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Research Article

Towards the Procedure Automation of Full Stochastic Spectral Based Fatigue Analysis

[1]Khurram Shehzad, [1]Ren Huilong, [1]Feng Guoqing and [2]Asifa Khurram
[1]College of Shipbuilding Engineering,
[2]College of Materials Science Engineering, Harbin Engineering University, Harbin 150001, China

Abstract: Fatigue is one of the most significant failure modes for marine structures such as ships and offshore platforms. Among numerous methods for fatigue life estimation, spectral method is considered as the most reliable one due to its ability to cater different sea states as well as their probabilities of occurrence. However, spectral based simulation procedure itself is quite complex and numerically intensive owing to various critical technical details. Present research study is focused on the application and automation of spectral based fatigue analysis procedure for ship structure using ANSYS software with 3D liner sea keeping code AQWA. Ansys Parametric Design Language (APDL) macros are created and subsequently implemented to automate the workflow of simulation process by reducing the time spent on non-value added repetitive activity. A MATLAB program based on direct calculation procedure of spectral fatigue is developed to calculate total fatigue damage. The automation procedure is employed to predict the fatigue life of a ship structural detail using wave scatter data of North Atlantic and Worldwide trade. The current work will provide a system for efficient implementation of stochastic spectral fatigue analysis procedure for ship structures.

Keywords: Ansys, automation, hot spot, spectral fatigue, stochastic, stress response

INTRODUCTION

Ships are prone to fatigue due to high cyclic loads predominantly caused by waves and varying loading conditions (Fricke *et al*., 2011). Fatigue strength evaluation is an important criterion in ship design as accurate prediction of the fatigue life under service loading is imperative for both safe and economic design and operation (Cui *et al*., 2011). The fatigue strength of ship structure is generally assessed either by simplified method or spectral based Method. These techniques are categorized based on the method used for determination of stress distribution (Bai, 2003). Excessive sensitivity of the estimated fatigue damage to the weibull shape parameter and selection of basic design SN curve, confine the use of simplified approach to complex structures and novel hull forms (ABS, 2003). On the contrary, spectral method is considered as the most reliable method for fatigue life estimation of ship structure due to its ability to cater different sea states as well as their probabilities of occurrence (Wang, 2010). It is a direct calculation method based on linear theory in the frequency domain of a stationary and ergodic but not necessarily narrow banded Gaussian random process with zero mean (Kukkanen and Mikkola, 2004).

Full stochastic spectral fatigue calculations are based on complex stress transfer functions established through direct wave load analysis combined with stress response analysis. In full stochastic analysis, hydrodynamic loads are directly transferred from the wave load analysis program to Global FE model. Wirsching and Chen (1988), Sarkani *et al*. (1990), Pittaluga *et al*. (1991) and Wang (2010) have presented in detail the theoretical background and method of spectral based fatigue analysis. Chun-Bo *et al*. (2012) investigated the fatigue strength of trimaran cross deck structure by spectral approach. Shehzad *et al*. (2012) applied spectral method to estimate fatigue life of selected critical details of trimaran structure. In spectral approach, wave loads in regular waves Or Response Amplitude Operators (RAOs) and corresponding wave induced stresses in ship structural components are computed for a specific range of frequencies and headings to obtain stress transfer functions at the hot spots. Each transfer function is valid for a specified ship velocity, wave heading angle and loading condition. Wave data in terms of a wave scatter diagram and a wave energy spectrum are incorporated to generate stress-range response spectra, which is used to define the magnitude and frequency of occurrence of local stress ranges at hot spots in a probabilistic manner. Fatigue damage from individual sea state is calculated using Rayleigh's probability density function describing the short-term stress range distribution, spectral moments of various orders and S-N curve

Corresponding Author: Khurram Shehzad, College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China

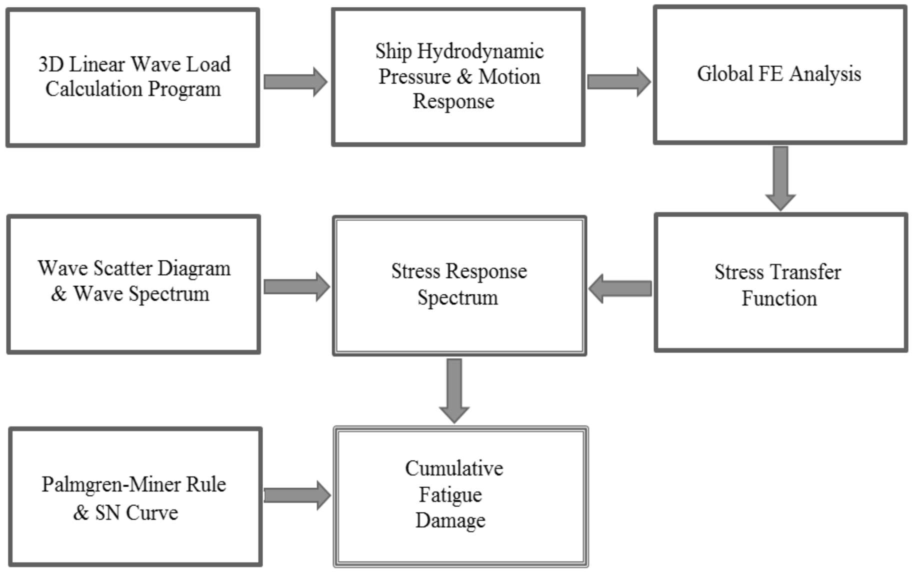


Fig. 1: Spectral based fatigue analysis flowchart

of the structural detail and zero crossing frequency of the response. Based on Palmgren-Miner linear damage accumulation hypothesis with occurrence probabilities of the different operational and environmental conditions, total or cumulative fatigue damage is determined by combining the short-term damages over all the applicable sea states (Siddiqui and Ahmad, 2001).

The analysis procedure of spectral based fatigue is shown in Fig. 1. Although underlying theory of spectral fatigue is simple and straightforward, yet the analysis technique itself is quite complex and numerically intensive owing to various critical technical details. These include computation of response amplitude operators RAOs, mapping of fatigue loading wave pressure from hydrodynamic model to structure model, generation of load cases for base vessel loading conditions, displacement boundary condition, hotspot stress extraction, transfer function formulation and spectral fatigue damage calculation. Therefore, efficient implementation of spectral fatigue method for ship structures requires a robust automated workflow of the process in order to reduce the simulation development cycle time and to increase the quality and consistency.

This research study is focused on the application and procedure automation of spectral fatigue analysis of ship structure using ANSY and 3D linear sea keeping code AQWA. In this study, above mentioned technical aspects of spectral based fatigue simulation are discussed in detail. For each aspect, APDL macros are created and subsequently implemented to reduce the pre/post processing time and to eliminate the repetitive work involved in the simulation process. In addition, ANSYS-AQWA guidelines are established to generate hydrodynamic model and to compute RAOs for any hull form. A MATLAB program is developed to calculate cumulative fatigue damage based on direct calculation procedure of spectral fatigue. Finally, numerical case study is conducted by implementing the developed automation procedure of spectral based method to compute fatigue damage of a ship structure detail.

AUTOMATION METHODOLOGY OF SPECTRAL FATIGUE

Response Amplitude Operator (RAOs): The main objective of motion and load calculations in spectral based fatigue analysis is the determination of RAOs, which are mathematical representations of the vessel responses and load effects to unit amplitude sinusoidal waves. Present study deals with the computation of RAOs for wave induced motions and hydrodynamic pressure loads at zero forward speed using AQWA, utilizing three dimensional potential flow-based diffraction-radiation theory. ANSYS-AQWA procedure guidelines are developed to generate hydrodynamic model and to compute RAOs for any hull form in an efficient manner. Various parameters used in RAOs calculation are summarized in Table 1.

Pressure mapping on Fe model: Mapping of pressure distribution from coarse hydrodynamic model to fine meshed structural model requires interpolation. This mapping issue of pressure loads from hydrodynamic panel model to global FE model is resolve by AQWAWAVE, which creates pressure load files for each combination of frequency and heading. Thus, a combination of 19 frequencies and 12 headings will

Table 1: Wave load RAOs calculation parameters

S. no	Parameter		Range	Increment
1	Frequency	ω	0.2 ~ 2.0	0.1
2	Heading angle	θ	$0^0 \sim 330^0$	30^0
3	Heading probability	p_i	1/12	-

result in 228 AQWA pressure files for 01 base vessel loading condition. However, reading AQWA pressure file in ANSYS to apply loads on structure is a tedious, laborious and time consuming task, as it requires prior deletion of line mesh from global structure model so as to remove beam elements and remeshing afterwards. Consequently, manual implementation of pressure loads on structure model to perform FE analysis is not a feasible and time efficient solution.

An automatic pressure loading technique was developed utilizing APDL based subroutine ALSFG (Automatic Load Step File Generator). ALSFG macro working include removal of line mesh, systematically reading of AQWA pressure files, conversion to corresponding ANSYS load step files and finally remeshing of the lines to generate beam elements. These load step files can be used directly in ANSYS to perform quasi static FE analysis. This pressure loading approach turns out to be a useful tool as it greatly enhances the study efficiency.

Boundary condition and solution: Application of proper displacement boundary condition in quasi-static FE analysis to constrain rigid body motion is a challenging task. Spring supports are generally used to restrain relevant degrees of freedom of the structure to ensure non singularity of structural stiffness matrix. However, proper selection of spring stiffness constant is vital in order to keep corresponding spring force to be small enough to obtain valid results.

In this study, Inertia relief method in ANSYS is used to solve the problem of displacement boundary condition. It is a latest technique, which perform inertia relief calculations, compute and apply equivalent accelerations that counterbalance the applied loads. An APDL macro IRBCS (Inertia Relief Boundary Condition and Solution) is developed that apply inertia relief boundary condition and solve all load step files generated in previous step.

Stress extraction and stress transfer function: The hot spot stress based fatigue design is based on the stresses at a weld toe obtained by a linear or quadratic extrapolation of stresses over 2 or 3 points in front of the weld toe under consideration (Kim *et al*., 2009). Hot spot stress or geometric stress includes all stress-rising effects induced by the structural detail but excluding all stress concentrations due to the weld profile itself. Extraction of hot spot stress and formulation of stress transfer function, which represents the relationship between the stress at a particular structural location, wave frequency and heading, is the key step in spectral fatigue analysis. This tedious cumbersome job of hot spot stress extraction and generation of transfer function is automated using APDL macro "HSSTFG" (Hot Spot Stress Transfer Function Generator". HSSTFG macro working is based upon the hot spot stress extraction methodology of DNV classification notes for fatigue assessment of ship structure (DNV, 2010). It derives hot spot stress for each load case by linear extrapolation over reference points 0.5 and 1.5 x plate thickness away from the hot spot and saves the final stress value at appropriate location in the matrix to generate stress transfer function.

Fatigue damage calculation: Mathematically, spectral-based fatigue analysis begins after the determination of the stress transfer function. Wave energy distribution S_η in short term sea state over various frequencies, is modeled by parametric Pierson-Moskowitz wave energy spectrum (DNV, 2010) and expressed as:

$$S_\eta(\omega|H_s, T_z) = \frac{H_s^2}{4\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-5}\, exp\left(-\frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-4}\right) \quad (1)$$

where,

H_s = Significant wave height
T_z = Zero crossing period
ω = Wave frequency

Stress energy spectrum S_σ is obtained by scaling Pierson-Moskowitz wave energy spectrum in the following manner.

$$S_\sigma(\omega|H_s, T_z, \theta) = |H_\sigma(\omega|\theta)|^2 .\ S_\eta(\omega|H_s, T_z) \quad (2)$$

where, H_σ *(ω/θ)* is the stress transfer function and θ is the heading angle. The *nth* spectral moment m_n of the stress response process for a given heading is calculated as follows:

$$m_n = \int_w \omega^n\ .S_\sigma(\omega|H_s, T_z, \theta)\, d\omega \quad (3)$$

Assuming the short-term stress response to be narrow-banded, then stress ranges follow the Rayleigh probability distribution (ABS, 2004). Using spectral moments of various orders, Rayleigh probability density function *g(s)* describing the short term stress-range distribution and zero up-crossing frequency of the stress response *f* are calculated as follows:

$$g(s) = \frac{s}{4m_0}\, exp\left(-\frac{s^2}{8m_0}\right) \quad (4)$$

$$f = \frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}} \quad (5)$$

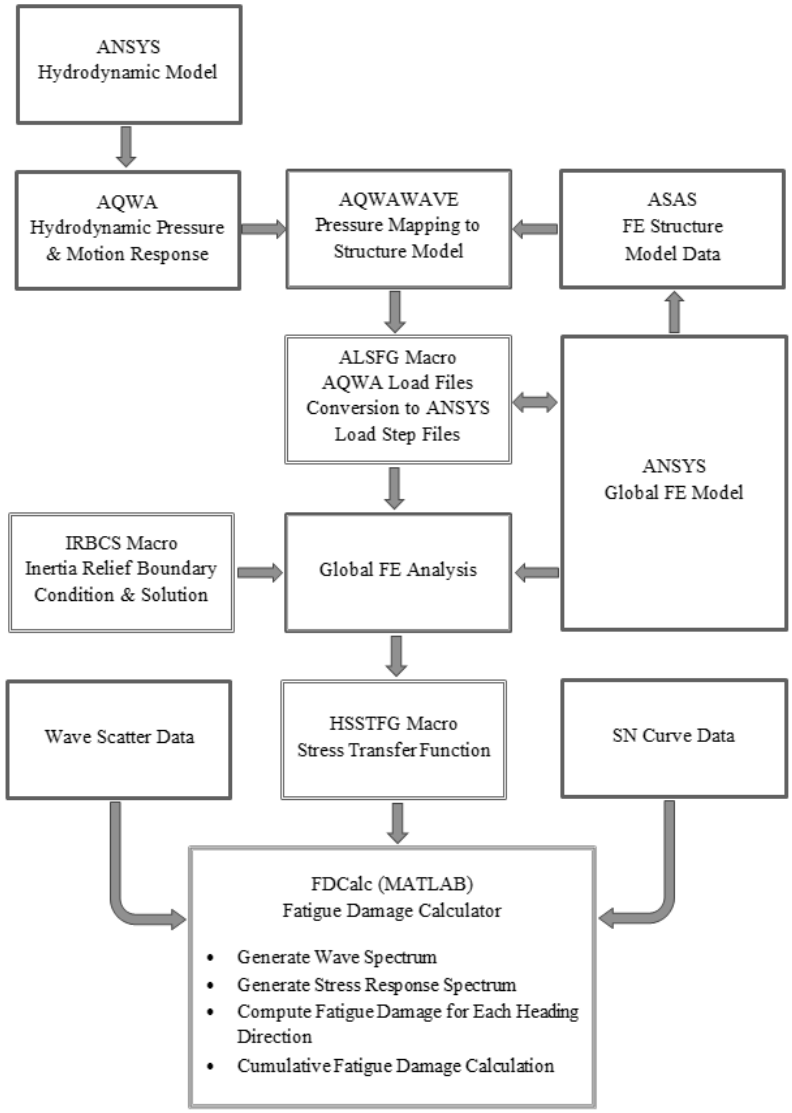


Fig. 2: Automation procedure of stochastic spectral fatigue analysis

$$\varepsilon_i = \sqrt{1 - \frac{m_2^2}{m_0 m_4}} \tag{6}$$

where,
s = Stress range
m_0, m_2 = Spectral moments

Using SN curve of the form $N=AS^m$, the short term fatigue damage D_{ij} incurred in the ith sea-state is given by the relation:

$$D_i = \left(\frac{T}{A}\right) \int_0^\infty s^m f_{0i} p_i g_i(s)\, ds \tag{7}$$

where, f_{0ij} is zero-up crossing frequency of stress response in Hz, T is design life in sec, m and A are constants of SN curve and p_i is the probability of occurrence of individual sea state. Substituting the value of $g(s)$ from Eq. (4) and after mathematical manipulations, above equation takes the form as:

$$D_i = \left(\frac{T}{A}\right) \left(2\sqrt{2m_{0i}}\right)^m \Gamma\left(1 + \frac{m}{2}\right) p_i f_{0i} \tag{8}$$

where, Γ represents gamma function. Based on Palmgren Miner rule, the total or cumulative fatigue damage D is calculated by the linear summation of the damage in individual sea state and is expressed as:

$$D = \frac{T}{A} \Gamma\left(1 + \frac{m}{2}\right) \sum_{n=1}^{N_{Load}} p_n \cdot \sum_{i=1}^{n_s} \sum_{j=1}^{n_h} p_i p_j f_{ijn} \left(2\sqrt{2m_{0ijn}}\right)^m \tag{9}$$

where,
N_{load} = Total number of loading conditions considered
p_n = Fraction of design life in loading condition n

n_s = Total number of sea states
n_h = Total number of headings
p_j = Occurrence probability of heading j
f_{ijn} = The zero crossing frequency in short term stress condition i, j combined with loading condition n.

Effects of swell are not accounted for in above calculation, as the wave scatter diagram is used to represent the wave environment. Wirsching's rain flow correction factor is used to cater swell effects in short-term fatigue damage calculation (Wirsching and Light, 1980):

$$\lambda(m, \varepsilon_i) = a(m) + [1 - a(m)][1 - \varepsilon_i]^{b(m)} \quad (10)$$

where, $a(m) = 0.926\text{-}0.033$ m, $b(m) = 1.587\text{m} - 2.323$ and ε_i is bandwidth parameter calculated by Eq.7. Addition of Wirsching's rain flow correction factor modifies Eq. (8) and (9) as:

$$D_i = \left(\frac{T}{A}\right)\left(2\sqrt{2m_{0i}}\right)^m \Gamma\left(1 + \frac{m}{2}\right) \lambda(m, \varepsilon_i) p_i f_{0i} \quad (11)$$

$$D = \frac{T}{A}\, \Gamma\left(1 + \frac{m}{2}\right) \sum_{n=1}^{N_{Load}} p_n \cdot \sum_{i=1}^{n_s} \sum_{j=1}^{n_h} \lambda(m, \varepsilon_i)\, p_i\, p_j f_{ijn} \left(2\sqrt{2m_{0ijn}}\right)^m \quad (12)$$

Both Eq. (8 and 11) can be employed to compute accumulated fatigue damage in a specific sea state. Cumulative fatigue damage is converted to expected fatigue life T_f by the expression:

$$T_f = \frac{T_d}{D}$$

where,
T_d = The design life of the ship

A MATLAB code FDCalc (Fatigue Damage Calculator) is developed to calculate spectral fatigue damage according to the above mentioned mathematical formulations. The program uses stress transfer function obtained by global finite element analysis, SN curve parameters and wave scatter diagram data as input to calculate cumulative fatigue damage. FDCalc initially computes the fatigue damage incurred during individual heading directions, which can be presented by means of polar diagrams to study its contribution towards cumulative fatigue damage. Figure 2 outlines the automation procedure developed to perform stochastic spectral based fatigue calculations.

APPLICATION OF AUTOMATION PROCEDURE FOR SPECTRAL FATIGUE

The above mentioned automation procedure of spectral method is adopted to predict fatigue life of a structural detail of a multihull trimaran craft. Main particulars of trimaran ship are summarized in Table 2, whereas global FE model is shown in Fig. 3. The structure detail selected to perform spectral fatigue analysis is the connection of wet deck with main hull at 3rd transverse bulkhead location from the aft. The structural detail along with hotspot fine mesh is shown in Fig. 4. For this structural detail, fatigue damage is calculated for one base vessel loading condition using wave scatter data of North Atlantic and Worldwide trade. Wave scatter diagram of North Atlantic and worldwide trade is shown in Fig. 5 and 6, respectively. Only long crested waves are taken into account with the assumption of equal probability of vessel heading relative to the direction of the waves. SN curve E of CCS rule having fatigue coefficient 1.026 x 10^{12}MPa and fatigue strength exponent m = 3 is used for fatigue analysis. Design life of the ship is taken as 20 years with 85% duration at sea. The factor of 0.85

Table 2: Main characteristics of trimaran platform

Parameters	Main hull	Side hull
Length [m]	154.6	41.16
Draught at mid ship [m]	5.33	2.94
Breadth at waterline [m]	10.15	1.76
Moulded depth [m]	14.94	12.5
Displacement [m^3]	3491	68
Cross deck Height [m]	2	
Dead weight [tons]	3627	

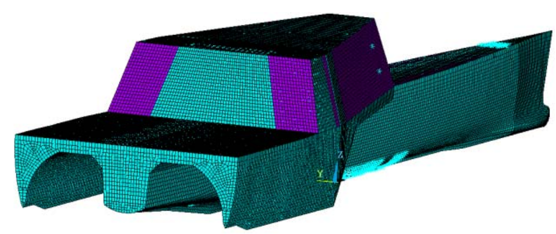
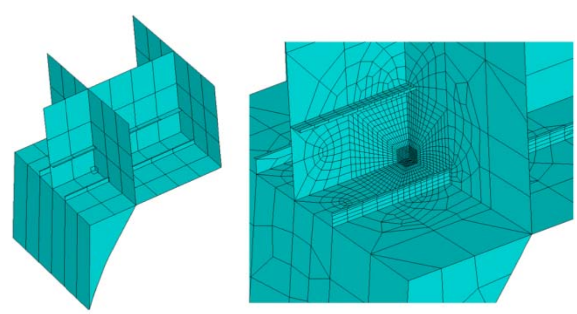


Fig. 1: Global FE model of trimaran



(a) (b)

Fig. 2: Connection of wet deck with main hull (a) area model (b) fine meshed model

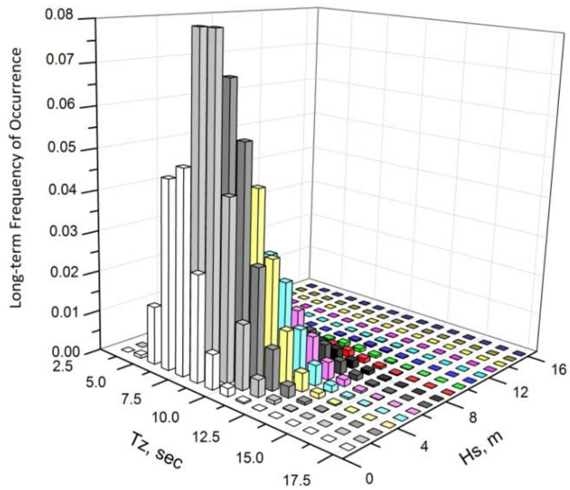


Fig. 5: North Atlantic (NA) sea scatters data

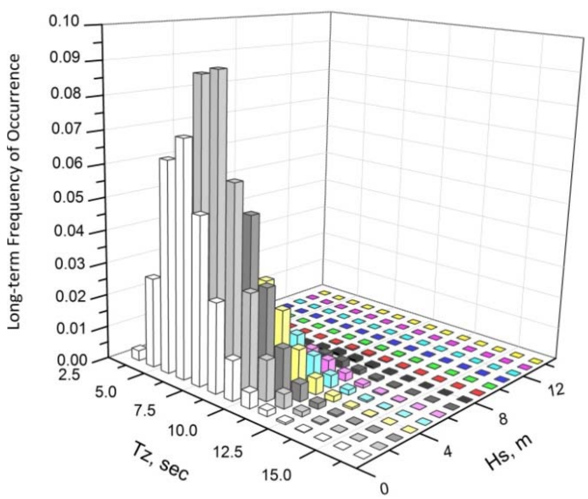


Fig. 6: Worldwide trade (WWT) sea scatter data

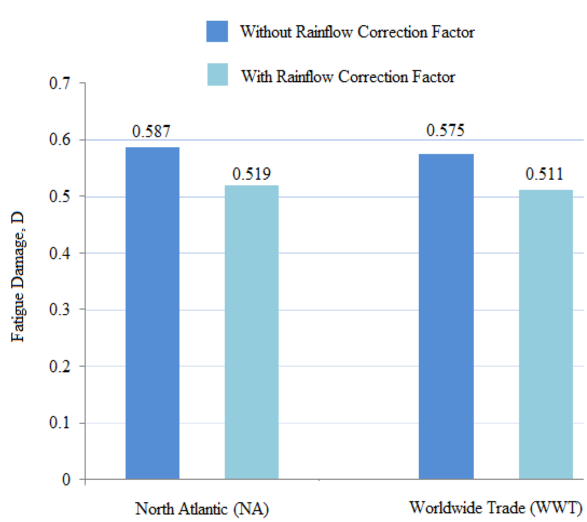


Fig. 7: Fatigue damage for NA and WWT sea scatter diagrams

corresponds to the non-operational time of the ship at harbor.

RESULTS AND DISCUSSION

The result of fatigue damage calculation for various scatter diagrams and effect of Wirsching's rain flow correction factor on computed fatigue life is shown in Fig. 7. Predicted fatigue damage using WWT scatter diagram is lower than the North Atlantic scatter diagram. This is in accordance with the established fact of North Atlantic as the severest condition for fatigue damage calculation.

Also, an increase in predicted fatigue life is observed by the inclusion of Wirsching's rain flow correction factor in spectral fatigue calculations.

CONCLUSION

This study presents procedure automation of full stochastic spectral based fatigue analysis of ship structure using ANSY and 3D linear sea keeping code AQWA. Spectral fatigue analysis is considered as the most reliable among the numerous methods for fatigue assessment of ship structure. Stochastic spectral fatigue is a complex and numerically intensive technique and requires a robust automated workflow of the process for efficient implementation to ship structures. In this study, various technical aspects of spectral fatigue methods are discussed in detail. For each aspect, APDL macros are created and subsequently implemented to automate the workflow of the process and to reduce the pre/post processing time for efficient implementation of the method to ship structures. A MATLAB program is developed to calculate cumulative fatigue damage. A numerical case study is conducted and the automation procedure is employed to predict fatigue life of a structure detail of a multihull craft for different sea scatter diagrams. Effect of Wirsching's rain flow correction factor toward predicted fatigue life of the structure is also investigated. The research study will provide a system to perform spectral fatigue analysis efficiently and accurately.

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