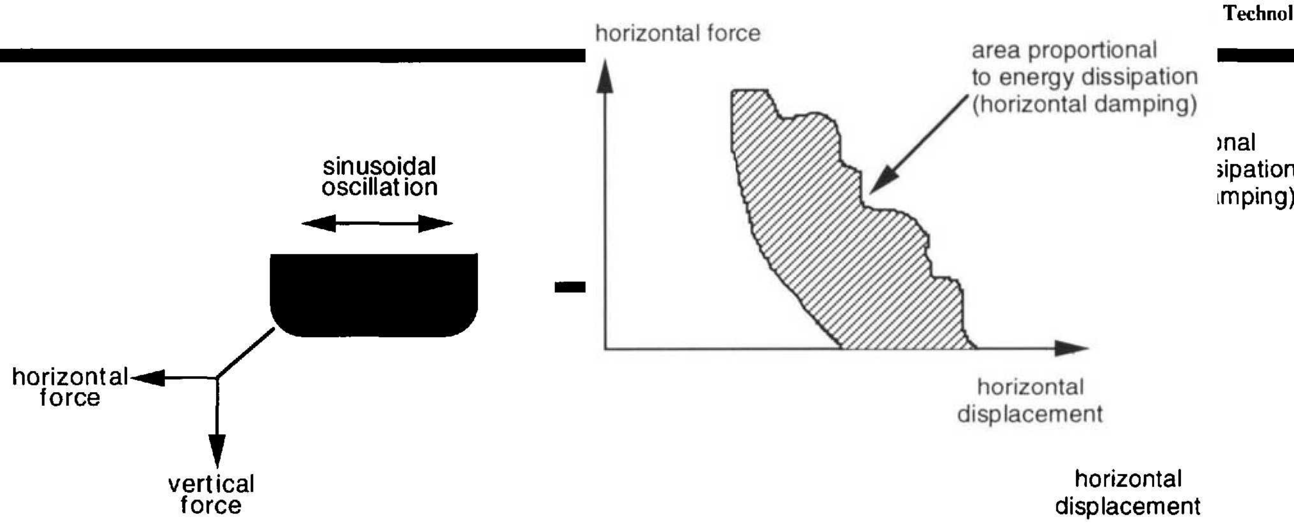


Fig. 6 'Indicator' diagram to derive mooring induced damping [23]

down) resulting in physically unrealistic tensions. The authors concluded that the dynamic tension could under certain circumstances exceed the static tension and under these conditions it was essential to correctly scale the free-fall velocity of the cable.

Howell and Triantafyllou [21] have carried out both theoretical and experimental work on the non-linear dynamics of hanging chain responding to harmonic top end excitation. They found that under conditions where the dynamic tension exceeded the static value, impulse-like tension forces were induced. For large top-end excitation the chain tension became negative near its free end. This could be predicted using numerical modelling by including bending stiffness terms which, although physically relevant only to wires, eliminated singularities in the cable equations.

Triantafyllou has also carried out work focusing on cable mechanics for moored floating systems [22]. The analysis was developed by separating the relevant equations depending on the associated amplitude and time-scale. Consequently the influence of the slowly varying motions, wave induced motions and vortex induced response were individually considered. The equations were coupled parametrically and hence the analysis was computationally intensive. The author has also analysed data from model and full-scale semisubmersible measurements [3], the calculated line damping being of similar magnitude to wave drift damping. The full-scale results were measured on a moored drilling semisubmersible with use of thrust control to give specified horizontal offsets. Neglecting drag amplification due to wave frequency motion and vortex induced vibration resulted in damping levels being underpredicted by approximately 50%.

Recent work performed by Webster [23] provides a comprehensive parametric study on the influence on line damping of pre-tension, oscillation frequency and amplitude, line stiffness, line length/water depth, current and drag coefficient. Using an efficient, finite element modelling scheme to represent a single line, time domain analyses were carried out. In the method the fairlead at the water surface was oscillated in horizontal and vertical directions with varying amplitude and frequency. By separately considering the relevant induced force components allowed 'indicator' diagrams to be prepared as shown in Figure 6. This style of presentation is similar to that used in the assessment of reciprocating engine performance and hence the same terminology was used. The energy dissipation was thus neatly evaluated as the area contained within the trace of each force-displacement plot.

Webster's work indicated that for specified top-end oscillation the transverse and longitudinal line motion competed, the balance being achieved depending on the relative 'impedance' of each response. For high pre-tensions the damping decreased with increased drag coefficient because the transverse motion response had a higher impedance than the stretch response. Also damping increased with line stiffness. At lower pre-tensions damping increased with excitation frequency. The work concluded that it may be possible to select line layouts to optimise damping contributions and hence reduce peak line tensions.

A severe drawback of much of the experimental work described above is associated with the relatively small geometric scale at which the model tests were performed (typically 1 to 100) and the fact that it is difficult to apply the results to field scenarios, that is water depths and chain sizes, other than those for which testing took place.

Current work taking place at University College London within the Uncertainties in Loads on Offshore Structures (ULOS) Research Programme is aimed at performing model testing at approximately 1 to 3rd scale on short sections of line to ensure that the Reynolds number flow regime is as close as possible to that encountered at full scale. The main requirement is to establish the contribution of hydrodynamic damping forces within the lines. Line segments are being tested at various inclinations and orientations to the flow to represent sections of single catenary mooring lines.

The segments are mounted on a moving carriage shown in Figure 7 to simulate in-line combined low frequency and wave frequency motion. An oscillator is attached to the carriage to provide transverse

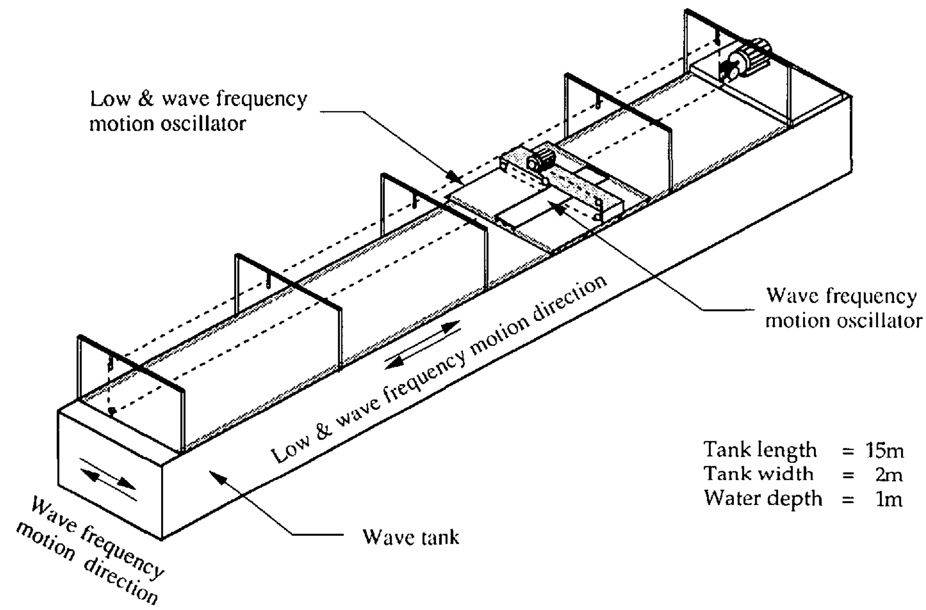


Fig. 7 UCL tests—Longitudinal and transverse oscillators for mooring line specimens

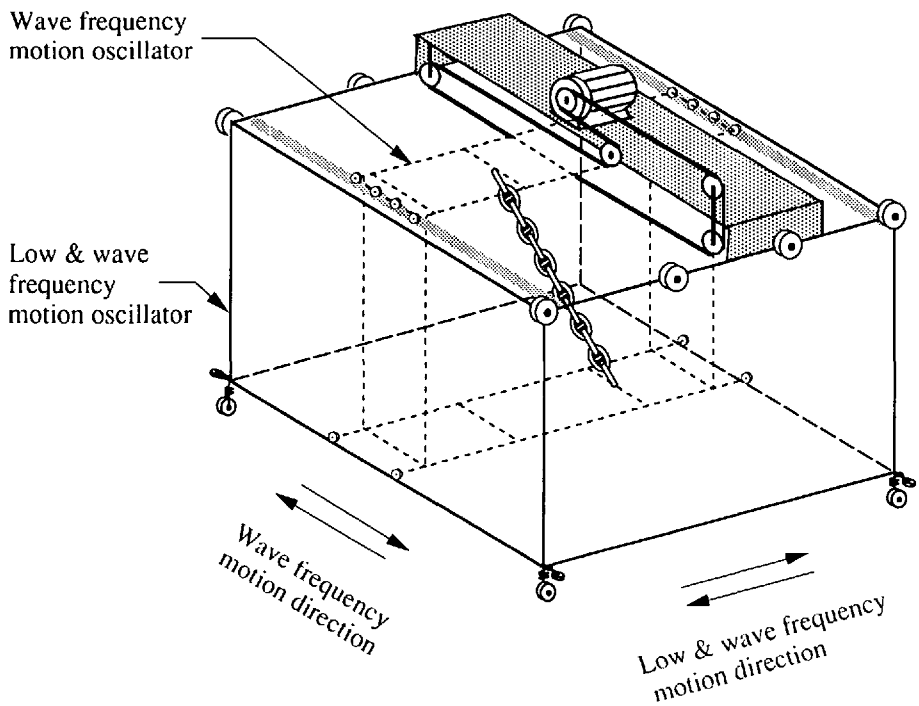


Fig. 8 UCL tests—Transverse oscillator and mooring line specimen

motion at wave frequencies as shown in Figure 8. Consequently the effects of vessel in-line (surge) and transverse (sway) wave motion together with the low-frequency high-amplitude response can be assessed. From measurement of the drag forces on a range of segments with differing wave and low-frequency motions, sectional added mass and damping forces can be found. Low and high frequency interaction is being investigated by performing comparative measurements with stationary oscillator/carriage combinations. The experimental tests are running in parallel with analysis work that utilises the measured forces within a finite-element formulation of mooring line behaviour to estimate the damping contributions for all lines. The work will be able to be applied to different field scenarios and weather conditions.

5. Conclusions

Reliable estimates of mooring line damping are required to predict the large-amplitude resonant horizontal motions of moored floating production systems. The research work performed to data indicates that combined low- and wave-frequency forcing should be considered simultaneously and a number of experimental studies, mainly at relatively small scale, have been completed. There is a need for large-scale modelling tests to be carried out (University College London is performing work in this area) and for the results to be used for further validation of the available analysis methods. These can then be utilized to develop design curves that can be applied for the practical range of mooring line layouts and field characteristics.

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