Application of GAP and ROD non-linear finite elements to determination of wave induced loads acting on open sea fish farms

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Abstract

The present paper includes structural analysis and assessment of a set composed of 6 cages. The set floating on a wavy sea surface is subject to pressure and inertial forces. The preliminary analysis neglects, however, the dynamic effects assuming that the set of 6 cages is self-balanced. Such assumption is possible due to the fact that the natural period of cage heave and pitch is several times less than sea wave period. The analysis has been made for the cage set on calm water and for steep sinusoidal wave coming from various directions. Finite element method version applied in computer program MSC Nastran 70.7 was used for the analysis.

For computation of 6-cage set special rod-type elements have been used in order to account for nonlinear relationship of local buoyancy versus tube immersion, fully emerged (or submerged) cross-section area, and for effect of structure deformability to the buoyancy forces. Global-local technique has been used for computation of local strength. Beam model of 6-cage set has been assumed as the global model, whereas cage corner and/or single cage are represented by local shell model.

1 Introduction

As the experience shows, fish raised in open sea farms grow greater and healthier, because better circulation of water favors oxygenation and dispersion of impurities. In this way the effects harmful for the environment can be avoided. Another advantage of open sea farms is the fact that, being located far from the seacoast, they do not affect the landscape and are less harmful for beaches, tourist industry, and development of towns.
The countries, which started their mariculture in closed water areas, such as fiords, tectonic lakes or areas protected by islands, are now tending to move the fishing farms towards the open sea. Raising the fish in open sea is now unique option for the countries having no protected areas. This is the case of Mediterranean coasts in some countries of Southern Europe, North Africa and Middle East.

On the other hand, the progress of mariculture in open sea is slowed down by several problems, the most important of them are:

- strong motions and loads of cages and nets;
- problems with regular supply of fish food;
- problems with monitoring the fish growth and health;
- necessity of using expensive and sophisticated means protecting the cages against poaching and collisions with ships.

The fish farmers are seeking technologically advanced solutions of the above-mentioned problems for reasonable price. Research institutions are preparing and developing such solutions and the manufacturers offer the marketable equipment. The fish cages in open sea farms are high technology product being the result of many years of research carried out with use of computer aided design (CAD), as well as towing tank tests. The floating structures discussed in this paper is of FUGO S.A. Konin design and will be applied in industrial mariculture of such sea fish as salmon or cod.

2 Scope of computation and method applied

The main supporting structure made (of steel tubes) in the form of square frame consists at the same time the main floating element suspending the net under it, which takes the form of rectangular prism immersed to the depth 30-35m. Platforms installed on the upper part of tubular structure are the foot-place for the workers. The floating structure is also the basis for equipment necessary for carrying out essential functions connected with fish farming and necessary for safety of the farm. The structural frame is equipped with hinges interconnecting the cages into multi-cage system for improving the fish farm productivity. The strength of the structure should be sufficient to withstand open sea conditions.

The present paper includes structural analysis and assessment of a set composed of 6 cages. The set floating on wavy surface of sea is subject to pressure and inertial forces. The preliminary analysis neglects, however, the dynamic effects assuming that the set of 6 cages is self-balanced. Such assumption is possible due to the fact that natural period of cage heave and pitch is several times less than sea wave period. The analysis has been made for the cage set on calm water and for steep sinusoidal wave coming from various directions. Finite element method version applied in computer program MSC Nastran 70.7 was used for the analysis.

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assumed as the global model, whereas cage corner and/or single cage are represented by local shell model.

3 Computational models

Various computational models have been used depending on the computation stage. All these models have been made with use of graphic pre-processor *MSC PATRAN 2000*.

The computational model assumed for the global analysis contains the structure of the whole set of 6 cages, including the hinges interconnecting adjoining segments. For the mesh of subdivision into finite elements, see Figs 2 and 3. The FE model consists mainly of 2-node beam elements. Articulated interconnections between the cages, as well as special elements (RBE3) for finding boundary displacements of shell model of the corner, are shown in Fig. 3. The Figure shows also nonlinear-elastic rod elements (NEROD) and gap elements (GAP), applied for modeling water buoyancy forces of the tubular section. Fig. 1 shows assumed stress-strain relation for substitute nonlinear-elastic material of rod type elements. The model of set includes 2616 finite elements, as well as 2599 nodes, which is equivalent to 15726 degrees of freedom. The boundary conditions, shown in Fig. 2, protect the system against rigid body motion.

![Fig. 1 Equivalent material characteristics for nonlinear-elastic supports](image)

Effective solution of cage load problem was possible thanks to assumption of wave loads exerted to the cage set (equivalent to the wave profile) as
displacements of basic nodes of rods modeling the forces of buoyancy. The effect of complete emerging (or complete submersion) of cage cross-sections could be taken into account thanks to assumption of non-linear characteristics of these rods (see Fig. 1). The influence of structure flexibility upon the buoyancy forces was automatically accounted for, which was particularly important in case of asymmetric loads, due to small torsional rigidity of the cage itself.

The fragment of extreme cage corner and entire extreme cage, or cage 2 (in the event of longitudinal and transverse wave) was selected for further global-local computation on the basis of global analysis results.

Local model of extreme cage corner, shown in Fig. 6, was prepared separately with use of MSC PATRAN 2000. The FE model consists mainly of 8-node shell elements, however the hawse pipe has been modeled as beam. The support has been modeled with use of rigid beam-type elements RBE2 with the support in the hinge axis. The corner model includes 2439 finite elements, as well as 7202 nodes, which is equivalent to 35730 degrees of freedom.

The FE model of cage contains the structure of entire segment, including the hinges interconnecting segments and hawse pipes. For the mesh of subdivision into finite elements, see Fig. 9. The FE model consist mainly of 4-node shell type elements, however the hawse pipes have been modeled as beams, as well as diagonal reinforcing tubes in the structure corners. The supports have been modeled with use of rigid beam-type elements RBE2. The model includes 26428 finite elements, as well as 25948 nodes, which is equivalent to 129716 degrees of freedom.

For symmetric loads (longitudinal and transverse wave) the partial model is supported vertically\(^1\) in all the corners, in singular points in the hinge axis for vertical balance of the structure.

In the case of asymmetric loads (diagonal wave), the cage model has been loaded with displacements (computed for the entire set of 6 cages) in the corners, in singular points in the hinge axis. In this case the effect of system flexibility on distribution of water pressure in shell models should be taken into account (with simplifying assumption, that only relative displacements of supports are taken into consideration).

4 Computation results

Figs 5 shows selected results of the global analysis (for 6-cage set). Displacements computed at this stage are used for finding the loads of partial models (cage corners or entire selected cage) modeled with use of shell-type elements. Stresses computed for beam idealization (i.e. without local effects taken into account) can be used only for selection of local models for further analysis.

Fig. 9 shows maximum V.Mises stress in the corner of extreme cage in diagonal wave through. Maximum displacements of corners amount to 0.9 m (Fig. 5) due to small torsional rigidity of the cage. Fig. 10 shows maximum

\(^1\) Remaining boundary conditions, shown in Fig. 1, protect the system against rigid body motion
stresses in modified structure. Reduced stresses are generally less than permissible value 160 MPa, except the stresses in the area of connection between the hawse-pipe and shell, where they amount to 170 MPa, exceeding slightly the permissible value. In the computations in question the hawse-pipe is modeled, however, as a beam, which may cause excessive stress concentration in the connection area.

Table 1 show comparison of maximum reduced stresses in the original and in modified structures, also for symmetric loads and for the loads induced by mooring chain. It follows from the results of computation, that structural modification reduced maximum stresses for diagonal wave by more than 50%. However, the maximum stress, amounting now to 170 MPa, occurs in the area of joint between hawse pipe and main tube, instead in the area of weld interconnecting of both perpendicular main tubes, as took place previously. In cases of longitudinal and transverse waves, the maximum stresses near the hinges were also reduced (by about 20%). The following computations should be carried out for improving the accuracy of stress assessments:

- More accurate computation of stress concentration at the joint between hawse pipe and main tube, while modeling the hawse pipe with shell elements;
- Computation for 2 support points within the area of hinges (instead of only one), taking into account effect of hinge gap and distortion of bush.

<table>
<thead>
<tr>
<th>Load condition</th>
<th>Original structure [MPa]</th>
<th>Modified structure [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Still water</td>
<td>15.1</td>
<td>78.5</td>
</tr>
<tr>
<td>2. Wave trough direction X</td>
<td>99.7</td>
<td>78.5</td>
</tr>
<tr>
<td>3. Wave peak direction Z</td>
<td>154</td>
<td>124</td>
</tr>
<tr>
<td>4. Diagonal wave trough</td>
<td>342 (296)</td>
<td></td>
</tr>
<tr>
<td>5. Chain reaction 10T</td>
<td>59.8</td>
<td></td>
</tr>
</tbody>
</table>

5 Conclusions

The following conclusions, concerning strength of main structure with 6 cages, can be deduced from above discussed results:

1. In case of diagonal wave, maximum V.Mises stress amounts to 170 MPa and appears in the area of connection the hawse-pipe with main tube, rather than in the area of welded joint interconnecting two perpendicular main tubes, as in the original structure. However, in discussed computation, the hawse-pipe is modeled as a beam and this may cause excessive stress concentration in the area of connection with the shell. For more accurate stress assessment the computation of stress concentration should be made in above-mentioned area with hawse-pipe modeled by means of shell elements.

2. In case of longitudinal and transverse wave, maximum V.Mises stress amounts to 124 MPa in the area of hinges, and is less than permissible value.

\(^2\) The value in brackets results from computation with flat 4-node finite elements
However, the assumed boundary conditions (single support in the hinge axis) may reduce the stress within this area. For more accurate stress assessment the computation of stress concentration should be made for two supporting points in the area of hinges, taking into account the effect of hinge gap and distortion of bushes.

3. When neglecting hinge axis bending, maximum stress in the extreme cage, induced by 10T force in the mooring chain, amounts to 60 MPa and appears in the area of lower edge of the hawse-pipe.

4. Table 1 shows comparison of maximum reduced stresses in the original and in modified structures. As can be seen from the comparison of results presented in Table 1, the modifications introduced into the structure have reduced by 50% maximum stress for diagonal wave. For longitudinal and transverse wave, the maximum stresses in the area of hinges have been also substantially reduced (by about 20%).

5. The general conclusion is that described approach is a powerful tool in static and (hopefully) dynamic structural analysis of floating hinged systems.

Fig.3 Hinged connection between cages, as well as special elements (RBE3) for finding boundary displacements of shell model of the corner. The Figure shows also nonlinear-elastic rod elements (NEROD) and gap elements (GAP), applied for modeling water buoyancy forces of the tubular section.
Fig. 2 FE model of 6 cages set (2616 nodes, 2599 elements)

Fig. 4 6-cages set load distribution in the case of diagonal wave trough
Fig. 5 Deformation of cages in the case of diagonal wave trough

Fig. 6 Fine mesh FE model of extreme cage corner (7202 nodes, 3439 elements)
Fig. 7 Fine mesh FE model of the entire cage (26428 elements, 25948 nodes)

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Fringe: Scalar Pressure Plot

Fig. 8 Pressure distribution in the case of diagonal wave trough (with structure flexibility accounted for)
Fig. 9 Maximum V. Mises stresses in original structure for the cage on diagonal wave trough

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Fig. 10 Maximum V. Mises stresses in modified structure for the cage on diagonal wave trough

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SECTION 4

Navigation, ship operation and multimode transport