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EVALUATION OF PHYSICAL CHARACTERISTICS AND PHENOMENA;
SENSITIVITY AND INTERACTION EFFECTS; PERFORMANCE CRITERIA
AND OUTPUT REQUIREMENTS FOR A STATION KEEPING SUBSYSTEM
ENGINEERING EVALUATION TOOL (SKEET)

December 1979

Work Performed Under Contract No. EG-77-A-29-1078

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EVALUATION OF
-Physical Characteristics and Phenomena
-Sensitivity and Interaction Effects
-Performance Criteria and Output
Requirements
FOR A STATION KEEPING SUBSYSTEM
ENGINEERING EVALUATION TOOL (SKEET)

Submitted to
National Oceanic and Atmospheric Administration
Office of Research and Development

In fulfillment of the
requirements of Tasks III and IV
Contract No. NA-79-QA-C-00141

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I. INTRODUCTION

The fundamental purpose for SKEET is to provide a means of simulating and evaluating OTEC platform SKSS performance. This evaluation capability may be employed in the process of a design review, comparison of alternative concepts, operational planning, establishing risk and reliability criteria and a host of other applications. However, the central requirement is that SKEET have the capability to predict the excursions on motions of the platform and loads on the SKSS as a result of environmental effects under a range of operational conditions.

The principal elements which should be represented by the SKEET model include:

- environment (wind, current, waves)
- vessel/CWP configuration
- mooring system (including anchor/soil and electrical riser cable interactions)
- dynamic positioning system effects

The principal physical elements and forces which will affect the performance of the SKSS are shown in Figure 1. Each block represents an element for which certain descriptive information may be input to the mathematical model. The arrows represent physical processes (primarily forces and moments) which must be simulated by a suitable mathematical model. Corresponding to each of these processes are outputs, such as displacements or loads which will be predicted by the simulation. These outputs can then be interpreted in terms of various criteria to evaluate the performance of a particular SKSS.

This report summarizes the findings of the following two tasks that have been undertaken to formulate a definition of the requirements of SKEET:

- Task III - Identify and Classify the Physical Characteristics and Phenomena and Evaluate Interaction Effects
- Task IV - Establish Mooring Performance Criteria

The objective of Task III was to define the range of physical parameters that must be incorporated into SKEET and to make

ELEMENTS OF SKEET

FIG. 1. PRINCIPAL SYSTEM ELEMENTS AND FORCES

an assessment of the most appropriate manner in which to incorporate each of those parameters. The objective of Task IV was to define the required outputs from SKEET.

In approaching TASK III, all of the physical properties that could potentially affect SKSS performance were identified. The sensitivity and relative importance of each parameter was then assessed, as a basis for evaluating its inclusion in the SKEET. Interaction effects were also evaluated, as a basis for recommending coupled vs. uncoupled, linear vs. nonlinear and time vs. frequency domain modeling, and other simplifying assumptions in the recommended model formulation.

Task IV entailed an assessment of each of the performance characteristics that are significant in evaluating mooring systems. The most meaningful measures of these performance characteristics were then identified as a basis for specifying the required outputs of SKEET, for direct interpretation and as input for post processing.

II. PHYSICAL CHARACTERISTICS AND PHENOMENA

The physical elements and processes affecting SKSS performance are shown schematically in Figure 1. Each of the elements can be described in terms of several physical characteristics or parameters, the extent and level of detail of each being dependent on the physical processes that are being considered. These physical processes are the forces and moments that results from the interaction of two or more elements. They may be represented by transfer functions or similar relationships.

The remainder of this section is devoted to a series of tables describing the physical properties of each element to be included in the SKEET, as well as each of the physical processes to be modeled. Table number references are cited for the appropriate items on Figure 1. The physical properties are covered in Tables 1-9 with the associated processes appearing in Tables 10-18.

Associated with each table is a list of references citing relevant background material pertaining to each topic. This reference list appears in Appendix B of the Task II Final Report, "Assessment of State of the Art Technology Related to SKEET". It is arranged, for the most part, to correspond with the tables contained in this report. For additional detail on selected papers, refer to the Appendix C of the Task II Final Report.

More detailed discussions of the sensitivity and interaction effects related to each area are given in subsequent sections of this report, along with a description of evaluation criteria and recommended outputs.

TABLE 1

Vessel / CWP - Physical Properties

- 1) Superstructure/areas exposed to wind
 - a. Projected area
 - b. Shape
 - c. Moment arm
- 2) Hull and CWP/areas exposed to current and waves
 - a. Principal dimensions
 - b. Geometry and shape of stressed or unstressed CWP
- 3) Weight and Mass Distribution
 - a. Center of gravity (vert., lat., long.)
 - b. Radius of gyration (pitch, roll, yaw)
 - c. Total displacement (weight)
- 4) Appendages
 - a. Control surfaces
 - b. Propeller or thruster
 - c. Bilge keels
- 5) Motion Stabilizing Systems
 - a. Active
 - b. Passive

TABLE 2
Wind - Physical Properties

- 1) Mean wind speed at reference elevation
- 2) Mean wind direction
- 3) Vertical velocity profile

The following probabilistic measures of speed and direction are useful in selecting appropriate values.

- 1) Exceedance
- 2) Persistence

The following unsteady effects can generally be neglected in a basic SKEET but could be included

- 1) Gusts
- 2) Oscillations about the mean

The wind is assumed planar.

TABLE 3
Waves - Physical Properties

- 1) Height
 - a. Probability (exceedance)
 - b. Duration (persistence)
 - c. Extreme values (for given return period)
- 2) Spectral Characteristics
 - a. Spectral ordinates
 - spectral family
 - mean/covariance spectra
 - b. Characteristic periods
- 3) Directionality
 - a. Probability
 - b. Short crestedness/spreading
 - c. Directional spectra

TABLE 4
Current - Physical Properties

- 1) Mean surface current speed
- 2) Mean surface current direction
- 3) Subsurface current speed profile
- 4) Subsurface current direction profile

The following probabilistic measures of speed and direction may be useful in selecting appropriate values.

- 1) Exceedance
- 2) Persistence

Unsteady speed has been neglected for the basic SKEET, but provision for non-planar current profile is recommended. Use of a time domain solution would permit investigation of unsteady speed effects in an enhanced SKEET.

TABLE 5

Mooring Line - Physical Properties

1) Generic Type

a. Single Point Mooring (SPM)

1. SALM
2. CALM
3. Simple catenary

b. Spread Mooring

1. Symmetric
2. Asymmetric

c. Tension Leg

2) Dimensions

a. Length

b. Depth at Anchor

c. Anchor Location

d. Attachment Point on Vessel (fixed, variable)

3) Materials

a. Type

1. Chain
2. Synthetic
3. Wire
4. HCL
5. Deadweight
6. Floats

b. Characteristics

1. Elasticity
2. Yield strength
3. Ultimate strength
4. Weight in air
5. Weight in water
6. Drag coefficient

c. Long Term Behavior

1. Corrosion
2. Fatigue
3. Fishbite
4. Fouling properties

The basis SKEET should be able to model a variety of mooring configurations including simple, compound and complex mooring types.

Note: Definitions of the mooring types may be found in the glossary contained in Appendix C of Final Report.

TABLE 6
Anchor - Physical Properties

- 1) Gravity
 - a. Weight in Air and Water
 - b. Size
- 2) Drag Imbedment
 - a. Weight in Air and Water
 - b. Size
 - c. "Effectiveness" Factor
- 3) Pile
 - a. Diameter
 - b. Penetration

In general, it is assumed that anchor force is unlimited, and the maximum anchor load serves as a basis for anchor sizing and selection. However, to evaluate anchor drag transients, holding power for the appropriate anchor type would be required.

TABLE 7
Bottom - Physical Properties

- 1) Contour
 - a. Depth
 - b. Slope
- 2) Composition
 - a. Lateral Bearing Strength
 - b. Vertical Bearing Strength
 - c. Friction (coefficient)
 - d. Surface Cohesion

Depth and bottom slope affect mooring line response and required holding power. If anchor drag is to be modeled, the affect of soil composition on anchor holding power must be assessed in a subsidiary analysis.

TABLE 8
ELECTRICAL RISER CABLE - Physical Properties

- 1) Configuration
 - a. Simple catenary
 - b. Catenary with buoyancy elements
- 2) Dimensions
 - a. Length
 - b. Depth
 - c. Bottom termination location
 - d. Attachment point on vessel
- 3) Characteristics (of cable and/or buoyancy elements)
 - a. Elasticity
 - b. Strength
 - c. Weight in air
 - d. Weight in water
 - e. Drag coefficient

Multiple risers would be modelled individually to determine loads, bend radii and deflections, and assess the need for a bend limiter.

TABLE 9
DYNAMIC POSITIONING - Physical Properties

- 1) Propulsion System
 - a. Thrust characteristics
 - b. Moment characteristics
- 2) Control System
 - a. Position sensing system
 - b. Control logic

In a basic SKEET, implified force and moment equations and an elementary control law will be employed to determine steady state thruster effects. An enhanced SKEET could use a more complex treatment such as found in control system analysis.

TABLE 10
Wind on Vessel

Static Wind Forces and Moments

- Transfer Function - Determine from characteristic area and associated drag coefficients
- Output
 - Lateral and longitudinal components of force and yaw moments of primary importance to SKSS.
 - Heel and trim moments may be significant for some platforms.
 - Lift force generally negligible.

Unsteady Wind Effects

- Gusts and unsteadiness of wind speed not likely to excite system resonance
- Magnitudes are small compared to other forces
- Quasi-static modeling

TABLE 11
Waves on Vessel / CWP

- 1) High Frequency Effects (6 DOF, regular waves)
 - a. Frequency Dependent Hydrodynamic Coefficients
 1. Damping
 2. Added mass
 - b. Wave Pressure Forces and Moments
 - c. Vessel/CWP Dynamic Response
- 2) Slowly Varying
 - a. Mean Drift Force
 - b. Time Varying Drift Force

The primary dynamic excitation of the SKSS is due to vessel/CWP high frequency motion.

High frequency response of a linear system in the frequency domain is obtained by superposition with a wave energy spectra.

Nonlinearities may be handled by equivalent linearization techniques in the frequency domain, or by direct integration in the time domain.

Hydrodynamic coefficients may be determined or verified through model testing.

Outputs for irregular wave excitation

- High frequency forces/motions
 - root-mean-square or significant amplitude
 - maximum (within a stated return period)
 - average number of cycles per unit time
- Slow varying
 - mean wave drift force/motion (frequency domain)
 - time history of drift force/motion (time domain)

TABLE 12
CURRENT ON VESSEL/CWP

- Static Current Forces and Moments
 - Transfer Function
 - determine from characteristic area and associated drag coefficients
 - Output
 - forces and moments in 6 DOF
- Unsteady Current Effects
 - unsteadiness occurs at periods longer than the resonant period, and will not excite system resonance
 - vortex shedding is likely to occur on CWP and cause a quasi-static increase in drag

TABLE 13.
WAVES ON MOORING LINE

High Frequency Pressure Forces

- Normal
- Tangential

Outputs

- Cable loads

Slow Varying Effects

- Wave drift forces acting on cables are neglected since depth attenuation will reduce this effect below several hundred feet

TABLE 14
CURRENT ON MOORING LINE

Static Current Forces

-Transfer Function

normal and tangential drag
coefficients associated with
characteristic area

-Output

three components of force
at each section or node on
mooring line

Unsteady Current Effects

-Forces due to unsteady current
speed are neglected

-Vortex shedding is likely to
occur on mooring line leading
to a modified C_D

TABLE 15
VESSEL ON MOORING LINE

1) Static

Transfer Function (spring constraint)

1. Force due to lateral translation of vessel mooring attachment point
2. Force due to vertical translation of vessel mooring attachment point
3. Force due to longitudinal translation of vessel mooring attachment point

2) Dynamic

Transfer Function

1. Inertial effects
2. Damping and added mass of mooring line due to vessel induced motion

Vessel motion is the principal source of dynamic excitation of the mooring line system.

TABLE 16
Mooring Line on Vessel

1) Static

Transfer Function

1. Vertical force due to mooring line tension
2. Lateral force due to mooring line tension
3. Longitudinal force due to mooring line tension

2) Dynamic

Mooring force components supplement exciting forces in vessel equations of motion

- primary significance is in horizontal plane motions (sway, yaw, surge)
- secondary effect on other motions (pitch, roll, heave) except for tension anchor leg

TABLE 17
Mooring Line on Anchor
and
Anchor on Soil

Basic Mode - Anchor Fixed

Maximum vertical and horizontal loads will
determine required holding power

Alternate Mode - Anchor Drag Possible

Relaxation of anchor position constraint permitted
if allowable load exceeded.
New position determined, or progressive failure
results.

TABLE 18
Dynamic Positioning System on Vessel

Static Forces

- a. Net lateral force
- b. Net longitudinal force
- c. Net moment

Dynamic Excitation

Neglected - assumed quasi-steady. A more complex
treatment may be provided using control system
analysis.

III. SENSITIVITY AND INTERACTION EFFECTS

In order to establish the requirements for the SKEET analytical model, it is necessary to ascertain the relative importance of each of the contributing factors, and to estimate the sensitivity of the results to any simplifying assumptions and restrictions that may be imposed. It will then be possible to identify the degree of complexity and sophistication required to achieve a tool that is suitable for engineering purposes, without incurring unnecessary penalties in development or implementation cost or complexity.

In the same vein, possible interaction effects must be evaluated to ascertain if certain phenomena can be analyzed separately or if results are materially effected by other processes. This influences the degree of coupling that is necessary, for example, between wave and current effects, or vessel and mooring line motions. Interactive influences impact on the degree of modularity that can be achieved to provide a greater degree of versatility or tailoring to a specific requirement.

These factors are discussed and summarized in the remainder of this section, under the following categories:

- Environmental Modeling
- Quasi-Steady Factors
- Wave Drift Forces
- Vessel/CWP Dynamics
- Mooring Line Responses

Environmental Modeling

The principal environmental factors are wind, current and waves. The first two may be expected to have both steady and unsteady components, while the latter is entirely a dynamic phenomena with certain quasi-static characteristics. The following discussion concerns itself primarily with the manner in which the environment is represented; consideration of the resulting loads, forces and motions is given in the later section.

Wind Velocity - The wind velocity is described in terms of speed and direction, either of which may vary temporally and spatially. The platform is small enough (on the order of several hundred feet) that spatial variations need be considered only in the vertical direction, as approximated by various assumed vertical wind profiles. Furthermore, for most conceivable platform sizes, even the vertical variation in wind speed should be only a few percent. Therefore it should be adequate to consider the wind to be spatially uniform both laterally and vertically over the vessel's exposed surface.

Temporal variations in wind velocity, or unsteady wind, are generally manifested as gustiness, or as a long period oscillations in mean wind speed. Reference is made to Table 19 from Bretschneider and St. Denis (1969), which illustrates that the strongest gust will usually be of relatively short duration, and so, the most severe gusts will be essentially a form of impulse loading to which the OTEC platform should not respond significantly due to its large inertia. This implies that, in treating wind gust effects, it would be sufficient to assume a constant wind speed and adjust the average wind speed to allow for the effects of extended gusts. Long term variation in wind speed, on the other hand, could be modeled simply as a change in the static conditions; i.e., the time period of such oscillations is generally far beyond any system resonant period, and would not likely result in any dynamic response.

Current Velocity - The basic components of any current are a geostrophic or ocean current, a tidal current, and a wind current, and so, the magnitude and direction of each component may be considered in arriving at an assessment of the whole. Since these current components originate from unrelated causes, and each vary differently with depth, it would be reasonable to expect that a significant net current variation with depth may result. Specifically, in the northern

TABLE 19

Probable Values of the Maximum-Gust Factors
Averaged Over Short Periods of Time, t,
When Mean Hourly Wind Speed has Various Values*

Mean hourly wind speed (knots)	Period t ₁ sec						1/2
	600	60	30	20	10	5	
20	1.10	1.25	1.30	1.35	1.40	1.50	
30	1.10	1.23	1.33	1.37	1.43	1.47	
40	1.10	1.25	1.32	1.35	1.42	1.48	(1.63)
50	1.08	1.24	1.32	1.36	1.42	1.48	(1.64)
60	1.08	1.23	1.31	1.35	1.42	1.48	(1.60)
70	1.08	1.24	1.31	1.35	1.42	1.49	(1.59)
80	1.09	1.24	1.33	1.36	1.43	1.48	
Average	1.09	1.24	1.32	1.36	1.42	1.48	(1.61)
G/U (10 min)	1.00	1.15	1.21	1.25	1.30	1.36	1.48
G/U (1 min)	--	1.00	1.07	1.10	1.15	1.19	1.30

G = gust speed

U = mean speed

*Values calculated from data presented in
Extreme Wind Gusts in Australia, Common-
wealth Australia, Bur, Meteorol, Bull.
46, 1964.

hemisphere, Coriolis force causes the direction of the wind driven current to veer the wind direction by 45° at the surface and to continue to veer with increasing depth so that the net flow will be at a 90° angle to the wind. It may be noted that field ice is often observed to drift at a $25-35^{\circ}$ angle to the wind direction (Van Dorn, 1974). Since the current profile is nonplanar and at an angle to the wind, the common assumption that the mean wind, current and wave forces are all in the same direction is not correct and could be a very poor assumption in view of the relative magnitudes of these forces. These magnitudes are discussed in a later section.

Although it is not necessarily the case at the Punta Tuna site, it is certainly likely in other deployment sites that strong currents may persist to considerable depth, with variations in direction including reversals. It is therefore important that SKEET have the capability to model currents whose speed and direction varies with depth. Temporal variations, on the other hand, as in the case of wind, have quite long periods and can generally be treated as quasi-steady.

Waves - The basic requirement for describing the wave input to a simulation is to specify the direction of the wave system relative to the platform, and to define the magnitude and distribution of the wave energy. The relative direction of the wave system is generally defined in terms of the vessel's heading with respect to the predominant wave direction, with some sort of spreading specified to account for short crestedness of the waves. The wave energy is most frequently described in terms of two key parameters; wave height and period. A more comprehensive description is obtained through the use of a wave spectra, based on mathematical formulation, measurement or hindcast.

The use of wave parameters such as height and period to describe the wave system is convenient because the nomenclature is widely recognized. However, to characterize a random sea (irregular waves) for the purposes of dynamic re-

sponse assessment it is necessary to utilize a representation of the wave energy spectra. If the only available data are wave parameters such as height and period, the wave spectra are most conveniently developed from a mathematical formulation which can be incorporated directly in the program. Alternatively, if measured or hindcast spectra are available, the ordinates of the spectral density function can be specified at several discrete frequencies to describe the shape of the distribution.

Given that the ordinates of the spectra can be defined, either mathematically or as input, the question to be resolved is: What are the potential differences that result from the two approaches? Hoffman, et al (1977) has shown significant variations, as high as 50%, in response predictions using measured compared to mathematical spectral formulations. However, it is noted that from the standpoint of the capability of the simulation, it is sufficient to require that the wave energy be defined in terms of spectral ordinates; specification of data sources is beyond the scope of this task and is subject to further investigation.

Regarding the requirements for directionality of the wave system, the use of a spreading function, such as cosine-square, to represent short crestedness is a commonly accepted technique. Because the maximum values of the various horizontal plane motions (yaw, surge and sway) occur at different headings, it is necessary to consider the effects of short crestedness, since it cannot be determined, a priori, what the most severe heading condition will be, especially in the presence of non-coplanar wind and current.

The alternative to a mathematical spreading function is the use of full directional spectra. This is a more realistic approach, since it allows a separate directionality and spreading to be associated with each of several concurrent wave systems. From the standpoint of modeling capability, however, there is no more involved in handling directional spectra than in applying a spreading function to point

spectra, as a means of accounting for short crestedness.

In addition to describing wave energy and directionality, it is also necessary to specify certain statistical parameters related to wave climatology. Among these are wave exceedance, persistence and extreme values. These are most often the result of a preliminary assessment of the wave characteristics, and are generally a wave height and period associated with a given return period. Thus, this imposes no additional demands on the model, since this capability has already been established as a requirement. It is noted, however, that the use of an extreme wave height does not ensure that the extreme wave load will result.

Estimates of extreme responses to a random variation such as waves can only be achieved statistically, through the application of wave exceedance data. Similarly, operability analysis based on extreme or peak responses must be based on wave persistence data. Both of these analyses, however, would normally be obtained through post processing based on the outputs from the basic simulation model.

Quasi-Steady Factors

These are processes or effects which will influence the steady state or static equilibrium condition. They include:

- Wind Loads on Vessel/CWP

- Current Loads on Mooring and Vessel/CWP

- Mean Wave Drift Force

- Bottom Contour Effects

(It is noted that the mean wave drift forces, which is mentioned below in the context of its significance relative to other factors, is discussed more fully in the following section.)

One source of information on the various environmental loads is the preliminary design work of Lockheed (1979) on the mooring system. Table 20, taken from the Lockheed report, gives their estimates of wind, current and wave drift forces

that would be experienced by the vessel/CWP during storms with return periods of three and 100 years. While the values shown are obtained largely from empirical data representative of the one condition shown (head seas), they serve to indicate the relative severity of the various load components. The wave and current forces may be of generally comparable magnitude, while the wind loads account for only about 5 to 15% of the total platform loading.

Wind Loads - The wind can conceivably produce forces and moments on the platform in six degrees of freedom. The lift force, however, will be very small, and furthermore will have virtually no effect on SKSS performance, and can therefore be neglected. Similarly, heeling and trimming moments will similarly have only a limited effect on SKSS performance, but should be included because of their potential effect on the overall operability of the OTEC platform, i.e., limits on total angular displacement from the vertical.

The steady lateral and longitudinal forces and yaw moment are the predominant effects of the wind on SKSS loading. It is noted that the values shown in Table 20 do not include an allowance for wind gusts. While gusts can result in increases in the wind loading on the platform by as much as 100%, these loads are not generally transferred to the SKSS. Wind loads are transmitted to the SKSS solely by virtue of movement of the platform. However, the inertia and damping effects are large, and the gust duration is short, therefore the resulting additional displacement due to gusts will be small, and correspondingly so will be the additional loading on the SKSS. The effect of gustiness can probably be adequately included by a suitable increase in the effective mean wind speed over several gust cycles. Because of the relatively small contribution of the wind loading, even if such an approximation is as much as 50% in error, the net result on total SKSS loading will be less than 10%.

TABLE 20
Summary of Loads - Barge

Coplanar wind, wave and current
Barge - Head Seas

Return Period (Years)	3 ⁽¹⁾	100 ⁽²⁾
Significant wave		
- Height (ft)	18.9	35.1
- Modal wave period (sec)	10.0	13.0
- Wind (kts)	29.5	79.1
- Surface current (kts)	1.7	2.4
Force (lb)		
- Wind	20,315	146,075
- Current	188,839	348,277
- Wave	110,274	422,194
TOTAL	319,428	916,546

(1) Operational condition

(2) Survival condition

From Lockheed Report on Preliminary Design
of SKSS.

Current Loads - Another source of estimated current loads is Hove, et al (1978), who consider loads on the cold water pipe under extreme current conditions. Their estimates of the maximum current forces that the OTEC plant will experience are substantially higher than those of Lockheed. Since there are some logical gaps in Lockheed's description of how they arrived at their numbers, it is difficult to assess their correctness, however, there do appear to be several reasons why Hove, et al developed higher estimates. The key is recognition of the effects of vortex shedding which characterizes flow around bluff bodies in the transcritical Reynold's number region whose value is a function of the CWP diameter and the current velocity. One effect is the introduction of a sinusoidal lift force which is perpendicular to the current flow and the CWP axis. Another possible effect is lock-in. This is a resonance phenomenon which occurs over an unusually broad band of frequencies (within 20-30% of the natural frequency) due to nonlinearities in the CWP/fluid system. It increases the virtual drag by a factor of 1.5 to 2.3 (Skop, et al, 1977) and also increases the lift amplitude.

Hove, et al assumed fully correlated vortex shedding which may be viewed as a conservative assumption, but it is consistent with recent experiments (Vandiver and Mazel, 1976). They also assumed a planar current profile with a surface velocity of 6.0 ft/sec which is somewhat higher than the 4.76 ft/sec used by Lockheed. It is possible to adjust their numbers to the lower current velocity by scaling with $(\frac{4.76}{6.0})^2$, and the following table results:

	<u>No lock-in</u>	<u>Lock-in</u>
Drag force	.82 x 10 ⁶ lb.	1.37 x 10 ⁶ lb.
Lift force amplitude	.43 x 10 ⁶ lb.	.94 x 10 ⁶ lb.

The lift force will have a period on the order of 33 to 45 seconds.

The diameter of the mooring lines are such that they will, in all probability, experience subcritical Reynold's number

characterized by vortex shedding. If the very rough approximation is made that

$$\frac{\text{forces on mooring line}}{\text{forces on CWP}} = \frac{\text{mooring line diameter}}{\text{CWP diameter}}$$

then an assessment of the total force on the mooring line can be made. Whether or not current forces on the mooring lines may be neglected, as they often have been, will depend partially on size and number of lines. One mooring system design currently being considered calls for 16 lines of 7 inch diameter. Though each line represents less than 2% of the projected area of the CWP, the sixteen lines as a whole will have a load which is about 30% that of the CWP. It is recognized, however, that the platform will contribute a significant share of the current loading, particularly since it is exposed to the generally higher surface currents. However, for some configurations, the current load on the mooring line may still account for as much as a quarter of the total current loading.

One other aspect of current loading is related to the planarity of the current profile. While it is clear that the total applied forces will be greatest for a vertically planar current, the resulting line catenary will be influenced by the horizontal directionality of the subsurface current profile. It is therefore possible that line loads, at some point in the cable and scope requirements, will be greater for a non-planar current than for a planar current. This is particularly true in the case of non-coplanar wind and wave loads. An investigation of the effects on non-planar current profiles on the equilibrium configuration of moored cable systems is presented by Wang (1978).

Since the modeling of 3-D non coplanar currents is within the SOA, it is recommended that this capability be regarded as a desirable feature; because the development effort to incorporate it is not great. However, program execution costs will be higher because of this capability.

It may, therefore, be desirable to add it as an option that can be exercised for analysis of specific circumstances, rather than as a general capability.

Bottom Contour Effects - The bottom contour may be adequately described in terms of the depth and slope at each anchor location. Differences in water depth at each anchor have a significant effect on mooring line loads, as illustrated by Stanton et al (1970). Assuming no bottom slope, the tension resulting from an offset of 8% water depth increased by 125% when the depth is reduced by 35%. This reduction in depth is equivalent to the variation in depth corresponding to a 5° slope for a typical spread moor.

The same investigation showed that for a bottom slope of 5° or less the differences in line tension between the shallow side and the deep side would be less than 10%. However, for a slope of 10° , the differences were nearly 20%. Therefore, it was concluded that bottom slope should be considered in the analysis for any site with a slope of 5° or more.

In addition to consideration of the effects of overall slope, and its influence on the length of suspended cable and resulting tensions, local variations in slope will effect anchor holding power. It is therefore important to include the capability to arbitrarily specify both water depth and bottom slope at each anchor position.

Wave Drift Forces

Wave drift forces are comprised of two components; mean and slowly varying. A structure in regular waves is acted upon by a constant horizontal force, i.e., the mean wave drift force. In irregular waves, the drift force is no longer constant, but is a time varying phenomena.

The magnitude of the wave drift force has a significant influence on OTEC SKSS design, because of the requirement that the vessel remain on station during the most severe weather conditions. As shown previously in Table 20 the mean wave drift force in the extreme wave environment may account for about one-half of the total loading on the SKSS. In addition, if the periodicity of the slowly varying drift force

is close to a natural period of one of the vessel's six degrees of motion, significant amplification may occur because the system is lightly damped.

Several methods and approaches have been developed for estimating the wave drift forces. The more commonly used formulation is referred to as the "far field theory", based largely on extensions of the original work done by Maruo (1960). A more recent approach has been developed by Kim and Breslin (1974), based on "near field theory". A more extensive description of these and other methods is given in the SOA Assessment and by Loken and Olsen (1979). Either of the theoretical approaches can be applied to predict both the mean and slowly varying drift force components.

It is noted that, in the work done by Kim and Breslin (1974) and Loken and Olsen (1979) that good agreement between the various methods and with model tests is demonstrated for the prediction of mean wave drift force in beam seas for a ship or barge shape. Good agreement with measurements has been demonstrated by Molin (1979) for ship and box shape hulls, both longitudinally and transversely at headings of 0° , 45° and 90° using finite element techniques.

Experience with and validation of the computation of slow varying drift force is much more limited. Hsu and Blenham (1970) and Newman (1974) have developed methods for approximating the time varying drift forces based on discrete time interval regular wave components. Others have employed more rigorous solution techniques. However, there is not a general agreement between the various methods, as there is in the case of the mean wave drift force, although Loken and Olsen (1979) show good correlation with Newman's results.

As a basis for assessing the requirement for SKEET, consideration must be given to the effect of the drift force on the mooring loads. It has been established that the mean drift force produces a significant effect. The slow varying force, on the other hand, may produce large variations in drift force, but because their magnitude varies, they may

not be fully imparted to the mooring system. Figure 2, taken from Loken and Olsen (1979), shows the variation over time in wave drift force, along with the resulting variations in line tension.

It therefore seems reasonable to assert that the exact nature of the time varying force may not be of critical importance to the SKSS design criteria. A simple, computationally efficient approximation based on the mean wave drift force may be adequate for most purposes. Note, however, from Figure 2 that if the horizontal excursion is critical the time varying drift force component must be accurately modeled.

The wave drift force acts predominantly on the hull of the OTEC platform. In addition, there is a small component of drift force acting on the upper portion of the mooring line and CWP. However, this force alternates exponentially, and is insignificant below 300-400 feet. Depending on platform configuration, the area and hence the drift force component resulting from the CWP and mooring line is generally small and probably accounts for no more than 5-10% of the total force on the mooring.

The wave drift force is influenced by the frequency distribution of the energy in a seaway. Therefore, wave grouping may tend to produce strong excitation of the mooring system. Wave groups result from the fact that the speed at which a wave propagates is related to its frequency. Therefore waves of the same frequency tend to cluster together, producing a concentration of energy in a limited frequency band. If this frequency band corresponds to a natural frequency of the platform, then large drift forces and mooring tensions may result. The response of the system under these circumstances will be determined by viscous damping. It is therefore important to have a satisfactory means of representing viscous damping effects, so that unrealistic mooring tension predictions can be avoided.

Figure 2. Simulated slowly varying motions and line tension-linear mooring system restoring force.

Figure 3. Simulated slowly varying motions and line tension-non-linear mooring system restoring force.

There is also the possibility of an interaction between the current and the wave drift force. This effect is analogous to the effect of forward speed on added resistance in waves. However, at the normal current speeds (< 2 knots) it is unlikely that this effect would be significant, particularly in light of other areas of uncertainty related to drift force prediction. The interaction can therefore probably be ignored, unless and until model testing or more refined analysis should indicate otherwise.

Vessel/CWP Dynamics

The wave induced high frequency oscillation of the vessel/CWP represents the principal dynamic excitation of the QTEC SKSS. Furthermore, the first order vessel motion has a direct bearing on the second order wave drift force, which is one of the principal quasi-steady load sources. Therefore, modeling of the vessel/CWP dynamics in 6 degrees of freedom is highly critical to SKSS performance evaluation.

Modeling of the coupled vessel/CWP motions have been achieved by both Paulling (1979) and Barr, et al (1978) in the frequency domain, using an equivalent linearization technique to represent the coupling effects. Acceptable agreement with scale model tests suggests that this approach is suitable. A more comprehensive non-linear process would require considerable development effort, as well as consume inordinate computational resources in comparison to the marginal improvement in accuracy which could not be justified.

The method of modeling the coupling between the vessel and CWP should permit five degrees of freedom, as employed by Barr, et al (1978). This permits the representation of a wide range of coupling methods, including rigid, pin, ball joint or no coupling at all. Neglecting the damping of the coupling has no significant effect on the vessel motions and their resultant effect on the mooring loads.

In general, the most significant coupling exists between the vessel and the mooring lines. The mooring produces a

large restoring force which manifests itself in the vessel equations of motion and can influence the vessel's dynamic response. This effect is most predominant in the horizontal motions, where there is normally no hydrostatic restoring force. The introduction of the mooring effect is of the same magnitude as the hydrodynamic effects and can drastically alter the sway, yaw and surge responses. The responses dependent on vertical plane restoring forces (pitch, heave, roll) are largely governed by hydrostatic effects, and are not significantly influenced by mooring effects. The exception is, of course, the case of the tension anchor leg platform, which is specifically configured to restrain the platform vertically. However, in most conventional moorings the vertical stiffness is not large enough to affect the vessel response.

Vessel motions are generally modeled as a linear process, even for very large amplitude motions. The validity of this approach depends largely on the shape of the platform. For a barge, ship, spar or other basically vertical-sided structure, the assumption of linearity is generally acceptable within reasonable limits. However, for highly non-linear vessel shapes, such as a sphere, linear analysis can lead to errors of 100% or more in the presence of large waves.

Modeling of non-linear motions is best accomplished in the time domain. Changes in hydrodynamic coefficients due to large waves and/or large amplitude motions can be accommodated within a time domain algorithm. However, program execution time can increase by several orders of magnitude, since the responses must be calculated for every wave condition, instead of storing a response amplitude operator. Therefore, a non-linear time domain approach is recommended only in exceptional circumstances.

It is noted that, as a basis for mooring analysis, the vessel motion represents the primary dynamic excitation. Furthermore, the mooring and vessel may be only loosely coupled. Therefore, it is not inconsistent to assume that the response of the vessel is linear, even though the mooring behavior may be highly nonlinear.

Mooring Line Response

A general treatment of cable analysis is, at best, a difficult task, especially when consideration is given to large displacements and complexities resulting from hydrodynamic forces that tend to deform the cable into nonplanar, non-catenary configurations. For these problems the terms quasi-static and psuedo-dynamic are used alternately with steady-state. In many circumstances a reasonably accurate and effective engineering solution may be obtained on the basis of ignoring the effects of cable inertia and direct wave action on the cable. In addition, the hydrodynamic and structural responses are treated in an uncoupled manner, i.e., the general pattern and character of the fluid motion are assumed to be essentially undisturbed by the presence of the cables. The interaction between the vessel and the mooring lines are treated by representing the mooring line tensions as a set of forces applied at discrete, prescribed attachment points. An initial estimate for these forces are assumed, and the resulting vessel motions determined. The new position of the vessel is used to determine new mooring line forces. If these forces differ by a value greater than some prescribed tolerance, the process is repeated with the more recently determined forces used as an estimate for the next iteration.

An interesting comparison of results between a dynamic solution and a quasi-static solution is presented by Wilson and Garbaccio (1969) for the tension variation with time for a steel-wire mooring cable. The results indicate that the quasi-static results may be valid within engineering accuracy. However, these results can be somewhat unconservative with respect to extreme values and are generally out-of-phase with the dynamic results.

Loken and Olsen (1979) also show a comparison of quasi-static and dynamic analysis, and conclude that the dynamic analysis yields results some 25-30% higher than the quasi-static method. Figure 3 shows the results obtained.

Cassarella and Parsons (1970) have reviewed the physical

nature and modeling characteristics of the hydrodynamic loading forces on cables for the steady-state and dynamic situations. It has been determined that for the two-dimensional coplanar situation, the major issue in the literature is the nature of the normal and tangential forces on the cable. These forces contain components of the cable weight and hydrodynamic current forces on the cable.

There have been two principal approaches to the modeling of the hydrodynamic forces on the cable. The first, based on a procedure described by Pode (1950), considers "loading functions" that are the ratio of the hydrodynamic force component of interest to the hydrodynamic force on the cable when oriented normal to the fluid flow. This treatment has been used by many investigators since it leads to a force model that may be represented in terms of a single variable, the instantaneous cable angle, ϕ . This simplified approach neglects any change in Reynold's number with cable angle. Whicker (1957) modified the work of Pode by developing cable functions using a hydrodynamic force model applicable to faired as well as round cables.

The second approach towards modeling the hydrodynamic force considers the drag force defined in terms of the following:

- a drag coefficient
- mass density of the fluid
- a characteristic dimension of the cable (such as chord length)
- the fluid velocity.

The normal and tangential components of the drag force may be written in terms of corresponding velocity components, and normal and tangential drag coefficients that are proportional to the velocity component Reynold's number. When the drag coefficients are assumed to be constant, as is done in many steady-state problems, this approach is similar to the aforementioned "loading function" method.

Loken and Olsen (1979) also did a comparison of linear

and nonlinear modeling of restoring forces. For the case that was considered, the difference in tension prediction was insignificant. Therefore, as a basic approach to analysis, linearity would seem to be an acceptable assumption. However, because of the possibility of pronounced material and geometric nonlinearities, a nonlinear large displacement analysis should be performed at the final stages of analysis.

IV. EVALUATION CRITERIA AND RECOMMENDED OUTPUTS

The objective of the SKSS is to keep the OTEC platform on station throughout its design life. To fulfill that objective, it must have the capability to withstand loadings from all environmental conditions expected at the deployment site. In addition, it should resist long term degradation effects, such as fatigue, biofouling and creep.

A more specific definition of the SKSS requirements would be that the platform must remain within a specified radius (watch circle) from the deployment site, under specified environmental conditions, and that the maximum load in any member not exceed the allowable stress for that member. Long term performance can be similarly assessed by considering appropriate reductions in load capacity, elasticity, etc.

The load carrying ability of any particular design can be assessed either probabilistically or deterministically. In the latter case, the displacement and loading of all elements can be computed for a specified environment, and judged on a go-no-go basis. If all the criteria (watch circle, maximum load) are met, the preferred design might then be selected on the basis of cost, servability, ease of deployment or other factors.

If the design performance is assessed probabilistically, however, then the degree of risk, safety or reliability can also be introduced. This permits a quantifiable distinction between two alternatives that may meet or exceed the required load or displacement criteria, by assigning a probability level with exceedances of various response values.

In either case, there are certain performance parameters which are of interest. These are:

Position of platform

- heading
- offset from reference position

Motion or orientation of platform

- 6 DOF

Position of mooring line(s)

- length of suspended cable
- angle at top, bottom and each discontinuity or attachment

Mooring loads

- stresses at top, bottom and each discontinuity or attachment
- horizontal and vertical force at anchor
- lifting of anchor clumps or other events

Applied forces

- wind loads
- current loads
- wave drift forces
- dynamic position system forces

Note that each parameter may be interpreted either statistically or dynamically. Furthermore, in the latter case, the value may be given in terms of mean, r.m.s., significant or maximum.

For a deterministic analysis of mooring performance, the desired program outputs would be in terms of short term maximum values (static and dynamic combined). As a basis for probabilistic evaluation, significant or r.m.s. values would be required as input to the long term statistical computations. In either case, the average period of the dynamic tension response would also be required, at a range of load intensities.

For evaluation of deployment, maintenance operations, and contingencies, the same parameters would be required; however, transients or maximum values would be required, and the SKSS may have to be modeled in a partially deployed configuration. Detailed simulation of each mooring line would be required for deployment transient simulation. Evaluation of failure modes and progressive failure could also be undertaken, by allowing the degraded system to reach a new equilibrium position. In each of these cases, the entire time history of the event would be of interest, in addition to the maximum, or other measures cited.

Therefore, the output format will depend on the operational mode selected, and the method of analysis employed (time vs.

frequency domain). The parameters of interest are basically the position forces and loads of the platform and mooring line in each case.

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