MIECZYSŁAW HANN, Assoc.Prof.,D.Sc.,M.E.
Technical University of Szczecin
Faculty of Maritime Technology
Ocean and Ship Technology Institute

Dynamics of hoisting cables for submersibles as a basis of random safety analysis

SUMMARY

A method of safety analysis of submersible's hoisting cables is sketched in the paper. The problems of description of loads applied to the cables and their influence on system's service reliability is also discussed.

INTRODUCTION

A basis for safety analysis of cable hoisting systems of submersibles, when taking into account their random service conditions, is to know load spectra and results of the experiments to obtain response to the applied loads of the complex cable systems. The information is used to determine a reliability function of a cable assumed to trigger occurence of a failure. Load spectrum of a cable of the multi-cable system can be determined by solving first a static and next dynamic problem of the structure, usually for the condition of its motion forced by a ship which the system is attached to. If a method of determining cable forces in the function of excitation frequency is known, it is possible to obtain response characteristics of the system. It is then possible, basing on sea wave energy spectra, to predict the magnitudes which characterize random process of cable force variability. When assuming a random character of the sea waving encountered by a system in service, a random process description of cable loads during all its operation period can be obtained.

For an assumed cable failure mechanism test results (of tensile strength or fatigue) can be taken to assess random process of cable capacity against loads. If parametres of the random processes of cable load and capacity are known it is possible to calculate the probability of occurence of a failure which can trigger the loss of safety by the entire system. The probability of loss or lowering of safety of the entire cable hoisting system can be determined by using one of the methods of random event path analysis applicable to complex systems (e.g. event tree analysis).

STATIC ANALYSIS

The static analysis method of hoisting cables applied in ocean technology consists in making use of the equilibrium conditions of the cable elementary segment dy_i (Fig. 1) to describe the sag curve of the immersed cable and tensile forces in it [2, 3].

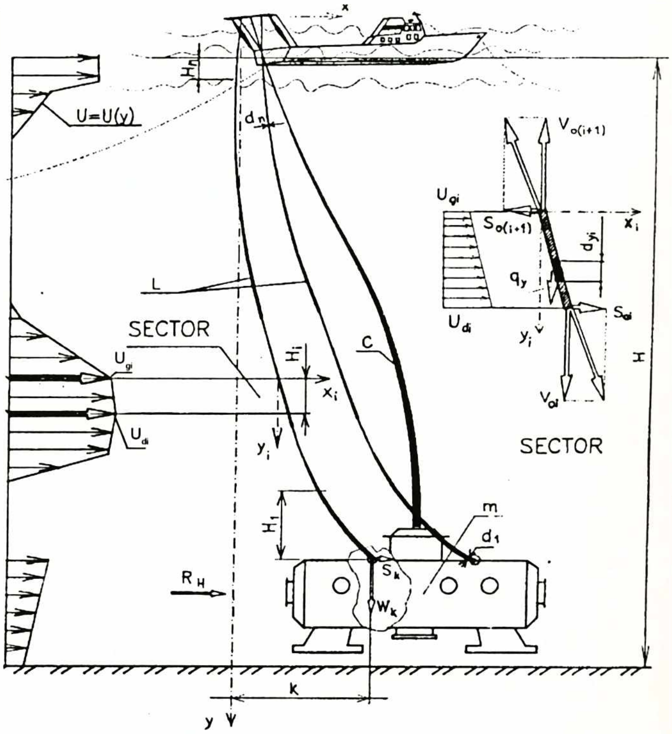

Fig. 1. Scheme used in static analysis of a multi-cable system

---

The paper presented at the Symposium on Ship Structure and Mechanics: Ultimate Capacity of Ship Structures , held ad memoriam of prof. M. Kmiecik, 20 and 21 March 1996, Szczecin

The following magnitudes are taken into account:

- the variable cable diameter d_n
- the horizontal hydrodynamic thrust due to sea currents with the velocity U arbitrarily distributed in function of the water depth y, as well as boundary conditions.

The condition of the common displacement k of the lower cable ends is applied to obtain loads relevant to each cable of a multi-cable system (Fig. 1). It leads to description of the sag curve coordinates by a nonlinear relationship in respect to the immersed cable weight, local flow velocity and tension force in a cable in question. In result the force variability in the cable with the water depth is established. The method was used to prepare MULTICASTA computer program for static analysis of multi-cable systems. The program can be used for systems with five types of cables in respect to their functions:

- load-carrying (hoisting) cables
- load-carrying cables of controllable tension
- stretched guiding cables
- free guiding cables
- ballast cables.

The program makes the following consecutive locations of an immersing object possible.

In Fig. 2. results are exemplified of such analysis performed for the diving bell hoisting system shown in Fig. 4. This is the system comprising one load-carrying steel cable N, two guiding steel cables P, which are stretched with a set-up force, and one load-carrying stretched cable-pipe K (of a large diameter and mass, but the minimum apparent weight).

The static sag curve is the coordinate system applied in the vibration analysis of the cables and the submersible.

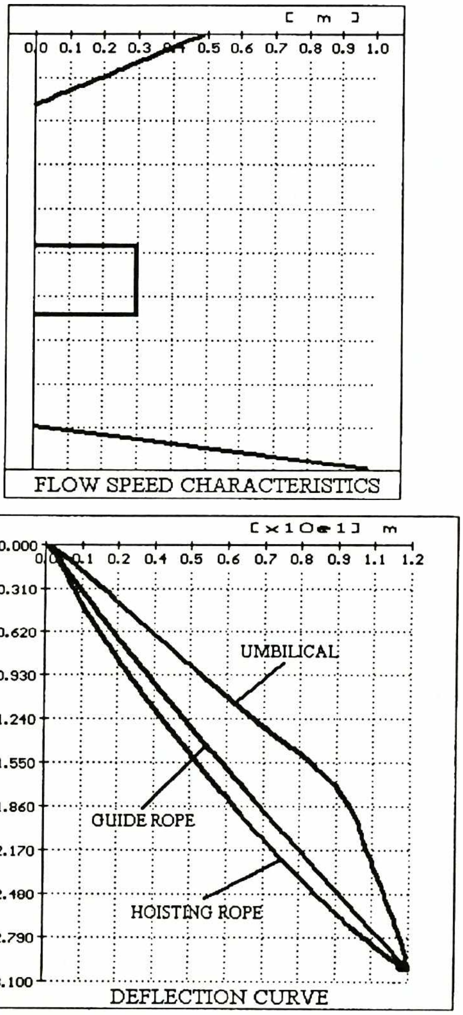

Fig. 2. Example of static analysis results

DYNAMIC ANALYSIS

Dynamic analysis methods of the submersible hoisting cables are developed with the assumption that the cables are an elastic continuum of a curvilinear form. When applying e.g. discretization [7] or FEM methods serious difficulties may be met due to an unsufficient computer capacity, excessive computation time and ,often, numerical instability. This can be felt especially while solving multi-cable system problems where the method of successive approximations is to be used to fulfil cooperation conditions of the cables connected with a hoisted object and often these due to operation of deck machinery.

An outline of the continuum analysis method is presented below, where the in-plane stationary vibration of both cables and submersible, which are kinematically excited by the harmonic motion of the upper end of each cable, is considered.

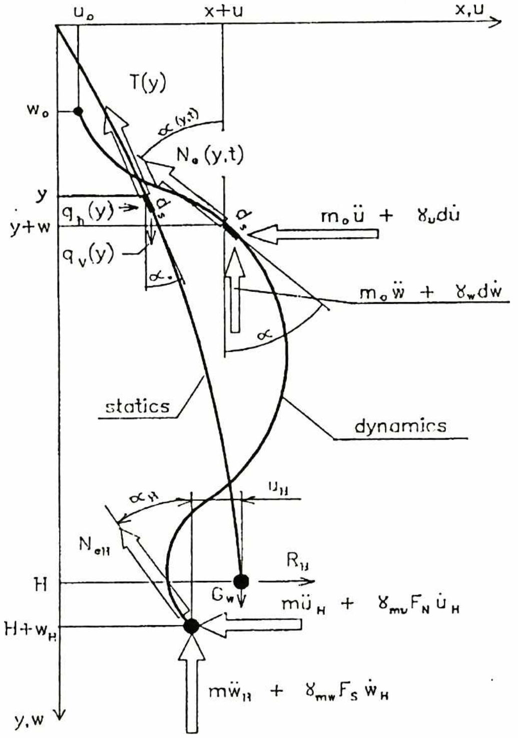

Fig. 3. Scheme for the in-plane vibration analysis of a single cableloaded by a submersible

The dynamic equilibrium analysis of the cable elementary segment d_s provides description of its small vibrations by using the following nonlinear differential equations of motion with the partial derivatives in respect to the depth y and time t:

$$\ddot{u}+2n_u\dot{u}+k_m g\left[u'-\left(H_1-y\right)u''\right]=\frac{EF}{m}\left(\varepsilon' x'+x'\right) \qquad (1)$$

$$\ddot{w}+2n_w\dot{w}+k_m g\left[w'-\left(H_1-y\right)w''\right]=\frac{EF}{m}\varepsilon' \qquad (2)$$

and the linearized relationship of strains and displacements is of the following form:

$$\varepsilon = x'u' + w' \qquad (3)$$

where:

$u = u(y, t)$ - horizontal coordinate of vibrations
$w = w(y, t)$ - vertical coordinate of vibrations
$e = e(y, t)$ - cable longitudinal strain
m - cable unit mass
H_l - object's equivalent depth of immersion
H - object's real depth of immersion
y - vertical coordinate (depth)
n_u - horizontal damping coefficient

n_w - vertical damping coefficient
k_m - cable apparent weight coefficient
E - cable Young's modulus
F - cable cross-section area

The equivalent depth takes into account the static load T_H of the lower cable end and it serves to determine η, a new depth coordinate:

$$\eta = 2\lambda_n \sqrt{\frac{H_1 - y}{k_m g}} \qquad H_1 = H + \frac{T_H}{k_m g} \tag{4}$$

It can be shown, after transformation of the problem to the uniform one and separation of the variables, that the Bessel's function of zero order is the eigenfunction of the boundary value problem [1]. The function is of the following form:

$$F_n(\eta) = Y_0(0) I_0(\eta) + I_0(0) Y_0(\eta) \tag{5}$$

Determining the eigenvalues λ_n for uniform boundary conditions a set of orthogonal eigenfunctions of the boundary value problem is formed. The in-plane vibrations of the cable and submersible are described by using the following solutions obtained when expanding them into finite series in respect to the set:

$$\begin{gathered} u(y) = A(y)\sin(\omega t) + B(y)\cos(\omega t) \\ u(H) = C_3 \sin(\omega t) + C_4 \cos(\omega t) \\ w(y) = M(y)\sin(\omega t) + N(y)\cos(\omega t) \end{gathered} \tag{6}$$

where:

$$A(y) = X_m + \frac{C_3 - X_m}{H} y + \sum_{n=1}^{k} C_{1n} F_n(\eta)$$

$$B(y) = \frac{C_4}{H} y + \sum_{n=1}^{k} C_{2n} F_n(\eta)$$

$$M(y) = Y_{m1} - \frac{C_3 - X_m}{H} x - \sum_{n=1}^{k} C_{1n} \int x' F_n'(\eta) dy + \frac{1}{EF} \int \Omega_A(y) dy$$

$$N(y) = Y_{m2} - \frac{C_4}{H} x - \sum_{n=1}^{k} C_{2n} \int x' F_n'(\eta) dy + \frac{1}{EF} \int \Omega_B(y) dy$$

The constants C_{1n}, C_{2n}, C_3, C_4 are determined from the set of algebraic equations, obtained on the basis of the equations of motion, among which are motion equations of the submersible which connects cables with the fulfilled condition of the common displacement of their ends attached to the submersible. Each of the constants C_{1n}, C_{2n} is related to a given cable.

This basic description of the in-plane vibrations can be utilized to analyse dynamic behaviour of the real objects equipped with the facility which can compensate sea waving influence on submersible's oscillations. An example of such a system is the diving bell hoisting facility shown in Fig. 4. It consists of a double-drum hoisting winch for one hoisting cable and two guiding cables and a hoisting winch for the cable-pipe feeding the bell. The system compensates oscillations in such a way that, while the guiding cables are anchored and stretched with an automatically controlled pull, the hoisting cable drum follows the motion of the guiding cable drum. The guiding cable drum motion is a linear function of motion of the cable attachment point, loaded with an error due to longitudinal deformation of guiding cables. Therefore the accuracy of stabilization of bell's location mainly depends on the accuracy of stabilization of forces in the cables.

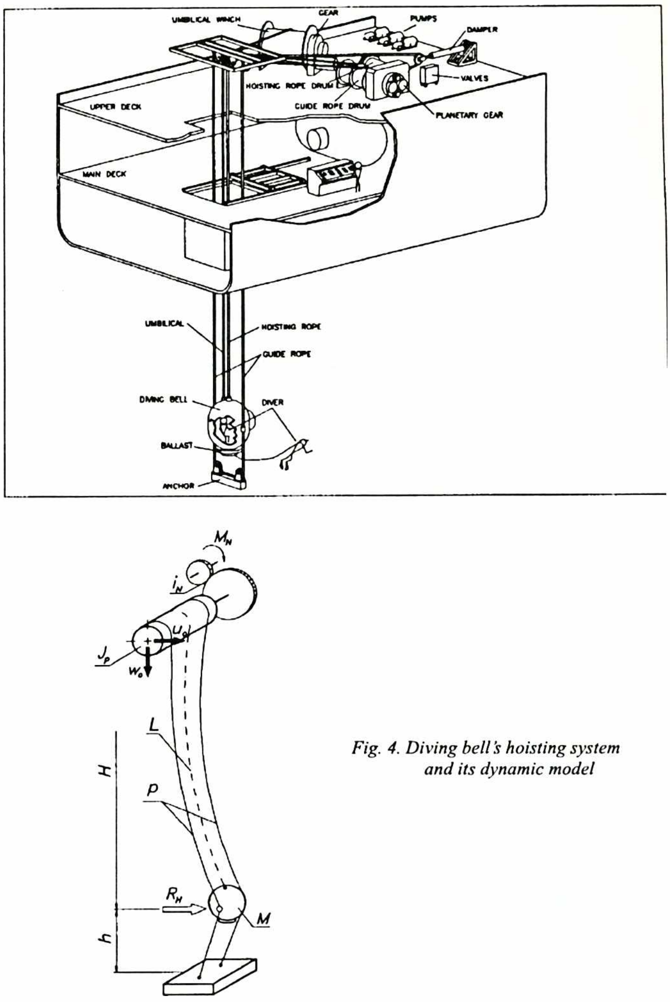

Fig. 4. Diving bell's hoisting system and its dynamic model

Such a system can be analysed when assuming an operation error inherent in an automatic control of guiding cable forces. Having assumed the error one can calculate system's response e.g. a relationship of object's vibrations and cable forces versus frequency of excitations. Results of such analysis are exemplified in Fig. 5 which shows the excitation motion amplitudes X_I (horizontal) and Y_I (vertical), related to the wave height h_v, in function of the frequency of excitations w, calculated for the research vessel, WITIAZ, in regular waves.

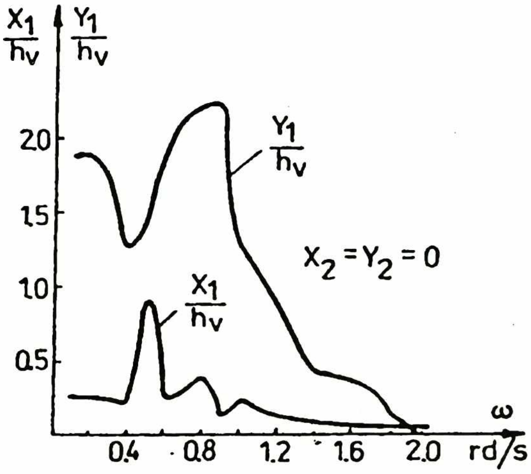

Fig. 5. Amplitude-frequency characteristics of excitation (an example calculated for the research vessel, WITIAZ)

In Fig. 6 a frequency characteristics of the „dynamic factor" Ψ_d related to the wave height h_v is presented. The factor is the ratio of the cable kinetic force S and its static force. The presented characteristics are given for a system of one hoisting cable and no compensating facility and a multi-cable system with compensation.

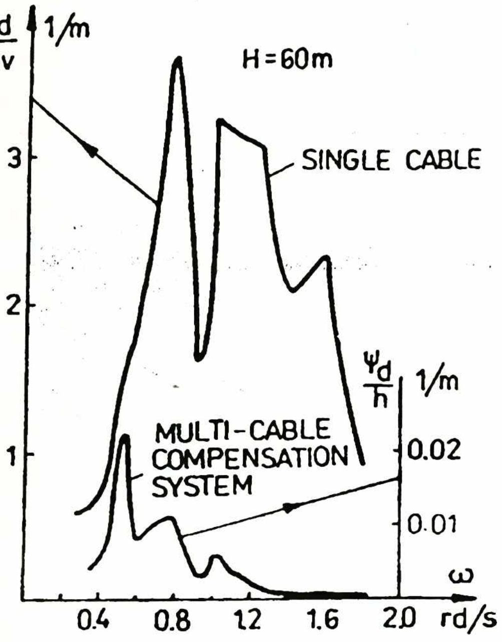

Fig. 6. „Dynamic factor"-frequency characteristics of cable forces (an example calculated for two types of hoisting systems)

Such a dynamic problem is much more complicated if free vibrations are accounted for which can be generated periodically at the moment of each compensating reversal of the winch drums. The reversal is accompanied with a momentary stand-by of the drums and in result a momentary loss of compensation. In this short-time period the tension in the guiding cables grows which is a source of energy generating extensive oscillations of the submersible [4].

The amplitude-frequency characteristics of cable forces are a starting point for system's safety analysis.

SAFETY ANALYSIS

It is possible to perform safety analysis of a system during its useful life if reliability characteristics of its components are known. Assuming cables the most important system's components and their failure mechanism known it is possible to determine the reliability function of them. The proposed method [5] consists in the determination of a degree of fatigue failure of the cable due to its multifold hog-sag bending against pulleys while making reversible compensation motions.

As the above described frequency characteristics of the forces S, denoted $\Phi_{(\omega)}$ here, can be known, it is possible to determine the variance of variability of their random process as follows:

$$D_s^2 = \int_0^\infty \left|\Phi(\omega)\right|^2 S(\omega)\, d\omega \qquad (7)$$

It makes it possible to calculate probability density function of the process e.g by applying Rayleigh's approach:

$$f(S) = \frac{S}{4D_s^2}\exp\left(-\frac{S^2}{8D_s^2}\right) \qquad (8)$$

Applying now the linear cumulation hypotesis of fatigue failure, the equivalent force S_k can be determined for a sea state which limits the energy spectrum S(ω) assumed in (7):

$$S_k = S_f + 2.5\sqrt[k_w]{\int_0^\infty f(S) S^{k_w} dS} \qquad (9)$$

When generating a sea state „encountered" at random within the allowable system's operation states [6], a degree of growing fatigue failure during a given time period q can be determined in compliance with the following relationship:

$$U_z = \frac{1}{Z_0}\sum_{q=1}^{z}\sum_{k=1}^{f} n_k \left(\frac{S_k}{S_0}\right)^{k_w} \qquad (10)$$

where:

Z_0 - number of cycles to failure determined from cable bending fatigue tests
S_0 - cable tensile force during the tests
k_w - cotangens of Wohler's straight line slope angle
f - number of different operation phases in one operation cycle
n_k - number of cable bending cycles in a given phase

In result, the probability that a load will exceed structural capacity can be determined according to one of the known probabilistic methods of I-level [8].

It is assumed additionally that the cable breaking force drops linearly along with growing degree of fatigue failure. The calculated probability is thus a function of time which makes it possible to determine the cable's reliability function.

An event tree can now be constructed in which an assumed accident, e.g. diving bell sinkage, is taken as the top event and a cable rupture as the initiating event. Occurence probability of the accident, viz. unreliability of safety, can be determined by applying Boole's algebra method or computer simulation [9].

The problem is only outlined here, but it is its solution that could provide a satisfactory response to the system's safety question.

FINAL REMARKS

In the paper an itegral approach to the operation safety of hoisting submersibles was outlined. To proceed an analysis in this way many physical phenomena which occur while operating such systems should be known. Understanding the phenomena is often uncomplete which causes limitation of such analyses or even reducing them to the deterministic ones based only on safety factor evaluation. In each case however the starting point is finding the loads, especially dynamic ones, acting in hoisting cables.

NOMENCLATURE

Indices

$\dot{u}$, $\ddot{u}$ - the first and second derivative in respect to time
u', u'' - the first and second derivative in respect to depth
n - succesive number of eigenvalue
k - work phase number

Denotations

c - special cable (umbilical)
d_l - diameter of the lower part of cable
d_i - cable (or cable sector) diameter
d_n - diameter of the upper part of cable
d_s - elementary cable section
D_g - guide cable drum diameter
E - Young modulus of cable
F - cable cross section
F(η) - eigenfunction in Bessel's form of zero order
F_N - submersible side surface
F_S - submersible front surface
g - gravity acceleration
G_w - submersible weight in water

h - distance between submersible and sea bed
H - submersible position depth
H_1 - equivalent submersible position depth
i_N - transmission ratio between drum and motor
I_p - winch moment of inertia
k - horizontal static displacement of submersible
k_m - weight coefficient of cable in water
L - load (hoisting) cable
m_o - cable unit mass
M - submersible mass
M_N - hydraulic motor stretch moment
n_k - fatigue cycle number of cable in bending
n_u - cable horizontal damping coefficient
n_w - cable vertical damping coefficient
N_{eH} - effective cable drag force at the lower point
N_o - effective (static and dynamic) cable drag force
p - guide cable
q_n - horizontal water flow pressure
q_v - cable unit weight in water
q_y - cable unit weight in water
R_H - horizontal hydrodynamic force applied to submersible
S_f - cable static force
s_k - horizontal component of static force applied to the end of cable
S_{oi} - cable static force horizontal component
t - time
$T(H)$ - resultant static force applied to the cable lower end
$T(y)$ - cable static force
$u(y, t)$ - cable horizontal vibration amplitude
$u_H = u(H,t)$ - horizontal vibration amplitude at the lower point of cable
u_0 - horizontal excitation
U - water flow speed
U_d - water flow speed on the level of the lower end of depth sector
U_g - water flow speed on the level of the upper end of depth sector
V_i - cable static force vertical component
V_{0i} - vertical component of static force applied to the cable section end
$w(y, t)$ - cable vertical vibration amplitude
$w_H = w(H,t)$ - cable vertical vibration amplitude
w_0 - vertical excitation
W_k - vertical component of static force applied to the lower end of cable
x - cable horizontal static displacement in global coordinate system
x_i - cable horizontal static displacement in local coordinate system
X_m - horizontal excitation amplitude component
y - vertical coordinate (depth)
y_i - local vertical coordinate
Y_m, Y_n - vertical excitation amplitude components
$\alpha(y,t)$ - cable dynamic angle of inclination
$\alpha_H = \alpha(H,t)$ - cable static angle of inclination at the lower point
α_0 - cable static angle of inclination
γ_{mu} - submersible horizontal damping coefficient of proportionality
γ_{mw} - submersible vertical damping coefficient of proportionality
γ_u - cable horizontal damping coefficient of proportionality
γ_w - cable vertical damping coefficient of proportionality
ε - cable elastic strain
η - function of depth acc. to (4)
λ_n - eigenvalue

BIBLIOGRAPHY

1. Hann M.: „ Dynamika cięgien podnoszących obiekty podwodne przy wymuszeniu oscylacyjnym na powierzchni morza ". Technika Morska, PAN Oddz. Gdańsk, 1991, vol.2
2. Hann M.: „ Theoretical and Experimental Investigation Procedure of the Submersible Hoisting Systems ". ESDA proceedings of 1994: Engineering Systems Design and Analysis Conference, July 1994, vol. 8, part C
3. Hann M.: „ Statics and Dynamics of Multi-cable Systems for Submersible ". Elsevier Science Ltd, Marine Structures, 1995, no. 8
4. Hann M.: „ Investigation procedure of diving bell stabilization as an effect of operatio of automatically controlled planetary winch ". Ninth Congress of Theory of Mechanisms and Machines, Milano, 1995
5. Hann M.: „ Metoda określenia funkcji niezawodności cięgien podnoszących obiekty podwodne ". II Konferencja Okrętownictwo i Oceanotechnika - Rozwój Maszyn Pokładowych i Techniki Przeładunków - Bezpieczeństwo, Międzyzdroje, 1995
6. Józiak W., Rosochacki W.: „ Przykłady zastosowań symulacji komputerowej w badaniach bezpieczeństwa systemów podnośnych obiektów podwodnych ". II Konferencja Okrętownictwo i Oceanotechnika - Rozwój Maszyn Pokładowych i Techniki Przeładunków - Bezpieczeństwo, Międzyzdroje, 1995
7. Liu F.C.: „ Snap Loads and Bending Fatigue in Bell Handling Systems ". Offshore Technology Conference, Houston, 1981
8. Murzewski J.: „ Niezawodność konstrukcji inżynierskich ". Arkady, Warszawa, 1989
9. Ważyńska-Fiok K., Jaźwiński J.: „ Bezpieczeństwo systemów technicznych ". PWN, Warszawa, 1990

Conferences

Conversatoria on Marine Corrosion revived

Twenty domestic meetings of corrosion specialists, held before 1988, were rare opportunities of gathering the specialists from all over the country. Topics of the meetings always dealt with the latest scientific and practical achievements in corrosion fighting and prevention technology with a special attention paid to corrosion of marine facilities.

The meetings always attracted practitioners from other industries because corrosion fighting in the marine environment was the best proof of its effectiveness also for the land-based structures.

It was the Marine Corrosion Department, Maritime Institute in Gdańsk, the initiator and main organizer of the *conversatoria*. Unfortunately they had been suspended for 7 years due to various reasons, and the XXI session was organized just in the last year.

XXI Conversatorium on Marine Corrosion was held on 20 to 22 September 1995 in Jurata at the Hel Penninsula, organized also by The Marine Corrosion Department. About 160 persons participated in it having an opportunity to be acquainted with 40 specialist papers and current reports which were presented during two plenary sessions:

- the first, opening session on „ General corrosion problems and economic aspects"
- the other, closing session on „ Measuring technique"

as well as four topic sessions:

- „Coatings"
- „ Novel materials and corrosion prevention technologies"
- „Surface preparation before painting"
- „Electrochemical protection against corrosion".

The papers were prepared by the authors from the technical universities of Gdańsk, Poznań, Silesia, Warsaw, Higher Technical School in Radom , the Maritime Institute, Institute of Fine Mechanics, Building Technology, Plastics and Paints and Airforce Technical Institute, Ship Design and Research Centre and Merchant Marine Academy in Gdynia, as well as several representatives of coating producers.

The conversatorium was, as usual, a disscussion forum and opportunity for direct personal contacts between theoretists and practitioners of corrosion prevention technology.