CHAPTER ONE HUNDRED EIGHTY THREE

TIME AND FREQUENCY LOADING ANALYSIS OF SUBMARINE PIPELINES

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ABSTRACT

Fatigue damage to marine pipelines subjected to wave forces is evaluated using time-domain and frequency-domain methods. Spectral techniques are applied to North Sea, Gulf of Mexico and offshore Atlantic Canada wave conditions. Time-domain analysis is applied to wave conditions in the Canadian North Atlantic Ocean.

The frequency-domain analysis is performed using spectral and probabilistic techniques suggested by L. Borgman (2). The pipeline dynamic characteristics are described by classical analytical descriptions. The time-domain analysis computes time histories of wave force loading on the submerged pipeline from actual wave records. The traditional Morison wave force equation is used to obtain the time history of the loading on the pipeline. Empirically determined wave spectra are shown not to produce as good a correlation with the deterministic results as the actual wave spectra.

Free spanning submarine pipelines subjected to cyclic surface wave loading accumulate strength reductions leading to failure from material fatigue. The Palmgren-Miner rule for the linear accumulation of fatigue damage is applied to evaluate the time to failure. The American Welding Society X-X stress accumulation curve is applied.

The results of the deterministic analysis were compared with those of the more efficient spectral analysis. It is shown that comparable results can be obtained from the spectral analysis provided the actual spectra of the water surface elevation is employed in the spectral analysis.

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NOMENCLATURE

A_n	amplitude of nth wave compnent
a_i	water particle acceleration in the ith time interval
C_D	drag force coefficient
C_M	inertia Force Coefficient
C_1, C_2	Morison wave force equation coefficients
D_o	outer diameter of steel linepipe
D_{Con}	outer diameter of concrete coating
d	water depth
F	wave force per unit length of pipe
F_i	wave force in the ith time interval
F_M	magnitude of the Mth Fourier force coefficient
f	wave frequency
g	gravitational acceleration
H_s	significant wave height
L	length of unsupported span of pipeline
$S_{\eta\eta}(f)$	spectral density of water surface elevation
t_{Con}	thickness of concrete jacket
t_w	wall thickness of steel pipeline
$U_{19.5}$	wind velocity at a height of 19.5 meters
u_i	water particle velocity at the ith time interval
Z	distance above the sea bed
α, β	empirically derived constants that appear in the P-M formulation of the wave spectrum
η	water surface elevation
σ_i	bending stress in the ith time interval
ρ_{con}	density of conrete
ρ_{fl}	density of fluid
ϕ_n	nth Fourier cosine series phase angle

1.0 INTRODUCTION

Extensive production of petroleum and natural gas now takes place in coastal waters with the move being to exploration, and in the near future, production in deep ocean waters. Studies show that the most efficient way of transporting the hydrocarbon products onshore is by submarine pipelines, where possible. Some structures offshore have been at a particular site for over 20 years. Engineers have recognized that these structures have undergone long-term cyclic loading and have developed methods of evaluating the accumulated damage cuased by the cyclic wave loading. The analyses have been predominantly probablistic in nature, and have been extended by Alexander (1) to evaluate the fatigue life of a free span of submarine pipeline.

An increasing amount of actual water surface elevation records for particular sites are becoming available. More accurate probablistic analyses are now possible and as well deterministic (time-domain) analyses which involve no assumtions regarding wave spectra or the linearization of the drag term in the Morison (6) wave force equation, are also available.

The line pipe, Figure 1, used in the offshore industry is of circular cross-section, seamless, fabricated from steel and is generally jacketed in concrete to provide protection and insure negative buoyancy. Mogbo (5) has shown that the concrete jacket does not appreciable alter the flexible stiffness of the submerged steel pipe. The scour of sediment and sand from around a pipeline laid on the ocean bottom, due to the action of both surface waves and bottom currents, can cause submarine pipelines to be exposed and suspended as shown in Figure 2. Herbich (3) and Strating (9) have documented many cases of submarine pipelines becoming free spanning. These free-spans of submarine pipelines have the potential to fail from fatigue due to surface-wave induced, generally low level, cyclic loads. Vortex induced loading also caused by surface-waves and bottom currents, which may also contribute to the fatigue damage, are not included in this analysis.

In order for a structure to suffer from fatigue damage it must undergo a displacement process. Anytime a structure is displaced in a cyclic manner the possibility of the displacement of the structure being dynamically amplified exists. This analysis involved an evaluation of the range of frequencies over which the hydrodynamic loading might dynamically amplify the response of the free-spanning submarine pipeline structure. The range of natural frequency for a typical pipe span length is shown in Figure 3. Where dynamic amplification was significantly small a more efficient quasi-static method was used to evaluate pipeline response.

Airy wave theory was employed to describe surface-wave induced water particle kinematics. This theory allowed water particle velocity and acceleration to be determined at the elevation of the free-spanning pipeline. An Airy wave description is shown in Figure 4.

2.0 WAVE RECORD AND FORCE ANALYSIS

An ocean engineer faced with the task of analysing the wave climate at a particular location can proceed in two different directions. The traditional method developed by Pierson and Moskowitz (8) was to relate wave amplitude as a function of wave frequency and with further analysis the spectral energy density $S_{\eta\eta}(f)$ as a function of the wave frequency as given by Equation 1

$$S\eta\eta(f) = \alpha\, g^2/[(2\pi)^4\ f^5]\ \exp\ [-\ \beta(g/2\pi\ U_{19.5}f)^4] \qquad (1)$$

where α and β are empirically derived coefficients, respectively equal to 0.0081 and 0.74 and valid for fully arisen sea conditions. Significant wave height, H_s, and significant wave period may be determined from the spectral density relationship. Fully arisen seas are rarely encountered in coastal waters off the coast of Atlantic Canada. The spectral density of the water surface elevation is not accurately represented by the P-M spectrum at these locations.

When time histories of water surface elevation are available for a particular location the ocean engineer can proceed with an alternate analysis. Of late, extensive libraries of time histories of water surface elevation, in the coastal waters of Atlantic Canada, are available from the Marine Environment Data Service (MEDS) of Fisheries and Oceans Canada. Such a record is shown in Figure 6, for station 144 near the Sable Island region of offshore Atlantic Canada. This record will be presented as an example analysis. The twenty minute records available are assumed to represent the sea conditions which exist over a three hour period. Assuming that the water surface elevation function $\eta(t)$ repeats itself every twenty minutes a Fourier cosine series of the record may be written such that N equations describing the water surface elevation would be of the form

$$\eta_i = \sum_{n=1}^{N} A_n \cos(\pi\ i\ n/N + \phi_n) \qquad (2)$$

where A_n is the amplitude of the n^{th} wave component and ϕ_n is its corresponding phase angle. Similarly water particle velocity and acceleration, u_i and a_i can be written in discrete form. The Morrison equation can now be used in discrete form

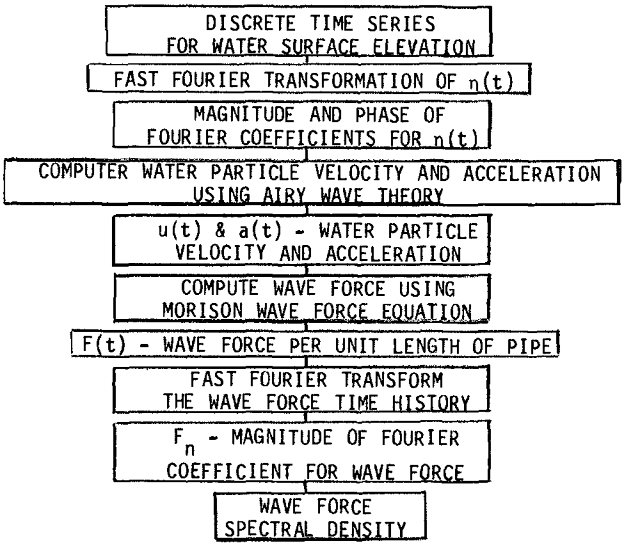
$$F_i = C_1 u_i |u_i| + C_2 a_i \qquad (3)$$

to obtain the response of the submarine pipeline to wave loading. Even efficient fast fourier transforms require significant computer time to analyze several twenty minute records each consisting of two thousand points.

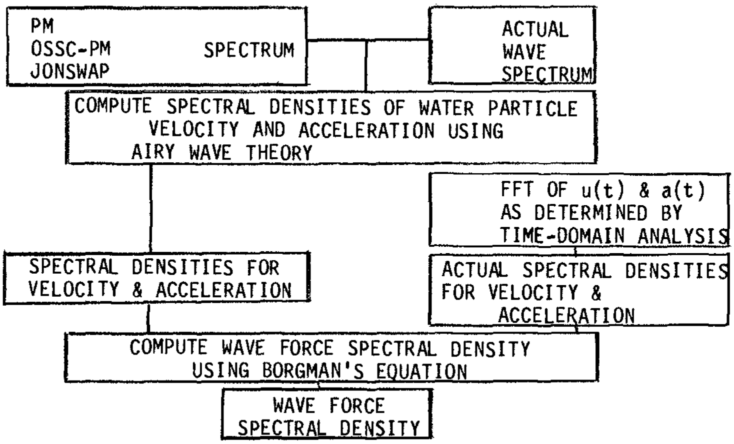
A more efficient method when the actual wave records are available is to obtain the actual spectral density of the surface elevation. The actual spectral density for wave record station 144 is shown compared with other empirically derived spectra in Figure 5. Little correlation exists between the actual and the P-M and the modified P-M spectra. The Jonswap spectrum shows acceptable correlation but only when the necessary coefficients are determined from the actual spectrum. This cannot be done a priori. Clearly, actual wave spectra should be employed when determining the hydrodynamic loading.

The spectral density for the wave force can be evaluated by several methods. Firstly, the wave force can be assessed in the time-domain using equation 3. A high degree of confidence can be placed in this method. Secondly, Borgman's transformation can be used to obtain the spectral density of the wave force from the Fourier transforation of the discrete time series. This hybrid time-frequency-domain analysis and results appear to be acceptable. The third method employs the Borgman transformation from an empirically formulated energy spectrum. Since poor correlation exists between the actual spectrum and the empirically formulated spectra only marginal confidence can be placed in this method.

Flow charts of the evaluation of the force spectral density for the time-domain analysis (method 1) and the frequency-domain analysis (method 2 and 3) follow:



TIME-DOMAIN ANALYSIS



FREQUENCY-DOMAIN ANALYSIS

3.0 FATIGUE ANALYSIS

Offshore structures which are subjected to cyclic hydrodynamic loading suffer a reduction in strength, which may eventually cause failure, through a process called fatigue. The fatigue life of structure may be determined by applying the Palmgren (7) and Miner (4) law of linear-accumulated damage. It states that fatigue failure will occur when

$$\sum_i \frac{m_i}{N_i} = 1 \qquad (4)$$

where m_i is the actual number of occurences of stress magnitude σ_i determined from the wave loading spectrum. N_i is the permissable number of occurences of stress determined from S-N curves which relate the number of cycles to failure to a certain stress range. The American Welding Society S-N curve, ASW-X was used as the failure criteria. The fatigue damage sustained by a submarine pipeline was assessed for a year. The reciprocal of this value was taken as the fatigue life.

The relationship between the force spectral density and the stress spectral density is determined by considering the force spectral density as an input to the linear free-spanning submarine pipeline system. The displacement response and the stress response are directly related and expressed in the frequency-domain.

In the time-domain analysis the uniformly distributed wave load is replaced by a concentrated wave load applied at the center of the pipe span, which produces the same maximum bending stress. This concentrated load is used as the forcing term in the dynamic equation of the pipeline motion. An iterative procedure is included to solve for the relative velocity between the structure and the water particles. Once the structure displacement is determined, bending stresses are calculated from simple beam theory assuming that the suspended line-pipe has pinned-supports. The exact procedure required to determine the stress-history in the time-domain is complex and time consuming even on high-speed digital computer.

4.0 RESULTS

The following pipeline and environmental parameters were used in the fatigue analysis as applied to six 20 minute wave records from Station 144.

Pipe diameter (D_0)	600 mm (24 inches)
Pipe wall thickness (t_w)	13 mm (0.5 inches)
Concrete jacket thickness (t_{con})	38 mm (1.5 inches)
Concrete density (ρ_{con})	2400 kg/m^3 (150

	lb_m/ft^3)
Hydrocarbon density (ρ_{fl})	800 kg/m^3 (50 lb_m/ft^3)
Length of span (L)	40 m (131 ft)
Water depth (d)	20 m (66 ft)
Height of span above sea bed (Z)	2 m (6.5 ft)
Inertia coefficient (C_m)	2.5
Orag coefficient (C_D)	1.5

When the fatigue damage incurred during the twenty minute period was extroplated to one year by assuming that the particular record persisted for the entire year the following fatigue life was determined for each record from the time-history analysis.

Wave record	1	2	3	4	5	6
H_s (m)	2.0	2.15	2.59	2.44	2.16	3.19
Fatigue Life (years)	8187	5048	515	214	1284	14

The value for the fatigue life yielded in this manner is only representative of the actual fatigue life in so far as the particular sea state chosen is representative of the wave climate averaged over one year. However, if the twenty minute wave record were analyzed statistically then there appears the probability of encountering larger waves and thus higher stress ranges than actually detected during the twenty minute time-domain analysis. Fatigue life results for each record assuming a statistical analysis of the twenty minute wave record are now:

Wave record	1	2	3	4	5	6
H_s (m)	2.0	2.15	2.59	2.44	2.16	3.19
Fatigue life (years)	2320	1690	1750	453	1150	18

The fatigue life predictions by the spectral method are presented for the actual wave spectrum, the P-M spectrum, the modified P-M spectrum and the JONSWAP spectrum.

Wave record	1	2	3	4	5	6
H_s (m)	2.0	2.15	2.59	2.44	2.16	3.19
Fatigue life (years)						
Actual Spectrum	2085	1561	2300	670	1573	47
P-M	7868	3350	420	795	3175	45
Modified P-M	2130	1295	4598	578	1687	46
JONSWAP	1628	860	160	269	799	40

It is shown that a particular empirical formulation for wave spectrum performs acceptably in a spectral fatigue analysis when it acceptably matches the actual spectrum. Fatigue life predictions by the spectral method are comparable when actual wave spectrum is employed.

5.0 CONCLUSIONS

Extensive wave record analysis would predict fatigue life by determinstic methods. This is expensive, often not possible and not necessary.

Segemented wave records provide sufficient data for an acceptably accurate fatigue life analysis by deterministic methods. This is still costly.

Spectral techniques, when applied using the actual wave spectrum are efficient and correlate reasonably well with the deterministic evaluation.

Submarine pipelines subjected to seas with significant wave heights less than 2.0 m (6.5 feet) need not be analyzed for fatigue failure.

Analysis of only six-twenty minute wave records predicts fatigue failure from 14 to 47 years. This is a matter of concern.

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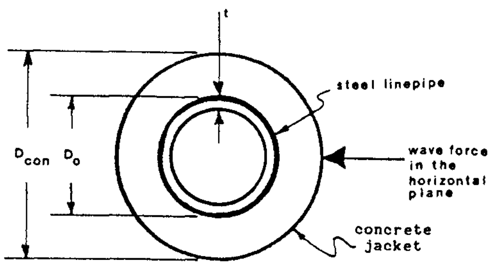

Figure 1. Concrete Jacketed Pipeline

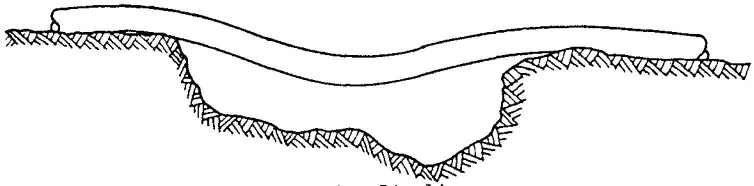

Figure 2. Free-Spanning Pipeline

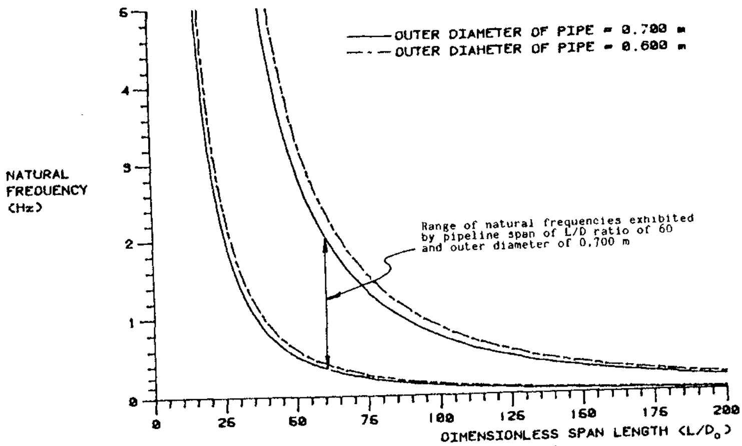

Figure 3. Natural Frequency of Vibration

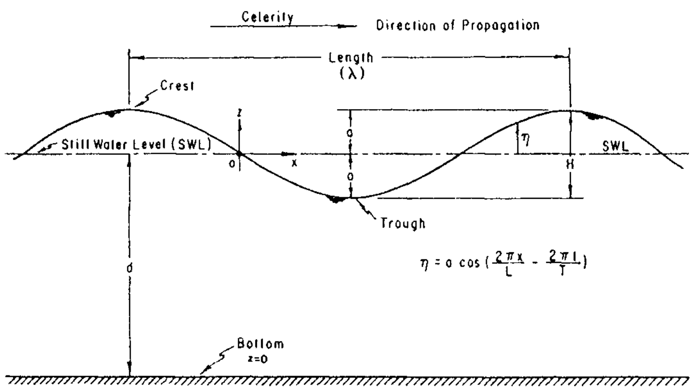

Figure 4. Airy Theory Wave Description

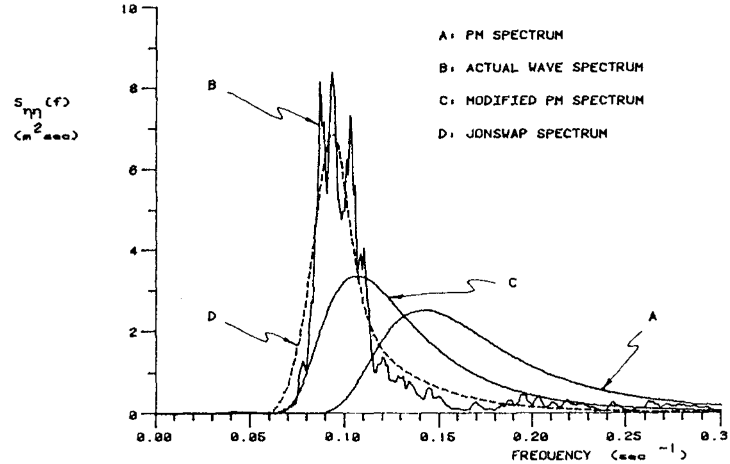

Figure 5. Water Surface Elevation Spectral Density

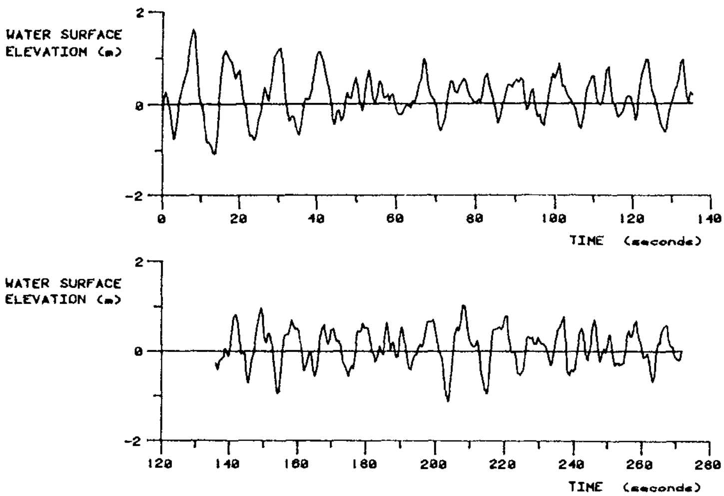

Figure 6. Water Surface Elevation Station 144