Efficient and accurate methods for computational simulation of netting structures with mesh resistance to opening

Doctoral Thesis

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Ferrol, November 2014
Introduction

• **Advantages of numerical simulation applied to fishing nets**
  - Different conditions can be simulated
  - Reduces the dependency on experimental tests (experimental validation is always required)
  - Provides information that is difficult to measure (forces in nodes, drag distribution…)

• **Relevance of the resistance to opening**
  - It is a key factor in the selective performance of a trawl
  - The inclusion of the resistance to opening in the numerical model is necessary to accurately approximate the net shape
**Introduction**

**Objective of this thesis:**

To include the mesh resistance to opening in numerical simulation of net structures

**Steps:**

1. Develop a twine model including the mesh resistance to opening → Article No. 1
2. Measure the resistance to opening → Article No. 2
3. Solve the equations that govern the net structure → Article No. 3
4. Implementation of the twine model → Article No. 4
Outline

Introduction

Article No. 1: Nonlinear stiffness models of a twine to describe MRO

Article No. 2: Quantifying MRO of netting panels

Article No. 3: Calculating the equilibrium shape of netting structures

Article No. 4: Numerical model for netting with MRO

Conclusions

Future work

Unpublished results
Article No. 1

Nonlinear stiffness models of a net twine to describe mesh resistance to opening of flexible net structures

*Journal of Engineering for the Maritime Environment*
Published online on 9th June 2014
Description of the twine model

• Literature
  - O’Neill’s analytical solutions (exact, asymptotic)
  - Priour’s linear model

• Assumptions from O’Neill’s model
  - Based on bending stiffness $EI$
  - 2D double-clamped beam
  - $x$ and $y$ coordinates and $F_x$ and $F_y$ forces
  - The insertion angle $\phi_0$ remains fixed
  - Bending moment proportional to the curvature

• Contributions of the new model
  - Solution obtained by FEM (ANSYS)
  - Twine extension is considered
  - Polar coordinates $R$ and $\varphi$ and $F_r$ and $F_\varphi$
Dimensional analysis

• Independent variables

\[ F = F(L, EA, EI, R, \varphi) \]

• Dimensionless similarity parameters

\[ \Pi_0 = f = F \frac{L^2}{EI} \]

\[ \Pi_1 = r = \frac{R}{L} \]

\[ \Pi_2 = \varphi \]

\[ \Pi_3 = \gamma = L^2 \frac{EA}{EI} \]

• Non-dimensional equation

\[ f = f(r, \varphi, \gamma) \quad \Rightarrow \quad f^{EA_i} = f^{EA_i}(r, \varphi) \]
Article No. 1: Nonlinear stiffness models of a twine to describe MRO

**Force-displacement response**

- Enforced displacement constraints in polar coordinates
- Geometric nonlinear static analysis to obtain the reaction forces

Grid surface representation of the dimensionless forces in polar coordinates \((f_r, f_\phi)\)
Approximate force models

1. Polynomial surface fitting

\[ f(r, \cos \varphi) = \sum_{0<i+j<m+n} c_{ij} r^i (\cos \varphi)^j \]

2. Spline surface fitting of the potential energy

\[ v_{ij}(r, \varphi) = \sum_{k=0}^{3} \sum_{l=0}^{3} c_{kl}^{ij} (r - r_i)^k (\varphi - \varphi_j)^l \]

Conservative field

\[ f_{ij}^{r} (r, \varphi) = \frac{\partial v_{ij}}{\partial r} \]
\[ f_{\varphi}^{ij} (r, \varphi) = \frac{1}{r} \frac{\partial v_{ij}}{\partial \varphi} \]

3. Spring-based model

\[ f_r (r, \cos \varphi) = EA \left( \frac{L^2}{EI} \right) (r - r_{eq} (\cos \varphi)) \]

\[ f_y \gg \gg f_x \]

\[ \frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \]
Test problem and results

• **Description:**
  - A twine with fixed $\phi_0$
  - A vertical force ($F_y > 0$) is applied to $P_1$

• **Different models are compared**
  - ANSYS solution (FEM)
  - Asymptotic solution
  - Exact solution
  - Model No. 1 Polynomial fitting
  - Model No. 2 Spline fitting
  - Model No. 3 Spring based

• Trajectory of point $P_1$ as the vertical force increases
- Force-displacement response

- Relative error in force
### Summary of the models

<table>
<thead>
<tr>
<th>Features</th>
<th>Linear model</th>
<th>Exact solution</th>
<th>Asymptotic solution</th>
<th>Proposed models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takes into account the bending stiffness ($EI$)</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Takes into account twine axial stiffness ($EA$)</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Forces as explicit function of position</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Highly accurate</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Easy to implement in existing formulations</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Conservative force field</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Compatible with large axial deformations</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Compatible with large transversal forces</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Article No. 2

Quantifying mesh resistance to opening of netting panels: experimental method, regression models and parameter estimation strategies

ICES Journal of Marine Science
Published online on 24th July 2014
Description of the experimental set-up

- Experimental set-up from Sala

- Expensive measuring instrument
- Imposed normal and transversal displacements
- Asymptotic solution as model
- Fixed constraint estimation strategy
- Disagreement between num. and exp. results

- Proposed experimental set-up

- Simple and inexpensive
- Imposed load in normal direction
- Previous twine models as models
- Different estimation strategies
Article No. 2: Quantifying MRO of netting panels

Methodology

• Experimental methodology
  - A normal load is applied and the normal elongation of the panel is measured
  - Different materials were tested
  - Loading and unloading cycle

• Data analysis
  - Parameters for the regression: $EI$, $b$, $L_{twine}$, $\phi_0$
  - Theoretical models for MRO:
    - Exact solution
    - Asymptotic solution
    - Polynomial fitting model
    - Spline fitting model
  - 4 parameter estimation strategies

<table>
<thead>
<tr>
<th>Estimation strategy</th>
<th>Constraint applied on parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L_{twine}$</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Min/max</td>
</tr>
<tr>
<td>3</td>
<td>Fixed</td>
</tr>
<tr>
<td>4(Sala)</td>
<td>-</td>
</tr>
</tbody>
</table>
### Summary of the results (loading cycle)

<table>
<thead>
<tr>
<th>Strategy No. 1</th>
<th>Strategy No.2</th>
<th>Strategy No.3</th>
<th>Strategy No.4 (Sala)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R² Estimates</td>
<td>R² Estimates</td>
<td>R² Estimates</td>
<td>R² Estimates ~0.7 for stiff materials results</td>
</tr>
</tbody>
</table>

**Asymptotic solution**
- -

**Exact solution**
- Small confidence intervals
  - Medium confidence intervals
  - Unusually high confidence intervals

**Polynomial fitting**
- >0.995 Occasionally out of physical limits or inconsistent
- >0.995 Acceptable results reducing the computational effort

**Spline fitting**
- >0.990 Inconsistent

### Article No. 2: Quantifying MRO of netting panels
Conclusions

• Start the analysis with Strategy No. 3

• Use Strategy No. 2 if Strategy No. 3 fails

• Use the same model to estimate the parameter and to predict the netting behaviour

• Limitations of this work
  - Difficulties to fit the unloading cycle
  - Does not consider the knot width
  - Accurate pre-tension cycles were not applied to the materials
Article No. 3

Assessing the suitability of gradient-based energy minimization methods to calculate the equilibrium shape of netting structures

*Computers and structures*
Published online on 10th February 2014
### Methods to calculate the static equilibrium

**• State of the art**

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newton Raphson Iteration (Priour)</td>
<td>Fast</td>
<td>Local convergence</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ill-conditioned Jacobian matrix</td>
</tr>
<tr>
<td>Dynamic simulation (Lee, Li, Takagi)</td>
<td>Robust and reliable</td>
<td>Very slow (hours)</td>
</tr>
<tr>
<td>Gradient-based energy minimization method</td>
<td>Avoids matrix operations</td>
<td>Only for conservative forces</td>
</tr>
<tr>
<td>(Le Dret)</td>
<td>Not affected by the Jacobian</td>
<td></td>
</tr>
</tbody>
</table>

**• Objectives of this work**

- Test different gradient-based energy minimization methods
- Include non-conservative forces in the analysis
- Compare Newton iteration and energy minimization methods
Article No. 3: Calculating the equilibrium shape of netting structures

Numerical model

- **Formulation developed by Priour**
  - Direct formulation of finite element method
  - Netting is discretized with triangular elements
  - Ropes and cables are discretized with bar elements

- **Applied forces**
  - Elastic forces in finite elements
  - Weight and buoyancy
  - Hydrodynamic drag (Fluid-structure interaction is not considered)
  - Contact with the seabed

- **Equilibrium equations**

\[ F(q) = f^{\text{twine}} + f^{\text{hydro}} + f^{\text{weight}} + f^{\text{buoyancy}} + f^{\text{contact}} \rightarrow F(q_{\text{equilibrium}}) = 0 \]
Article No. 3: Calculating the equilibrium shape of netting structures

Newton Raphson iteration

\[ F(q) = 0 \]

\[ d_i = -J^{-1}(q_i) F(q_i) \] Calculate search direction \( d \) with the Jacobian \( J \)

\[ q_{i+1} = q_i + \lambda d_i \] Perform step with step length \( \lambda \)

• Two approaches to achieve a globally convergent algorithm

1) Line search

\[ |F(q_i + \lambda_j d_i)| < (1 - \alpha)|F(q_i)| \]

- Calculate the step length \( \lambda \) with a line search and the Armijo rule

2) Step limit

\[ \lambda_i = \begin{cases} \frac{\lambda_{\text{max}}}{\max(d_i)} & \text{if } \max(d_i) > \lambda_{\text{max}} \\ 1 & \text{otherwise} \end{cases} \]

- Limit the step length \( \lambda \) to a fraction of the characteristic length (1%)
- Also used in method 1 when the line search stagnates (often)
Gradient-based energy minimization methods

• Find the equilibrium position by minimizing the total energy $v$

$$\min_{q} v(q) = E_p - W_{nc}$$

$E_p$: total potential energy of the system

$W_{nc}$: work done by non-conservative forces

• The gradient of $v$ is the opposite of the force vector

$$g = \nabla v(q) = -F(q)$$

• Tested 10 gradient-based methods $\rightarrow$ only 3 methods succeed:
  - Nonlinear conjugated gradient
  - Limited memory BFGS (LBFGS)
  - Newton-CG Trust region

• After comparing the 3 methods, LBFGS is the best suited to find the equilibrium of netting structures
Article No. 3: Calculating the equilibrium shape of netting structures

List of benchmark problems

- A set of benchmark problems is defined (400 variables)
- Reference solution obtained via dynamic simulation

<table>
<thead>
<tr>
<th>Feature</th>
<th>Test case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2A 2B 3A 3B 4A 4B 5 6A 6B</td>
</tr>
<tr>
<td>Large displacements</td>
<td>- ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>High initial stress</td>
<td>- ✓ - - - - - - -</td>
</tr>
<tr>
<td>Far initial position</td>
<td>- ✓ - - - - - ✓ -</td>
</tr>
<tr>
<td>Netting with low compression stiffness</td>
<td>- - - ✓ - ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Netting with very low compression stiffness</td>
<td>- - - ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Cable</td>
<td>- - - - ✓ ✓ - ✓ ✓</td>
</tr>
<tr>
<td>Cables, high stiffness</td>
<td>- - - - - ✓ - - -</td>
</tr>
<tr>
<td>Ground contact</td>
<td>- - - - - - ✓ ✓ ✓</td>
</tr>
<tr>
<td>Panel parallel to flow</td>
<td>- - - - - - - ✓ ✓</td>
</tr>
</tbody>
</table>

Test 1

Test 2A

Test 2B
Article No. 3: Calculating the equilibrium shape of netting structures

LBFGS versus Newton-Raphson: General trend

Test 2A: Large deformations. Far initial position

Test 2B: Large deformations. Close initial position
Effect of the problem size

- **Solved Test1**
  - Problem size: 363 – 5000 variables

- **The advantage of LBFGS over NR increases with the problem size**
  - It avoids matrix factorization
  - ×4 times faster (5000 variables)

- **The performance of NR is irregular**
  - Chances of getting tangled mesh configurations during the iteration increase with the number of finite elements used to model the netting
Summary of the results

<table>
<thead>
<tr>
<th>Features</th>
<th>Newton-Raphson</th>
<th>LBFGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robust</td>
<td>❌</td>
<td>✓</td>
</tr>
<tr>
<td>Easier to program</td>
<td>❌</td>
<td>✓</td>
</tr>
<tr>
<td>Faster in achieving medium precision solution</td>
<td>❌</td>
<td>✓</td>
</tr>
<tr>
<td>Faster in achieving high precision solution</td>
<td>✓</td>
<td>❌</td>
</tr>
<tr>
<td>Faster with the problem size</td>
<td>❌</td>
<td>✓</td>
</tr>
</tbody>
</table>

Newton-Raphson and LBFGS are complementary methods

- The use of each method depends on the application
- Both methods can be combined to solve problems
Article No. 4

An efficient and accurate model for netting structures with resistance to opening

Submitted to the *International Journal of Solids and Structures* on 25th April 2014
Description of the model

- **Lumped mass formulation (Takagi, Lee, Li)**
  - Point mass (knots) interconnected by springs
  - Intermediate nodes are usually required
  - The knot size is not considered

- **Objectives of this work**
  - Incorporate the *polynomial fitting twine model* in the lumped mass formulation
  - Include the knot size
  - Compare results from simulation with experimental measurements
  - Compare the new model with the traditional lumped mass formulation
Numerical model for a twine

- Twine model for large axial deformations

\[ f^{\text{twine}}(r, \varphi) = \alpha f^{\text{beam}} + (1 - \alpha) f^{\text{spring}} \]

\[ f^{\text{beam}} = (F_r^{\text{beam}}, F_{\varphi}^{\text{beam}}) \]

Polynomial fitting
- Twine model

Blending function

Spring for large axial deformation

\[ f^{\text{spring}} = (F_r^{\text{spring}}, 0) \]

\[ F_r^{\text{spring}}(r) = EA(r - 1) \]
Numerical model for a mesh

- A local frame is defined for each twine
  \[
  \{u_r, u_\varphi, u_z\}
  \]
  \[
  u_r = \frac{(p_1 - p_0)}{|p_1 - p_0|}
  \]
  \[
  u_z = t \times u_r
  \]
  \[
  u_\varphi = u_r \times u_z
  \]

- Spherical knot shape
  - The diameter is the average between the effective knot width \(a\) and height \(b\)
Numerical validation

• Comparison of the proposed model with FEM solution

• A net panel is stretched in normal and transversal direction
Experimental validation

• Reproduce the experiment from Article No. 2 for one sample panel

• Assumptions to validate
  - Lumped mass approximation
  - Spherical knots

• Results from fitting
  - $R^2 = 0.997$
  - $EI = 74.9 \pm 8.7\% \text{ Nmm}^2$
  - $L_{\text{twine}} = 41.5 \pm 2.6\% \text{ mm}$
  - $D = 2.1 \pm 0.7\% \text{ mm}$
  - $\phi_0 = 22.7 \pm 0.4\% \text{ rad}$
Analysis of the computational efficiency

- **Compare the proposed model with a classical spring model**
  - 100×100 mesh panel = 61812 variables
  - Vertical force is applied to the bottom edge
  - The panel is exposed to a constant water current normal to the panel

<table>
<thead>
<tr>
<th></th>
<th>Presented model</th>
<th>Classical linear spring model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical meshes</td>
<td>10000</td>
<td>10000</td>
</tr>
<tr>
<td>Total solution time (s)</td>
<td>305.5</td>
<td>162.4</td>
</tr>
<tr>
<td>Force evaluation calls</td>
<td>10933</td>
<td>10804</td>
</tr>
<tr>
<td>Time per call (ms)</td>
<td>27.9</td>
<td>15.0</td>
</tr>
<tr>
<td>Time per call per mesh (µs)</td>
<td>2.79</td>
<td>1.50</td>
</tr>
</tbody>
</table>
### Summary of the results

<table>
<thead>
<tr>
<th>Features</th>
<th>Lumped mass + springs</th>
<th>Lumped mass + polynomial fitting twine model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takes into account the bending stiffness (EI)</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Takes into account twine axial stiffness (EA)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Compatible with large deformations</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Easy to program</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Conservative field</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Avoids intermediate nodes</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Includes the knot size</td>
<td>✗</td>
<td>✓</td>
</tr>
</tbody>
</table>

Both models have a similar computational overhead
Outline

Introduction

Article No. 1: Nonlinear stiffness models of a twine to describe MRO

Article No. 2: Quantifying MRO of netting panels

Article No. 3: Calculating the equilibrium shape of netting structures

Article No. 4: Numerical model for netting with MRO

Conclusions

Future work

Unpublished results
Conclusions

• The proposed twine models have been demonstrated to be accurate, efficient, and easy to program

• The experimental procedure to measure the MRO is easy and accurate

• The LBFGS method has been proved to be efficient and accurate in the calculation of the equilibrium shape in problems with large number of variables

• The presented models and methods have been successfully applied to simulate netting structures: the twine model has been implemented, the LBFGS method has been used to solve the equilibrium equations and the experiment has been numerically reproduced
Outline

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Future work

Unpublished results
Future work

- Validate the present work with fishing trawls

- Apply parallelization techniques to improve efficiency

- Analyse the effect of how the loading history and plastic deformation affect the MRO

- Apply the presented models and methods to computer-aided design of trawls → topology optimization of trawls → testing the selective performance of cod-end
Outline

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Conclusions

Future work

Unpublished results
Use LBFGS method to calculate complete trawls

- Total computation time LBFGS: \( \sim 6s \) for 3978 variables and \( |g|/N = 0.5 \)
- Unable to compare LBFGS and Newton Raphson methods
- Numerical models for the catch and doors are not included
Unpublished results

Approximated non-conservative energy vs Winther’s method

Update non-conservative forces for the new position

Solve the problem as if the non-conservative forces were constant

if (|q_{i+1} - q_i| > \text{StopTolOut})

Test 3B

|g|/N

Proposed method

Winther’s method

Aprox. Energy

StopTolOut

Error in positions (m)

|g|/N

Test 3B

Winther Tol=0.01

Winther Tol=0.1

Winther Tol=0.5

Test 3B

0 0.5 1 1.5 2 2.5 3

0

0.5

1

1.5

2

2.5

x 10^{-3}

Error in positions (m)

StopTolOut

3 iters

4 iters

5 iters

6 iters

5 iters
Parallelization of the evaluation of forces for all the triangular elements of the netting structure

- Problem: unprotected shared memory with different threads
- Solutions (4000 variables)

<table>
<thead>
<tr>
<th></th>
<th>Time per evaluation (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No parallelization</td>
<td>3.6</td>
</tr>
<tr>
<td>Greedy coloring</td>
<td>1.9</td>
</tr>
<tr>
<td>Write the shared memory out of the parallelization loop</td>
<td>0.9</td>
</tr>
</tbody>
</table>

- In fishing nets it reduces the computational overhead in a 50%
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