STRUCTURAL MODELLING OF OIL SPILL CONTAINMENT BOOMS BY THE FINITE ELEMENT METHOD

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ABSTRACT

The first objective of this paper is to model the antipollution floating boom by considering it in the three different forms: the form of cables, the form of assemblies of articulated body, and in the form of membrane bodies. and then we make a comparison of its three different configurations.

KEYWORDS: cable, boom modelling, membrane, mechanical response, oil containment, minimization of leakage, finite element, coastal region, current effect.

INTRODUCTION

Few studies and significant progress were carried out during last years in the field of anti-pollution floating booms (CEDRE, 1995), however the problems related to the pollution of the coastal sea become increasingly crucial, and they become very important at the international level. Our works concern the numerical modelling of the floating boom, we consider three models to simulate the floating boom, we simulate the boom first under cable shape, second with articulated body and at least in membrane form.

In the first model, the cable element has undergone large displacements and rotations in three-dimensional space. The cable is discretized in finite elements and it undergone drags effects; this force is obtained from fluid mechanics by the marine current. The equilibrium equations are solved by using the iterative method of Newton.

In the second model, we consider also the assembly of body articulated elements, the solids are assumed to be mounted on systems compose of elastic springs and torsion spring.

At the last, we model the boom element by using the nonlinear theory of membranes, the boom is discretized in rectangular finite element with four nodes by using the Zienkiewicz-Irons (Haug and Powell, 1972) isoparametric element, the Newton-Raphson algorithm solves the non linearity of the problem.

In our applications, we exceed the speed 1m/s to 2m/s, which involve large effort of drag. The two end of the cable, bodies articulated, and membrane are fixed.

The analysis of the cable elements, solid articulated and the membrane boom allow releasing certain remarks and observations which make it possible to understand the floating boom behaviour and its dimensioning.

MATHEMATICAL FORMULATION OF THE PROBLEM

Cables elements

First we recall for numeric cable theory

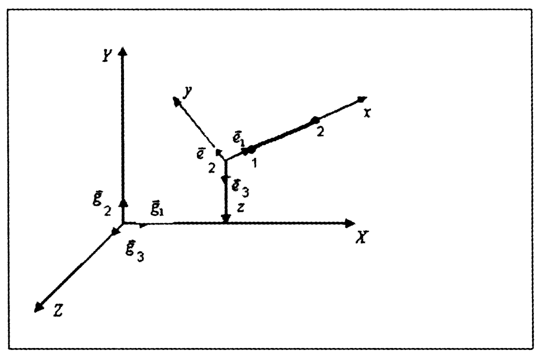

FIG.1. SYSTEM OF LOCATIONS.

Element cable is three-dimensional, it is considered that the material is linearly elastic and undergoes large displacements in three-dimensional space. Each node of cable element has three degrees of freedom which corresponds to three displacements for each node ($\xi_1\ \xi_2\ \xi_3\ \xi_4\ \xi_5\ \xi_6$). The various K systems are indicated in the figure (1). (X, Y, Z) are the global system, (x, y, z) is the local system, 1 and 2 are the nodes, (g_1, g_2, g_3) and (e_1, e_2, e_3) are respectively the unit vectors basic in the global system and local system with:

$$\begin{cases} \vec{e}_1 = \dfrac{\vec{L}}{L} \\ \vec{e}_3 = \dfrac{\vec{e}_1 \times \vec{g}_2}{\|\vec{e}_1 \times \vec{g}_2\|} \\ \vec{e}_2 = \vec{e}_3 \times \vec{e}_1 \\ L = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2} \end{cases}$$

Internal forces:

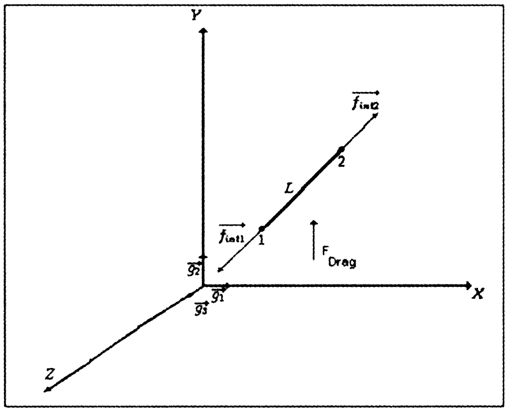

FIG.2. INTERNAL AND EXTERNAL FORCES.

L_o is the length of cable element in its initial state, L is the length of the deformed cable, the internal forces due to the elastic linearity of materials are:

E is the elastic module, A is the section of the cable, L_0 is the initial length. The derivative of

$$f^s = -P\begin{Bmatrix} \overset{\mathbf{l}}{e}_1 \\ \dots \\ -\overset{\mathbf{v}}{e}_1 \end{Bmatrix} \quad \text{with} \quad P = \frac{EA}{L_0}(L - L_0)$$

$$\frac{}{\partial \xi^{i,j}}$$

(ξ is the coordinates of the cable element, i indicates the number of the node, j indicates the dimension of the cable led to establishment of the matrix of elastic and geometrical tangent rigidity of the cable element (Haug and Powell, 1972b) $K_t = K_g + K_e$ with K_g is geometrical matrix, K_e is elastic matrix, the expression of K_g and K_e are:

Equilibrium equations:

$$K_g = -P\begin{bmatrix} \dfrac{\partial e_1}{\partial \xi} \\ -\dfrac{\partial e_1}{\partial \xi} \end{bmatrix} \quad \text{and} \quad K_e = -\begin{bmatrix} e_1 \\ -e_1 \end{bmatrix}\left\langle \frac{\partial P}{\partial \xi} \right\rangle$$

For a N number of degrees of freedom correspond a matrix column of force ΔF these forces are distributed in the following way:

$$\Delta F = F_l - F_i - F_d - F_s$$

F_i the inertia force, F_d damping forces, F_s forces of internal resistances, F_l forces due to the load. We consider the stationary situation of the cable; F_i and F_d are null. Finally the system of balanced equation is (Bonet, 2000):

$$\Delta F = F_l - F_s$$

Static equilibrium is reached by cancelling the forces balanced:

$$\Delta F = 0$$

The system of equations depends not linearly with the variables on the problems ξ. The method iteration of Newton is built for the increments displacements as follows:

$$\Delta\xi^{(i+1)} - \Delta\xi^{(i)} = -J^{-1}(\xi^{(i)})\Delta F(\xi^{(i)})$$

Or: $$[J(\xi_0)]\{\Delta\xi\} = -\{\Delta F(\xi_0)\}$$

With:

$[J(\xi_0)] = [K_t]_\xi$ is the total matrix of rigidity obtained by assembly of the elementary matrix of rigidity:

$[K_t] = \sum_1^{Nelt} k_t$ is the number of elements.

Articulated body elements

Let us now present the theory of rigid articulated bodies with elastic connections, we considers the elements solid and elastic springs, the assembly led to the following structure:

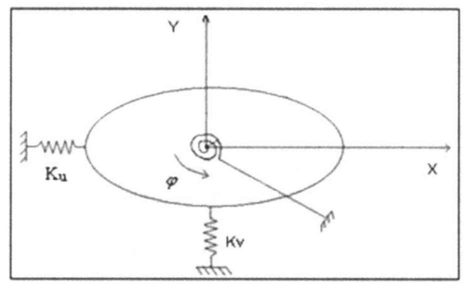

FIG.3. BODY ARTICULATED ELEMENT, KU , KV: RIGIDITY OF THE LONGITUDINAL SPRING, K_Θ RIGIDITY OF THE TORSION SPRING.

The figure (fig.3) above represents articulated body element, our system is composed of several assembly solid and elastic springs. The solids are assumed to be mounted on systems compose of elastic springs and dashpots. Thus displacements of these articulated solids due to the elastic strain are "drowned" in displacements more important, and the articulated solid movement is similar to the rigid evolution of body. Springs and torsion spring elements added to the articulated solid element allow displacements and rotations in the horizontal plane.

Methodology to follow in order to build this model of articulated solid consists to study each solid articulated separately and to calculate the matrix of stiffness by associating the corresponding degrees of freedom.

The spring element undergoes traction as well as the elements solid, which corresponds to the following rigidity matrix (Gay and Gambelin, 1999):

$$K_1 = \begin{bmatrix} Ku & -Ku & 0 \\ -Ku & (Ku + \dfrac{ES}{l}) & -\dfrac{ES}{l} \\ 0 & -\dfrac{ES}{l} & \dfrac{ES}{l} \end{bmatrix}$$

Ku is the stiffness of the spring generating displacement according to X, and it is supposed that the spring also moves according to Y whose matrix of rigidity is :

$$K_2 = \begin{bmatrix} Kv & -Kv \\ -Kv & Kv \end{bmatrix}$$

Kv is the stiffness of the spring generating displacement following Y. If the assembly solid and spring undergo flexion, we will have the matrix of following rigidity:

$$K_3 = \begin{bmatrix} K\theta & 0 & -K\theta & 0 & 0 \\ 0 & \frac{12EI}{l^3} & \frac{6EI}{l^2} & -\frac{12EI}{l^3} & \frac{6EI}{l^2} \\ -K\theta & \frac{6EI}{l^2} & (K\theta + \frac{4EI}{l}) & -\frac{6EI}{l^2} & \frac{2EI}{l} \\ 0 & -\frac{12EI}{l^3} & -\frac{6EI}{l^2} & \frac{12EI}{l^3} & -\frac{6EI}{l^2} \\ 0 & \frac{6EI}{l^2} & \frac{2EI}{l} & -\frac{6EI}{l^2} & \frac{4EI}{l} \end{bmatrix}$$

$K\theta$ is the rigidity of the dashpots. The matrix of rigidity of the whole of articulated solid is the sum of $K_1 + K_2 + K_3$. Finally we will have three degrees of freedom for each nodes, a rotation according to Z and two displacement respectively according to X and Y.

Membrane element

At last, we recall the numerical membrane theory (Boushaba, Muttin and Boulerhcha, 2004)

Discretization:

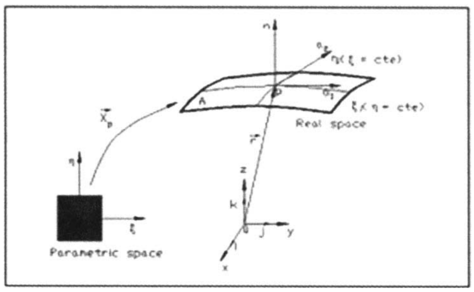

FIG.4. MEMBRANE ELEMENT: PARAMETRIC REPRESENTATION OF SURFACE (BATOZ AND GOURI, 1992)

We consider the membrane structure element discretized by using the finite element method, element is selected under rectangular quadrilateral isoparametric form with four nodes of ZienKiewics-Will (Haug and Powell, 1972a), element geometric is completely described with the global coordinates, the number of degrees of freedom per element is 12, 3 degrees of freedom by nodes which corresponds to displacements according to X, Y, Z. Displacements U and coordinates X are expressed with the interpolation functions (weight function) N in the following form:

$$\begin{cases} X_i = \sum_{j=1}^{4} N_j X_{ij} & i = 1,3 \\ U_i = \sum_{j=1}^{4} N_j U_{ij} & j = 1,3 \end{cases} \quad (1)$$

i is the index of the degrees of freedom by nodes, j is the index of the number of nodes per element. The explicit form of the interpolation function is:

$$\begin{cases} N_1 = \frac{1}{4}(1+\xi)(1+\eta) \\ N_2 = \frac{1}{4}(1-\xi)(1+\eta) \\ N_3 = \frac{1}{4}(1+\xi)(1-\eta) \\ N_4 = \frac{1}{4}(1-\xi)(1-\eta) \end{cases}$$

We locate the point P with the position vector $\vec{r}$ expressed with respect to the global system:

$$\vec{r} = \sum_{i=1}^{3} X_i K_i \quad (2)$$

K_i is the unit basic vector (i, j, k), we substitute (1) in (2)

$$\vec{r} = \sum_{i}^{3} \sum_{j=1}^{4} N_j X_i K_i$$

The basic vector of the surface is:

$$\frac{\partial a}{\partial \alpha} = \sum_{i}^{3} \sum_{j=1}^{4} \frac{\partial N_j}{\partial \alpha} X_i K_i \qquad \alpha = 1,2$$

Virtual works are given in the following form:

$$\delta w = \delta \lfloor dU_i \{kg_{ij} + ke_{ij}\} dU_j \rfloor$$

kg_{ij} and ke_{ij} are respectively geometric and elastic stiffness coefficients matrix. For more detail see (Haug and Powell, 1972a). The algorithm of Newton-Raphson makes it possible to counterbalance various forces so reaching equilibrium between the forces outside applied and the tension necessary in order to maintain the structure in the deformed state. The expression of the force necessary to ensure equilibrium of the element is given by virtual works; its expression associates the degree of freedom.

The efforts applied to the structure are discretised by using the definite interpolation function. These efforts must be apply on each nodes, the nodal loads are calculated using geometrical deformed element. The force of gravity, pressure and force of drag are descritised in the similar manner; we consider that the drag effect, pressure force is normal with deformed element. The drag force (Hanis and Chacon, 2000), is the predominate wave induced force on a submerged object in shallow water, this force is calculated using the classic Roberson drag equation as seen in the following equation:

$$F_{drag} = \rho C_D A \frac{U^2}{2}$$

Where C_D is the coefficient of drag, ρ is the density of sea water, and A is the projected cross sectional area as seen from the direction of the flow, U is the maximum horizontal water velocity. The only unknown in the equation is the coefficient of drag, it depends on the shape and surface roughness of the object, it must be determined experimentally. In the three cases we apply the same forces of drags.

APPLICATION

In this study, we simulate the antipollution floating boom with a cable in a horizontal plan maintained at these two ends. We discretize the cable (the length is) in elements with two nodes, the number of nodes and elements are respectively, the cable undergoes the effort of drag whose characteristics are as follows: the density of seawater $\rho = 1025 kg / m^3$, speed $V = 2 m / s$, the coefficient of drag $C_D + 1.12$ (these values are extreme values). The CPU time is 8.42s.

We can imagine that the floating boom is composed of an assembly of articulated solids, between each two solids, one interposes elastic element which plays the part of a spring element, this virtual spring can undergo traction according to and rotation following the plan according to. The figure (fig.5) shows the behaviour of the articulated solids and cables, under the effect of the drag force. We notes an excellent symmetry of displacements in the plan and also an excellent coincidence of displacements of the two articulated solid models and cables. The cable generates a maximum tension of 17 tons, while the articulated solid undergoes a tension of 19 tons, this difference can be justified by the choice and the calibration of the rigidity spring coefficients intercalated between two solids. We choose the same initial configuration in the form of spring (form in zigzag) see figure (fig.5). The CPU time of the articulated solid is 4.3s

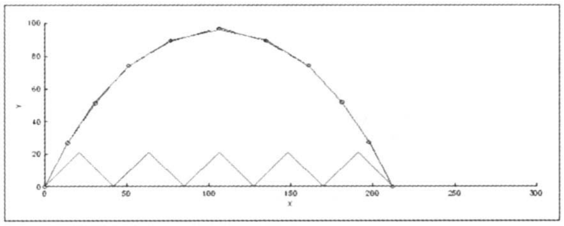

FIG.5. DISPLACEMENTS IN THE PLAN, SOLID LINE: CABLE, LINE WITH A CIRCLE: SOLID ARTICULATED, LINE IN ZIGZAG FORM: INITIAL CONFIGURATION.

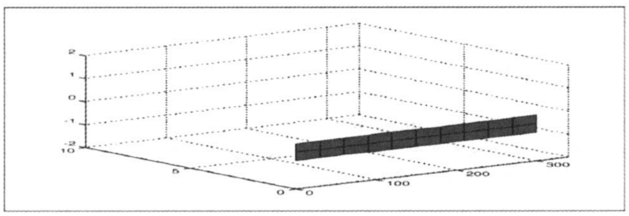

FIG.6. GRID AND INITIAL CONFIGURATION OF THE SKIRT

The skirt is modelled by using finite element Haug model, the skirt is the submerged part of the floating boom to prevent oil leaking. It is the essential part of the boom, it made with a flexible and resisting material. The skirt is discretized in finite elements with four nodes, the number of nodes and of elements are respectively 33, 20. We attack the skirt with efforts of drag. The figure (fig.6) represents the initial configuration before deformation, the figure (fig.7) represents a sight of top, we note an excellent symmetry in displacements, on the two ends we calculates a constraint of 27 tonnes, figure (fig.8) present the deformed skirt in the space.

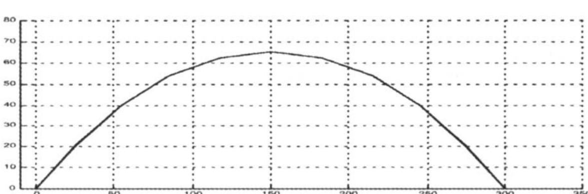

FIG.7. DISPLACEMENTS IN THE PLAN OF THE SKIRT

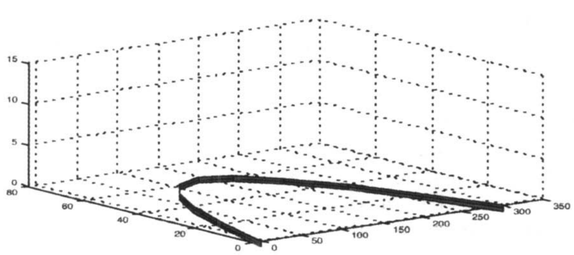

FIG.8. DISPLACEMENTS IN THE SPACE OF THE SKIRT

In the following example, we make a first case test of the floating boom, which is essentially composed of the floats, filled with air, which assure the buoyancy of the dam, the skirt which is the part which makes screen under the surface of floating. We analyze the behavior of section of floating boom which is made up of float and the skirt. The characteristic of this assembly are: diameter of the float is 0.55m the tie of water of the skirt is 0.75m and length 10m. The float as well as the skirt undergoes the force of drag of marine current v=2m/s, the coefficient of drag is 1.12; the pressure of inflation is of 350mbar. The dam is discretized in finite elements rectangular, the number of nodes and elements are respectively 121, 100 see figure (fig.9) as boundary conditions, we block the two ends of the skirt, we authorize the rotation of the float around axis Z. The CPU time of the boom is 5mn.

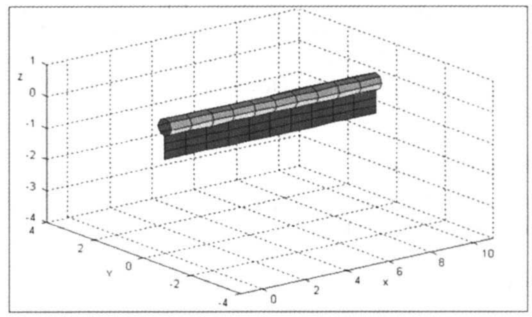

FIG.9. GRID USED IN THE PORTION OF THE BOOM

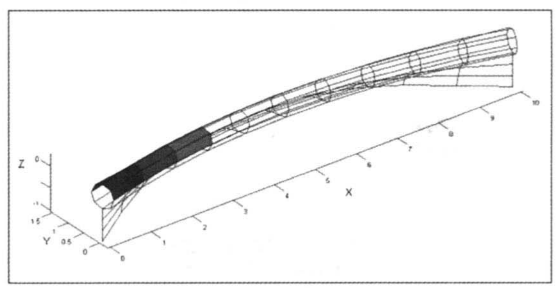

FIG.10. DEFORMED CONFIGURATION

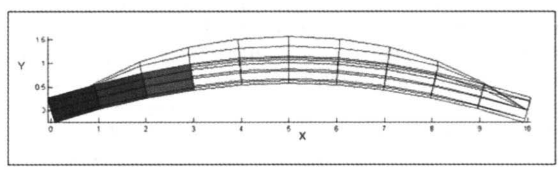

FIG.11. SIGHT OF TOP OF THE DEFORMED DAM

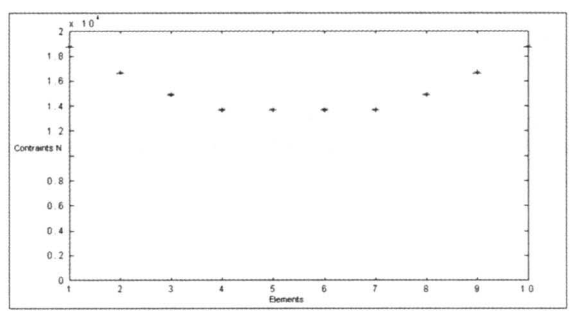

FIG.12. DISTRIBUTION OF CONSTRAINTS ALONG THE SKIRT

The (fig.10) shows the deformed configuration, the skirt undergoes a displacement and a deformation larger than the float. The sight of top see (fig.11) shows an excellent symmetry of the deformation in plan (X, Y), both extremities undergo a rotation around axis Z. On the level of the two ends of the skirt, we note an increase tension see (fig.12).

We made a success of the modeling of a section of floating boom by using the finite element method and the nonlinear theory of the membranes, but modeling proves to be heavy and expensive in computing times machine if one simulates an important length for example 1000 m.

CONCLUSION

To build a complete model of membrane proves to be heavy from numerical calculation, the basic idea is to build a simpler model which reproduces exactly the behavior of the floating boom in its natural environment. With this model of articulated solid, we can well simulate the model of cables of Haug. The simulation of solids articulated model is simple and so the computer code implantation, nevertheless certain difficulties appear when we want to adjust the coefficients of rigidities. We planned in next paper to reproduce the characteristics of the skirt (coefficients of rigidities) and inject into the model solids articulated in order to reproduce the behavior of the skirt undergoing the drag effort.

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