FATIGUE CRITERIA FOR JACKUP DESIGN

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INTRODUCTION

Several recent conversions of jackup mobile offshore drilling units to fixed production platforms have introduced the question of structural fatigue into the planning for production service. What was designed as a mobile unit which would operate in different environments with changing wave patterns, different water depths, wind and wave directions is now fixed in one position at a fixed geographical site. The locations of high stress points remain constant possibly over a period of years while the unit is in production service and fatigue damage accumulates at these specific points. This is of particular concern in trade wind or monsoon areas where the weather comes from a very narrow range of directions, incessantly, day after day.

The work described in this paper was carried out for a particular site in the South China Sea off the Philippine Islands. But the procedure was developed with a view toward universality so that it would be applicable anywhere in the world. The major parts of the procedure are shown in a block diagram in figure I.

In developing this procedure, we constantly found it necessary to make choices regarding assumptions and methods, such as number of cases for stress analysis, dynamic amplification, and coping with the rather massive amounts of wave data. To carry out these steps efficiently requires certain set procedures. The procedures we selected and the reasons behind their selection are developed in the paper.

WAVE FIELDS

The water depth for production jack-ups is shallow enough that most of the wave periods of any concern are considered to be shallow water waves. Various wave theories may be used to calculate the wave particle velocities and accelerations. One such theory that has been used extensively is the Stream Function (Ref. 1).

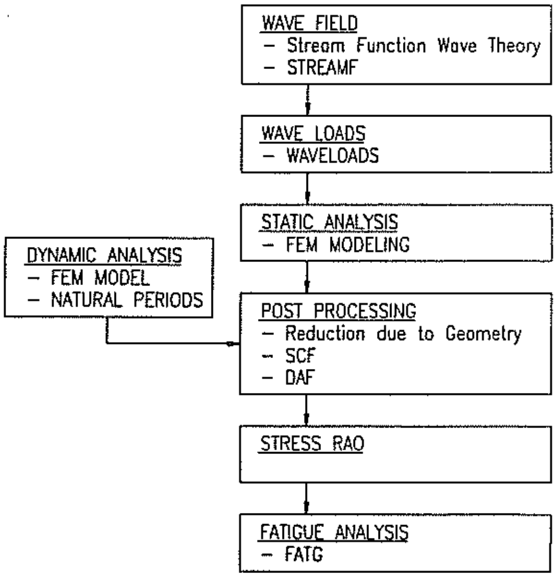

Figure 1

WAVE LOADS

Calculation of wave loads is performed taking into account member sizes, respective Cd and Cm values and their respective locations. The distance between the center of the legs for a given direction defines a particular base shear forcing function.

The wave periods chosen are based primarily on the base shear function, as well as the structural natural period of the rig and to a lesser extent the wave history for the particular production site. Figure II presents a jackup in plan view showing primary wave direction and distance between the upstream and downstream legs. Figure III shows a representative base shear curve.

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Enough wave periods are chosen to closely represent the base shear local maxima and minima. This generally means 6-10 points. The wave crest is located such that a maximum positive and maximum negative force is generated. Wave forces are calculated at these two conditions for each wave period chosen. These wave forces are used to generate the structural response amplitude operators (RAO's).

The wave heights used in this part of the analysis are chosen from the wave scatter diagram for the particular wave period. This means the wave slope will vary slightly between chosen wave periods.

In this manner wave forces for particular directions and wave height and period combinations may be determined.

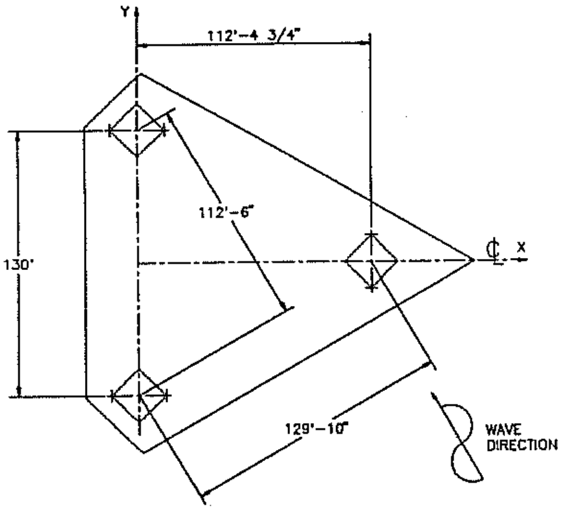

Figure 2

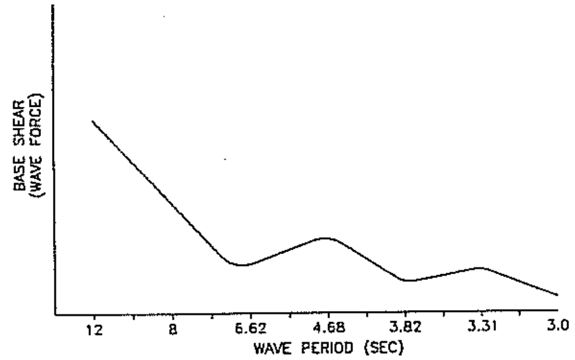

Figure 3

STRUCTURE MODEL

A structural analysis is done using any finite element program. The structure must be modeled to represent closely the stiffness of the whole system. The key here is the modeling of the jacking system and leg guides. As noted in the "Guideline for Site Assessment of Mobile Jack-up Units" (Ref. 2), this stiffness information may have to be obtained from detailed examination of the jacking mechanism. Considerable effort may be expended in this area to determine the most appropriate spring constants. This can have a large effect on the natural period of the unit, depending on the particular design.

For fatigue considerations, the spud cans are assumed to be pinned at the bottom. Work is ongoing in the area of spud can fixity with particular emphasis on the effect on the dynamic behavior of the unit.

Figure 4 shows a representative FEM model of a jackup unit. One leg has been completely modeled in detail while the other two legs are modeled as beam elements. All three legs are modeled in detail in the area of the leg guides and jacking system. This computer plot does not show the detail of the jacking system.

The magnitude and location of high stress points are found for each type of member (chord, horizontal brace and diagonal brace) for each load condition. The stress range is found by calculating the tensor difference between the highest stresses at a given location for each pair of load cases.

DYNAMIC AMPLIFICATION

The concept of dynamic amplification is based on repetitive input at a specific frequency. A structure excited at or near its natural frequency will exhibit a buildup in amplitude with repetitive cycles until an equilibrium is reached in which energy absorbed in damping equals the energy input. This situation would rarely, if ever, occur in a structure responding to random waves. One errs on the side of safety in applying the dynamic amplification factor (DAF). Further research should be directed to this question. On the other hand, it is not correct to apply the DAF to stresses which are not frequency-dependent.

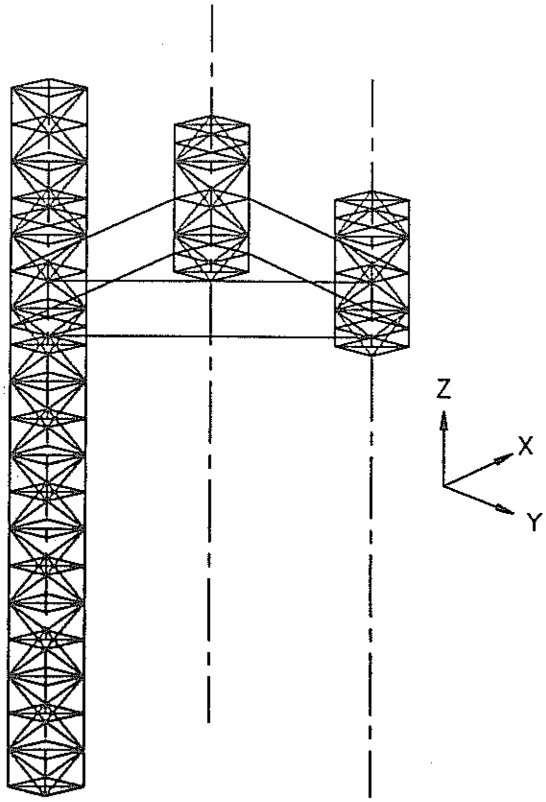

Figure 4

Dynamic amplification must be accounted for in the stress RAO. Hambly (Ref. 3) suggests a dynamic amplification factor (DAF) based on the response of a simple single degree of freedom system to periodic excitation. This function uses a ratio of the natural period of the structure to the wave period and the ratio of damping to critical damping. For a structure damping ratio of 5 percent, the effect is to amplify the stress RAO by 10 at the natural period decreasing asymptotically to 1 on either side.

This DAF may not apply to all members of the leg in cases where the relative stiffness between the leg and the jacking system is large. In other words, the jacking system support may be experiencing this dynamic amplification but not the chord.

Stress concentration factors (SCF) must also be applied to the stress range. This may be accomplished in several ways. The factors may be calculated using the API procedures in API RP-2A, depending on the design of the connections. They may also be determined by very detailed FEM modeling of the joint and calculated directly. The choice of S-N curve also takes into account the connection details.

The stress range is divided by its respective wave height to arrive at unit amplitude response. This is then multiplied by the SCF and DAF. This data is plotted over the frequency range to obtain a continuous stress RAO. Figure 5 shows representative RAO curves for chord and diagonal members.

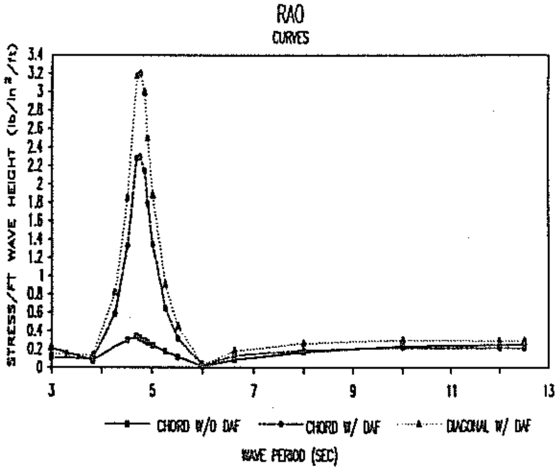

Figure 5

FATIGUE CALCULATION

We chose to determine the fatigue life of the structure using the spectral technique. The program FATG was written to perform all of the required data manipulation and calculations from this point. The program uses wave data occurrence in groups of height, zero-crossing period, and direction. Each wave height/period group is represented by a spectrum. A cosine squared wave spreading function is used. A one-year time period is used in the calculation with other time periods being simply multiples. The S-N curve is chosen depending on the type of members. The SCF's may be applied directly or may be inferred indirectly by the choice of a particular S-N curve. The stress amplitude responses are input over the full range of frequencies so as to fully describe the RAO curve. The frequency steps do not have to be uniform. Eighteen data points are generally used to describe the response curve. More points may be used if the particular RAO curve warrants.

Detailed wave data for the particular geographical site must be obtained from a reliable source. These data yield the percentage of time that one could expect each wave height/period group to occur. The typical data are broken down into approximately 25 height and period blocks to represent a year at the operating site. The data further broken down by direction.

The direction of the most severe wave heights from a fatigue standpoint is chosen as the primary direction. The waves are then grouped into three heading categories to obtain the respective percentages for each direction.

The number of sea spectra analyzed by FATG is unlimited. For each spectrum input:

H_s = Significant height for the spectrum
T_z = Zero up-crossing period, changed to peak period in the program: TP = $T_z/.71$
TPO = Total decimal fraction of occurrences of the height/period group
PER 0 = Decimal fraction in primary direction
PER45 = Decimal fraction at 45° to primary direction
PER90 = Decimal fraction at 90° to primary direction

A subroutine within the main program calculates a Bretschneider sea spectrum and, using the stress response operators at each frequency, calculates the significant stress (SIGMA-S) for the given wave height/period combination.

A Rayleigh Distribution of stresses over each wave spectrum is assumed.

It suffices to break the stresses into 10 groups, each corresponding to one-tenth of the total number of cycles. The highest stress is then the average of the highest 1/10 of the events, and so on. However to simplify the calculations, we divided the number of cycles into 3 groups, applying the highest 1/10 stress to the first one-third, the average stress of the middle third to one-third of the cycles, and the average of the lowest third of the stresses to the remaining 1/3 of the cycles. This is a conservative simplification since fatigue life is sensitive to stress. To obtain the stress range for each group, the program applies:

1/10 highest: SIGMA-S * 1.271
Middle 1/3: SIGMA-S * 0.59
Lower 1/3: SIGMA-S * 0.28

The stresses at each level, i.e., 1/10, 2/3, 3/3 are further modified by the angle of the wave propagation from the primary direction. Each spectrum is broken down into three octants, primary, 45°, and 90°, according to the wave occurrence data. The spreading factor determines the contribution to each octant.

The multiplier is determined as follows:

	Chords	Diagonals
Primary Octant	1	1
45° Octant	1	0.5
90° Octant	Cos(78.75)	1

The S-N curves E,F and T have been included as equations in the program. The curve T is for tubular members while curve E and F are for built up member connections. All three curves may be modified for members in water verses air. The equations were derived from DnV Classification Notes 30.2 (REF. 4). The user chooses the appropriate curve for the member being analyzed.

The number of cycles for one year for each spectrum is:

$$N^* = [31536000 \text{ sec/year}] * TPO / TP$$

For example, the number of cycles for the primary octant is:

$$N0 = N^*(PER0(1) + PER45(1) + PER90(0.195))$$

One-third of this number of cycles corresponds to each of the 1/10, 2/3, 3/3 stress range groups. The number of cycles in the 45° and 90° octants are found by similar means with appropriate spreading factors.

The amount of fatigue life used is then determined by the familiar Palmgren-Miner rule. The number of cycles encountered is divided by cycles to failure for each stress range group and direction. The summation of these values is the amount of fatigue life used in the particular spectrum. The total sum over the entire wave record set is the life used in one year. This is carried out for each type of member.

CONCLUSIONS

Fatigue life of a jack-up unit is highly dependant on the assumptions used in the analysis. Calculation of the natural period of the unit is itself dependant on the details of the structure being correctly modeled. By developing a set procedure for dealing with the many variables and incorporating it into a computer program, the confidence in the calculated fatigue life may be increased. As more jackup units are used as production platforms, the need for reliable fatigue life assessment will increase.

Several areas of fatigue life assessment warrant further study. One is the previously mentioned spud can fixity question. Another is the application of dynamic amplification to various parts of the structure.

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