A COMPLIANT SEMISUBMERSIBLE FOR OFFSHORE PRODUCTION

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ABSTRACT

This paper describes the structure and principles of operation of a compliant semisubmersible which offers improvements in deck payload and motion response to waves over conventional rigid semisubmersible designs. These improvements are obtained by separating the buoyancy and hydrostatic stability contributing members of the structure. The buoyancy is supplied by bottle legs directly below the vessel deck, and the hydrostatic stability is contributed by articulated stabilisers from submerged outriggers on the outer perimeter of the vessel keel. The stabilisers have small excess buoyancy and behave as inverted pendulums. These fundamental innovations make it possible to design vessels with a deck payload capacity in the range of 10,000 to 12,000 tonnes. The paper further describes analytical methods by which the vessel's hydrostatic stability, hydrodynamic response and the dynamics of the articulated stabilisers are predicted. Model test data, used for confirming these analytical results, are also presented.

1 INTRODUCTION

Many of the operations involved in the exploitation of offshore oil and gas reserves require that the equipment being used moves very little relative to a fixed point on the seabed. This has been achieved by using fixed, bottom standing structures such as piled steel jackets or concrete gravity platforms. Developments in technology have allowed moored floating production systems to be considered but it is still necessary to keep motions to a minimum and consequently the semisubmersible has been the favoured configuration for severe environments. Two semisubmersible based floating production platforms are currently operating in the North Sea.

Insufficient deck payload has been a significant limitation for oil production from semisubmersibles since a very large amount of equipment is necessary to achieve a high production rate. This may be necessary to exploit a field effectively and could rule out using a conventional semisubmersible. Thus, in deeper water where the cost of a fixed structure rises dramatically, the development of a hydrocarbon reservoir may be precluded by field economics.

The concept of a semisubmersible design with articulated members offers the possibility of a vessel capable of large deck payloads with reduced motions to waves - these two features being the primary requirement for a floating production platform. The idea of a compliant semisubmersible is not new. However, a real understanding of how this vessel can be made to work has not been appreciated. The feasibility of a compliant semisubmersible has been extensively investigated by a team made up of staff from Cluff Copson Designs Ltd, University College London and Single Buoy Moorings (UK) Ltd. The work of the team has been aimed at investigating the basic problems so that the advantages of the concept may be achieved whilst minimising the penalties. A specific compliant semisubmersible design is currently being evaluated with the aim of obtaining pre-certification design approval from a classification society. This is being done by a joint venture company called Interig Ltd with additional engineering participation from the International Drilling Co., Single Buoy Moorings (UK) Ltd and Davy McKee Ltd.

This paper reviews the overall structure and principles of operation of a compliant semisubmersible for floating production. It also presents the analytical methods by which the hydrostatic stability, hydrodynamic response and the dynamics of the articulated stabilisers are predicted together with results of 1:100 scale model tests of a compliant semisubmersible. The design tools being developed for more detailed evaluation of vessel characteristics are also described.

2 THE COMPLIANT SEMISUBMERSIBLE-GENERAL PRINCIPLES

In order to produce a semisubmersible with increased deck payload and no stability or performance sacrifices, a fresh look was taken at existing semisubmersibles and proposed designs. A brief review of the principles of operation of conventional rigid semisubmersibles is presented in order to develop an argument for the compliant semisubmersible.

Conventional semisubmersibles gain their improved wave induced motions partly by virtue of the deep submergence of the main buoyancy - as wave energy is largely confined to a region within half a wave length of the surface - and partly by wave force cancellations which occur for forces on horizontal pontoons and vertical columns. These cancellations serve to reduce the total wave force on the vessel. On the other hand, the stability of the semisubmersible is derived from the second moment of area of its water plane which is mainly dependent on the size of the water plane area and the square of its distance from the axis of rotation considered. At this stage, it is useful to note that the main columns of a conventional semisubmersible perform the three primary functions of providing the deck support structural connections, a significant proportion of the buoyancy and all the vessel stability through the water plane area. It is thus difficult to optimise a conventional semisubmersible with respect to one of these functions without incurring a penalty on the others.

In this context, consider the effect of an increase in deck payload and the design changes which must be made in order to retain sufficient stability and structural strength. The most obvious effect of an increase in payload is the requirement for more buoyancy through increased immersed volume either by an increased draught or by a hull modification - both of these have the effect of reducing the hydrostatic stability of the vessel. However, increasing the diameter of vertical columns would supply the required additional stability except that this would also induce larger wave forces through the larger water plane area resulting in the need for a stronger structure. This can be achieved through increasing the scantlings or number of structural members although the additional steel weight results in a further requirement for additional buoyancy and a vicious circle is established.

The increased stability requirement resulting from an increase of deck load can alternatively be achieved by moving the columns out from the geometric centre. Unfortunately, this results in a dramatic increase in the weight of the deck support structure due to the increased moment arm of deck loads and environmental forces. This increase in the weight of the supporting superstructure will result in increased stability requirements and the problem still remains.

However, an opportunity for breaking out of this vicious circle is afforded by the use of articulated stabilisers to supply the hydrostatic stability function of the vertical columns. These articulated stabilisers (shown in Figure 1) are freely pinjointed at their base on submerged outriggers from the main structure. The stabilisers have a small amount of excess buoyancy and will remain upright in still water in the manner of inverted pendulums. The large distance of the stabilisers from the vertical centreline of the vessel coupled with the absence of any deck support structure yields very high hydrostatic stability without the penalty of additional structural weight at deck level.

A perspective view of a likely compliant semisubmersible design is shown in Figure 1. The deck support is provided by a structurally efficient slender space frame and the buoyancy is supplied by simple cylindrical submerged 'bottle legs'. The great span of the structure (typically 150m) due to the outriggers and the mounting of the stabilisers on the periphery of the vessel permit major increases in hydrostatic stability over conventional vessel designs. It should be noted that the primary functions of deck support, buoyancy and stability are now separated and are provided by the space frame, the bottle legs and the articulated stabilisers respectively; this leads to much more flexibility and the opportunity for better optimisation of each of the functions.

3 HYDROSTATIC STABILITY

3.1 Weight Breakdown

The payload and weight breakdown for the deck of any semisubmersible will depend on a variety of factors including application (drilling, floating production), the specific facilities needed, the operator, national and international regulatory bodies and so on.

A conceptual payload for a floating production facility has been assessed and the following weights have been estimated for a typical application:

1	Payload weight, consisting of all equipment, materials, secondary steel and services at deck level.	10,560 tonnes
2	Primary structural steel.	3,600 tonnes
3	Applied vertical forces.	1,400 tonnes
		15,560 tonnes

Table 1 gives a more detailed breakdown of deck equipment weights for a floating production application and, in addition, typical vessel structural weights as used in the analysis. Note the presence of substantial applied loads.

A compliant semisubmersible of the type shown in Figure 1 has been designed in outline for the above payload. This design has been used as a basis for the analytical work and model tests described in the following sections.

3.2 Hydrostatic Analysis

Conventional hydrostatic analysis assumes a rigid hull for calculating stability and behaviour at various angles of heel in still water. However, the presence of the articulated stabilisers requires that the conventional theory be extended and modified to take account of the articulations.

This has been done and is reported in reference 1. The theory is re-evaluated on the basis that the centre of buoyancy of the whole structure at any orientation may be calculated as if the structure were rigid so long as the axes of the stabilisers remain perpendicular to the still water plane at any orientation.

An alternative approach is to consider the hydrostatics of the rigid part of the body only and to account for the stabilisers by a prescribed vertical tension acting on the rigid structure at the joint position. In this approach the restoring moment due to the stabilisers is applied to the rigid vessel as external forces, the value of which may be readily calculated from the vessel and stabiliser geometry.

The two methods are equivalent in the results produced. The main conclusions of the hydrostatic analysis are:

1 The presence of water plane areas on the articulated stabilisers at large distances from the vessel vertical centre-line yields substantial levels of stability with typical BM values (distance between centre of buoyancy to metacentre) of 25m and GM values (distance of centre of gravity below metacentre) of 11m.

2 Excess buoyancy in the stabilisers makes them behave like inverted 'crane hook loads'. As the vessel heels, this effect shifts the total vessel centres of buoyancy, gravity and flotation and induces changes in righting moment.

3 However, at large angles of heel, large angle effects on the stabilisers always cause a reduction in righting moment.

These features are illustrated by Figure 2 showing righting moments against angle of heel for the articulated vessel and the equivalent rigid vessel (with universal joints locked).

3.3 Wind Heeling Moments

Semisubmersible operations in Arctic waters and North of the 62nd parallel will require enclosed derrick and work areas. This has an impact in that the vessel is required to have a higher deck payload for the enclosing structure weight as well as a higher hydrostatic moment to counter the effects of increased wind heeling moments. The net requirement is for substantially greater hydrostatic stability which is available without a payload penalty in the compliant semisubmersible considered here.

The increased wind heeling moments with enclosed work spaces have been calculated following guidelines laid down by the IMO (see reference 2) intact stability requirements for floating vessels. The vessel deck, column and platform equipment frontal areas are combined with an enclosed derrick and the resultant heeling moments are calculated in a 100 knot (51.5 m/s) survival wind condition. The centre of lateral resistance of the vessel is taken to be at the keel to account for moorings attached at or above this level. Figure 2 shows the heeling moment curve as a function of heel angle. The areas under the two curves and their intercepts meet IMO intact stability requirements with a safe margin.

The compliant semisubmersible shown in Figure 1 has an integrated buoyant deck. Heel angles of greater than 20 degrees will submerge the deck edge and add substantially to the righting moment beyond this angle.

4 HYDRODYNAMIC RESPONSE

The hydrodynamic response of the vessel was evaluated during the design by a combination of analytical tools validated by 1:100 scale model tests. Hydrodynamic analysis of the vessel followed current practice for conventional semisubmersibles (see references 3 and 4) with additional work being done on the dynamics of the articulated stabilisers. The analysis was performed using a computer program called UCLRIG (reference 5) which is capable of evaluating the motions in the six degrees of freedom (surge,sway, heave, roll, pitch and yaw) of a semisubmersible vessel. A frequency domain solution is used after computing the wave force amplitudes on the vessel's submerged elements. The analysis uses a Morison equation formulation to account for inertia, drag and dynamic pressure induced forces on the vessel. At the initial stages of vessel design, UCLRIG was used to examine various vessel configurations and dimensions for the required deck payload and acceptable wave induced motions. Most of the preliminary design of the vessel was performed with UCLRIG assuming a rigidised vessel. In this case, for low wave heights, the stabilisers were assumed to remain stationary and vertical for the purpose of calculating wave loads. The program package has been developed further to calculate the wave forces on and motions of the compliant stabilisers and to include the effect of these on the motion of the main body. This program uses time stepping techniques to compute the response of the rigid part of the vessel and the angular motions of all six stabilisers. The time step approach allows proper consideration of drag force nonlinearities as well as Stoke's fifth order wave theory and the use of linear theory for long crested irregular seas. A subset of the above program enabled the dynamics of an isolated stabiliser mounted on a rigid joint to be calculated.

An extended suite of programs is currently under development to provide estimates of the response and forces for the vessel. These are described in section 6.

The compliant semisubmersible design shown in Figure 1 was obtained after optimisation through use of the programs already developed. A heave natural period of 24 s, which is typical of conventional semisubmersibles, was achieved. Roll and pitch natural periods of 35 seconds were obtained. These values are high despite the high stability of the rig because of the large physical and added inertia associated with a structure of large span.

The response of the articulated columns to waves forms a key part of the vessel design particularly from the point of view of acceptable stabiliser excursions and dynamic loads on the stabiliser joints. Both these requirements can be met by designing the natural periods of the stabilisers to be well above the range of predominant wave periods. Fortunately, this requirement also fits in well with the philosophy of the design that the primary buoyancy of the vessel is supplied by the bottle legs; the low net positive buoyancy of the stabilisers yields a low angular stiffness and this coupled with high angular inertia leads to a natural period of 25 s. Hydrodynamically, the motions of the stabilisers are inertia dominated at wave frequencies, with damping forces being of lesser consequence. At larger wave heights, the stabiliser dynamics become increasingly nonlinear due to higher order wave effects coupled with a nonlinear stiffness which is a result of the emergence and submergence of the stabiliser in waves.

5 MODEL TEST DATA

The theoretical work described above has been confirmed by model tests. An optimised vessel design was used as a prototype for building a 1:100 scale model which was tested in a wave tank at the Department of Mechanical Engineering, University College London. The model was built to have both the correct submerged hull geometry and mass distribution.

The tank is 15m long, 2.2m wide with 1.0m water depth. It is equipped with an electro-hydraulic wedge type wave generator controlled by a computer to generate specified regular and random long crested seas. A dedicated large minicomputer provides rapid data logging and processing services to greatly increase productivity in testing.

Classical hydrostatic inclining tests were performed first on the 1:100 scale test model in still water with the stabilisers held rigid and then with the stabilisers allowed to articulate. No specific comparisons between theory and test results are presented here.

For the hydrodynamic response tests, the motions of the test model were measured by a system of five conductive plastic rotary potentiometers. These were mounted with pulleys driven by thin lines from the model and tensioned by small weights. Three overhead potentiometers provide heave, roll and pitch measurements while potentiometers upstream of the model and on one side of it provide surge and sway outputs respectively. A wave probe well upstream of the model senses wave profiles during the tests. The wave elevation and five data measuring channels were reduced and calibration constants inserted by standard computer programs designed for these tasks. Stabiliser dynamic behaviour and articulation angles were measured by a video camera system calibrated to yield high resolution stabiliser displacement and angle measurements from video recorded test sequences.

The model was moored in the tank using a catenary system with soft rubber lines to qualitatively model the scaled stiffness of a prototype catenary mooring system.

In order to identify the effects of stabiliser dynamics on overall motions, all the model tests were repeated with the stabilisers allowed to move freely (referred to here as the articulated vessel) and with the stabilisers held rigid by light braces (referred to as the rigid vessel. (Figures 3, 4 and 5 show representative examples of the model test data and corresponding UCLRIG calculations with Figures 3 and 4 showing heave and surge motion response for both 'articulated' and 'rigid' stabiliser modes. Note that the agreement between these two modes and the UCLRIG analysis is good for both heave and surge motions. The heave amplitude exhibits a peak at 15.5 s wave period of 0.20 times the wave amplitude - this is approximately half the response of conventional semisubmersibles in this wave period range. The reduction in vessel motion is due to the high hydrostatic stability contributed by the stabilisers which permits a higher draught and therefore, improved 'transparency' to waves. The compliant design has a draught of 50m compared with 20 to 25m for typical conventional designs.

Figure 5 presents curves of stabiliser angular amplitudes against wave period for three wave heights of 6m, 12m and 24m. The marked reduction in 'per unit' response at high wave heights can be clearly seen - particularly between the 12m and 24m wave height curves where a doubling of wave height leads to a considerably smaller magnitude of increase in stabiliser angles. From the design viewpoint, maximum stabiliser angular amplitudes of 24° for the very severe condition of 24m high regular waves remain acceptable.

6 DESIGN TOOLS

The compliant semisubmersible is the result of two years work by Cluff Copson Designs Ltd in association with a number of British organisations.

The hydrostatic and hydrodynamic design of the vessel is being carried out by a company called Interig using the procedures outlined briefly in this section.

Figure 6 is a schematic of the computer programs developed to date and indicates the information flow between the programs. The approach of using an interconnecting suite of small programs was chosen so that checking of the intermediate results could be easily performed. In a design process it is essential that consequences of every change of geometry of the proposed vessel are quickly identifiable. The programs have been written so that checks can be made by comparing the results of differing programs which have the same outputs but use different calculation methods. One importand feature of the system is the data generation program SEMFDAT which at run-time prompts the user for the essential structural dimensions and generates a common data file which is accessed by all the programs in the system. This is to ensure uniformity of data for all the separate analyses. A short description of the other programs in the system follows:-

HYSTAT

This program calculates the volume and weight distribution for a floating body consisting of an assemblage of cylindrical members. Ballasted volumes are represented by point masses. The initial metacentric heights and other naval architectural quantities are output together with the natural periods in heave, roll and pitch.

RIG 1 Performs the hydrostatics and eigenvalue analysis of the vessel and assembles the mass and damping matrices together with the hydrostatic stiffness.

RIG 2 Performs the dynamic response analysis of the vessel giving the amplitudes and phase angles of the induced wave forces and motion response in all six degrees of freedom involved.

RIG 3 Calculates the member wave loads by segmenting the submerged part of each member and calculates the wave forces in the three coordinate directions.

RIG1, RIG2 and RIG3 are based on the UCLRIG program described in reference 5.

STAB

Evaluates the wave induced motions of a single stabiliser. The analysis is performed in the time domain and uses Stoke fifth order wave theory. This is necessary in view of the highly nonlinear dynamic behaviour of the stabilisers which have relatively shallow draught and are very sensitive to wave elevation.

HYRIG

This program calculates the large angle hydrostatic properties of the vessel particularly the restoring moment. The articulations at the base of the stabilisers are taken into account in the analysis. The calculation method used is that described in reference 1.

HEEL

HEEL evaluates the wind heeling and righting moments at various angles of heel taking into account the articulations and deck immersion as well as the phenomena of stabiliser instability and immersion. The program also calculates restoring moments for the vessel in a number of damaged states. The program uses a method which represents the stabilisers by joint tensions applied as external forces. The movement of the centre of flotation due to the stabiliser articulations is taken into account in the analysis.

The major programs under development at the time of writing are:-

DSTAB

This program calculates the equilibrium position of the vessel in certain damaged states by searching for the position of minimum potential energy.

SBARTIC

This is an extension of the UCLRIG program which calculates the fully nonlinear response of a compliant semisubmersible. The reaction forces at the universal joints will also be calculated.

The results of the computer simulations described above will be confirmed by a series of large scale model tests in a major wave tank facility.

7 DISCUSSION

This paper has presented an overview of the technical development and performance advantages of a compliant semisubmersible for offshore production. The coverage of technical detail has, of necessity, been brief due to space limitations. However, the key principles of the design are considered further here.

The improved deck payload for a given displacement achievable with this type of design is directly due to the high hydrostatic stability resulting from the large distance of stabiliser water plane areas from the geometric centre of the vessel. This is further reinforced by the weight saving obtained due to the absence of structural connections from deck level to the outlying stabilisers.

The high hydrostatic stability has a further effect in that a large separation distance between the centre of buoyancy and metacentre allows the vessel to operate at deeper draught. The decay of wave particle velocities and accelerations with depth contributes largely to the low motion response to waves although global force cancellation effects on the large span of the compliant semisubmersible structure also contribute significantly to lower wave induced motions.

The compliant nature of the semisubmersible requires fundamental changes in both hydrostatic and hydrodynamic design methods for the vessel.

The conventional rigid body theory of hydrostatic analysis has been extended to apply for compliant floating structures. Large angle hydrostatic calculations of the compliant semisubmersible also require special methods to treat the articulated members. The tension variations with stabiliser submergence or emergence has both upper and lower limits dependent on stabiliser freeboard or self stability at very high and low stabiliser draughts respectively. Both these effects have to be accounted for in the large angle hydrostatic analysis.

Although, the primary payload and wave induced motions of the compliant semisubmersible design arise from its hydrostatic characteristics, satisfactory dynamic behaviour of the stabilisers must also be ensured. The concept of separating natural frequencies and predominant wave frequencies has been followed with a stabiliser natural period of 25 s. The high natural periods and the desirability of low amplitude of stabiliser joint forces requires a stabiliser design with low excess buoyancy leading to the consequence that the buoyancy and stability contributing members of the structure have been separated. In practice, this separation of function leads to greater flexibility in design optimisation.

The requirement that the stabiliser must never impact the main structure is easily met due to the highly nonlinear nature of stabiliser angular response with wave height.

8 CONCLUSIONS

The arguments to support the case for a compliant semisubmersible design with stabilisers on outriggers might best be summarised as follows:

1 The large distance of the stabiliser water plane areas from the vessel centre-line leads to large hydrostatic stability.

2 This available stability permits a vessel to be designed with high payload and deeper draught giving lower wave induced motions.

3 The absence of bracing from the deck to stabiliser tops releases potential structural weight for use as payload.

4 The presence of the articulations results in lower forces being transmitted to the main structure.

5 The separation of buoyancy, stability and deck support functions within the structure allows more effective optimisation for each of them.

This paper has presented a case study which illustrates the major performance gains to be obtained over conventional rigid floating structures by introducing compliancy in selected components. The compliant semisubmersible offers an opportunity to extend the long standing traditions and science of naval architecture into an exciting new area of development.

9 REFERENCES

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4 Brebbia C.A., & Walker S., "Dynamic Analysis of Offshore Structures," Newnes-Butterworths (1979).

5 Patel M.H., & Badi M.N.M., "A Calculation Method for the Wave Induced Motions of a Semisubmersible Vessel; Program Manual for UCLRIG," OEG/80/6 Department of Mechanical Engineering, University College London, Torrington Place, London WC1E 7JE, July 1980.

		Tonnes
A	Typical Deck Equipment Weights	
1	Well system including production riser, pipe racks and spares, moon-pool equipment, dry sack goods, dry bulk goods, mixed liquids.	2150
2	Process train including control room, separators, transfer pumps, metering, water clean up, flare systems, miscellaneous spares.	1835
3	Water injection	1000
4	Gas injection	600
5	Work-over package including derrick, riser, stack, control room, winches.	565
6	Power package including main and amergency generators, main switching, high voltage A.C., diesel day tank.	830
7	Accommodation/hotel services.	460
8	Ships services including office with telecommunications, helideck and accessories, life saving equipment, mooring winches.	3120
		10560
B	Deck Structure	3600
C	Operational Loads	
1	Hook load	400
2	Mooring vertical tension	500
3	Ice loads	500
		1400
D	Vessel Structure including ballast, hull equipment, stabiliser and joints.	28695
	Total Displacement	44255

TABLE I WEIGHT BREAKDOWN FOR A TYPICAL COMPLIANT SEMISUBMERSIBLE

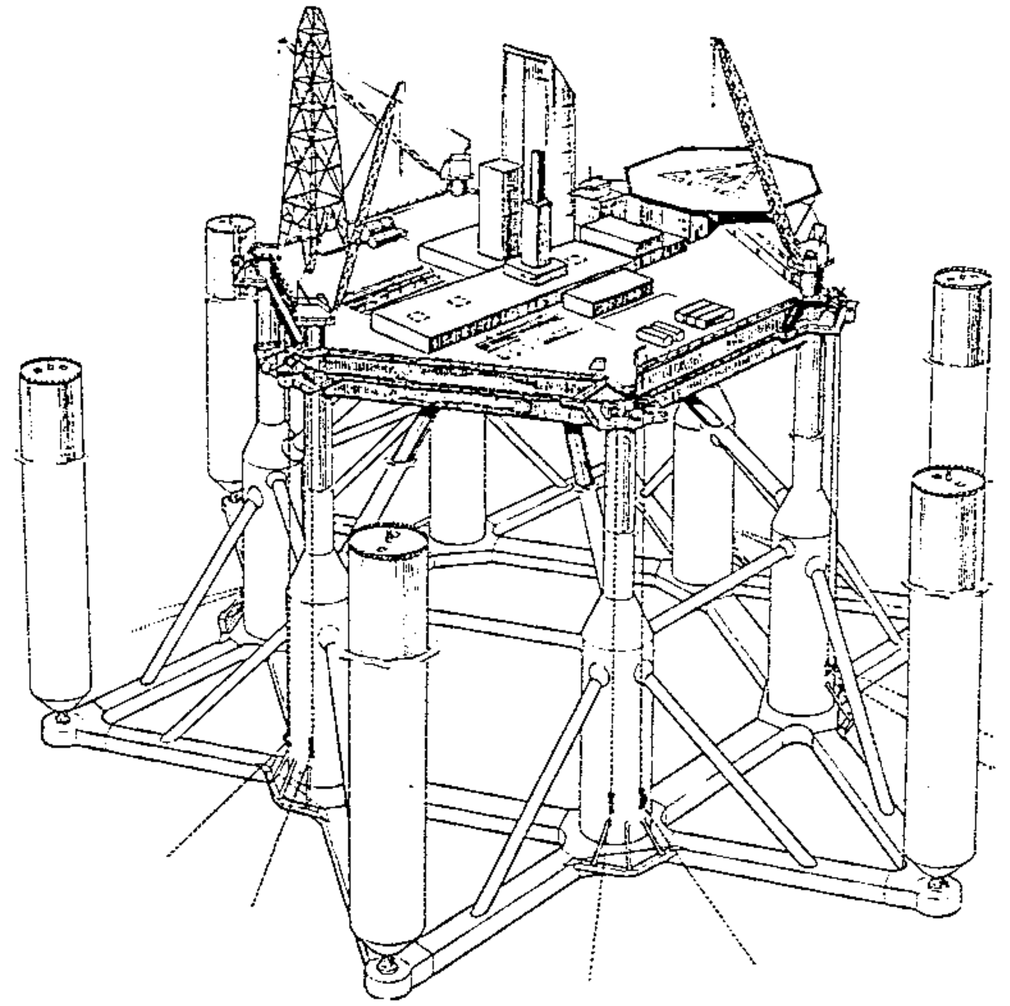

FIGURE 1 PERSPECTIVE VIEW OF A COMPLIANT SEMISUBMERSIBLE DESIGN

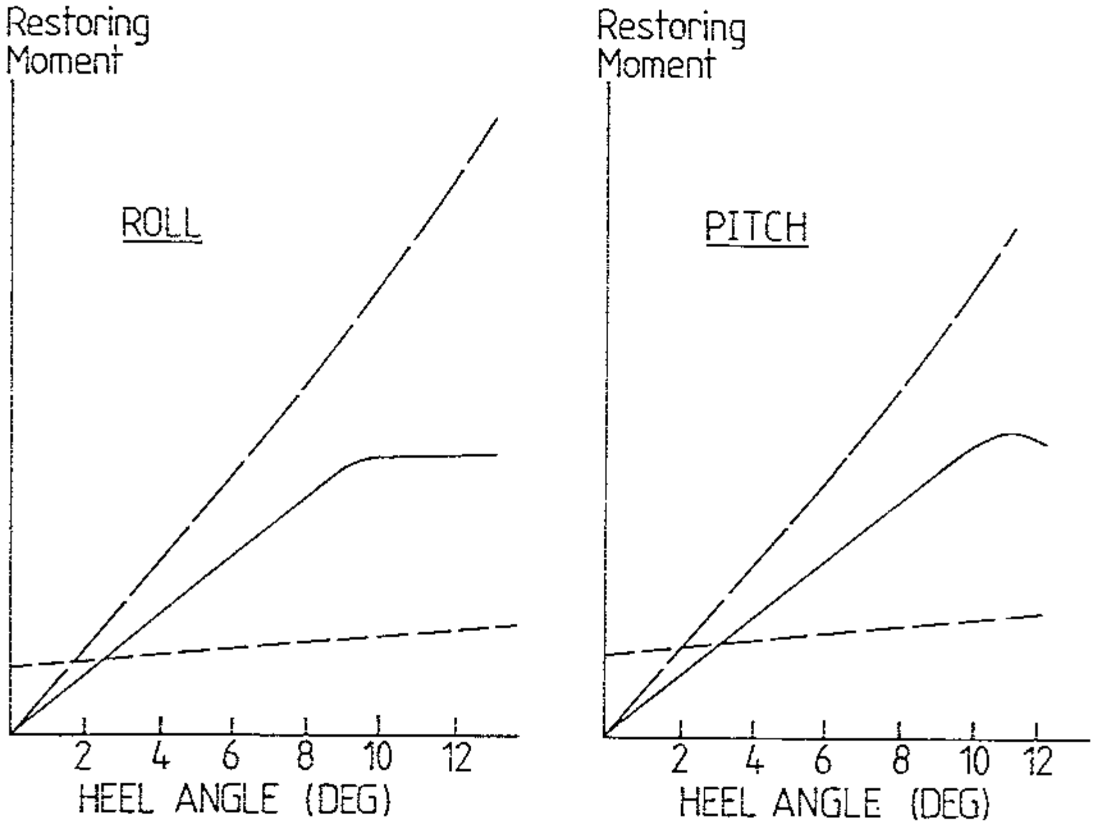

FIGURE 2 WIND HEELING AND RESTORING MOMENTS FOR RIGID AND ARTICULATED VESSELS. HYDROSTATIC RESTORING MOMENTS ARE DENOTED BY FULL LINE FOR ARTICULATED VESSEL AND LONG DASHED LINE FOR RIGID VESSEL. WIND HEELING MOMENT DENOTED BY SHORT DASHED LINE.

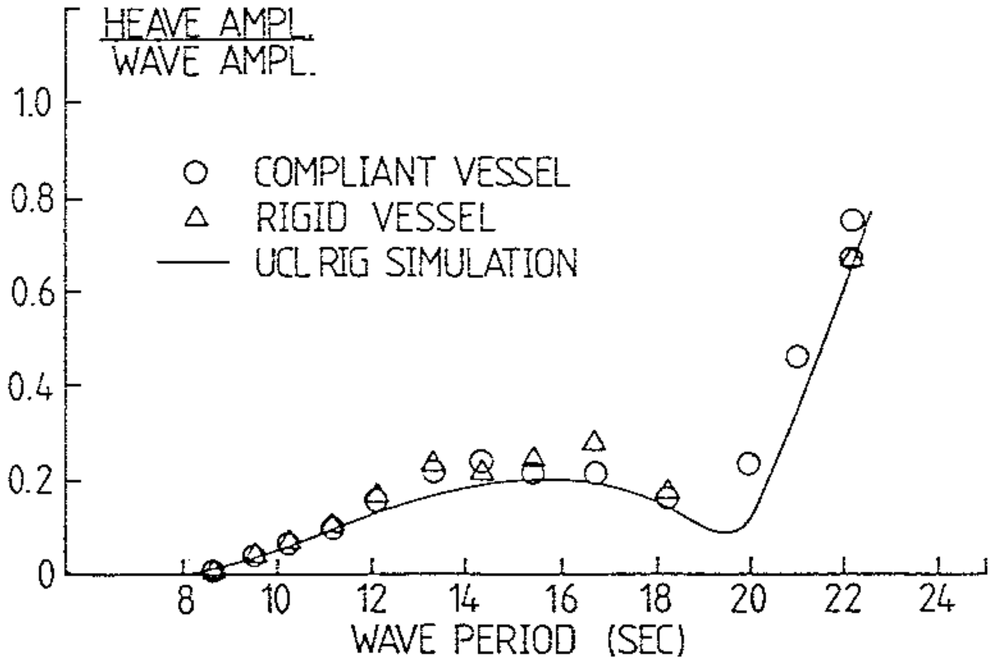

FIGURE 3 HEAVE TRANSFER FUNCTION (6 METRE WAVE HEIGHT)

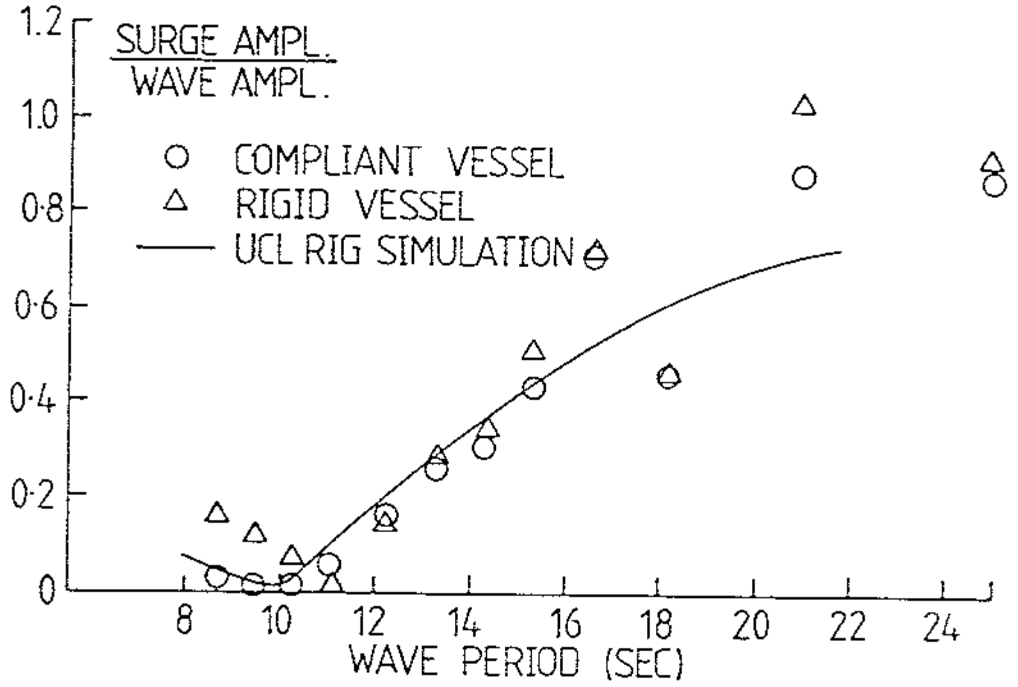

FIGURE 4 SURGE TRANSFER FUNCTION (6 METRE WAVE HEIGHT)

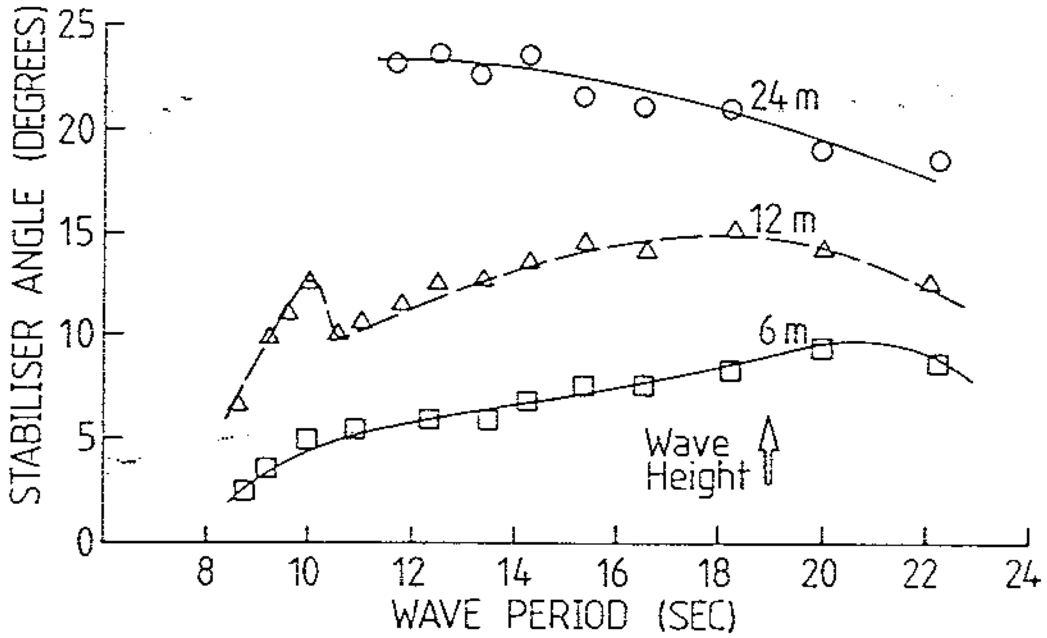

FIGURE 5 STABILISER OSCILLATIONS IN WAVES

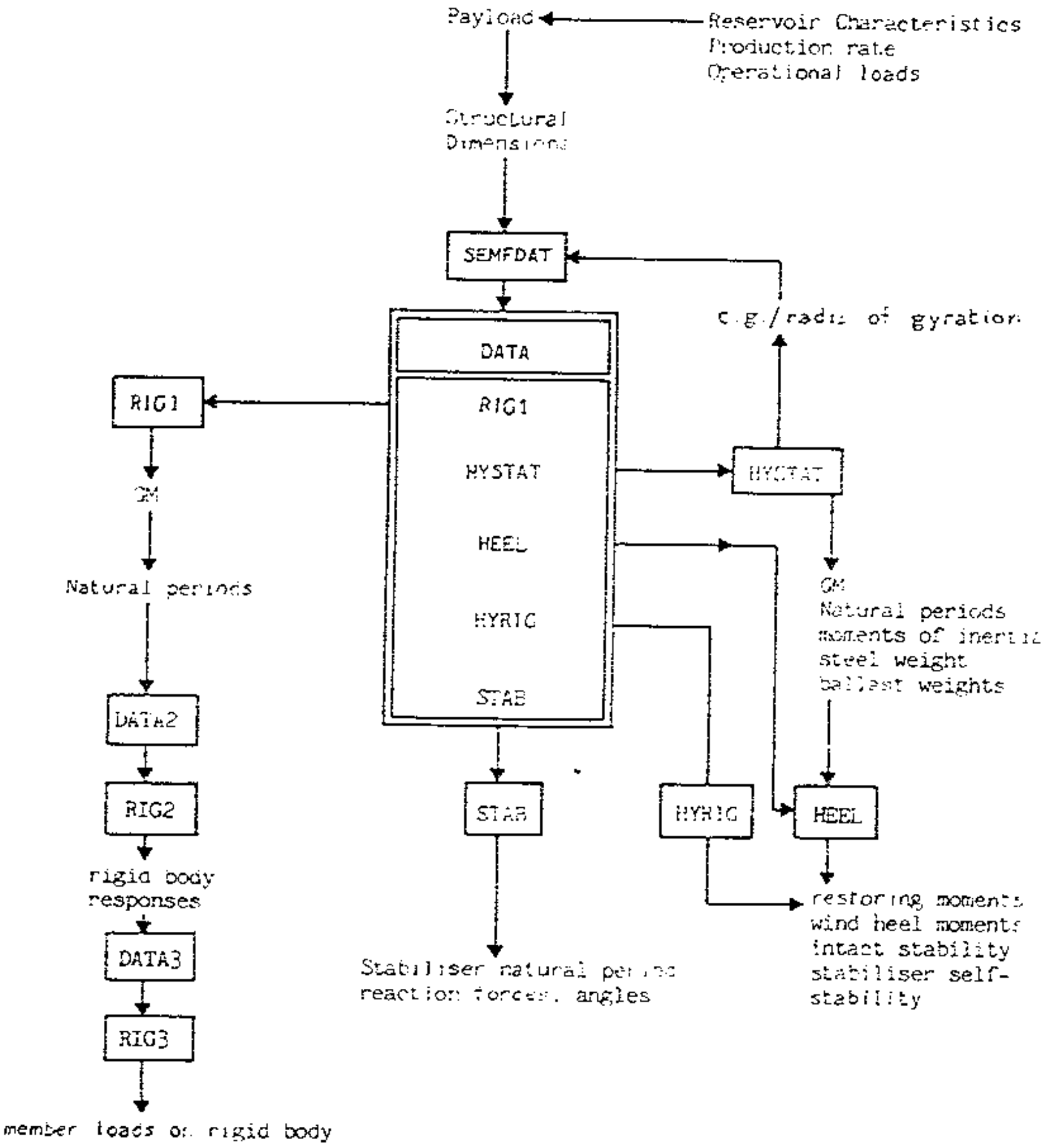

FIGURE 6 FLOWCHART OF DESIGN TOOLS