A NUMERICAL PROCEDURE FOR THE PREDICTION
OF THE FLOW FIELD AND RESISTANCE OF FISHING NETS

BY

FRANKY K.Y. CHU

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Department of Mech Engineering
The University of British Columbia
Vancouver, Canada

Date APR 28, 1989
ABSTRACT

This thesis presents a numerical model for the calculation of the flow field and resistance of a fishing net. This numerical method is based on the potential flow theory and an empirical formula to predict the force acting on a mesh of the netting.

An experiment to determine the shape, flow field, and the resistance of a conical net has been carried out in the flume tank at the Marine Institute located at St. John's, Newfoundland, and the experimental results are presented as well.

The net drag force obtained by this numerical procedure is compared with the flume tank experiments as well as with methods developed by other researchers. Although the result from the numerical model does not agree well with some methods developed by other researchers, it does have better agreement with the results obtained from the flume tank experiments. The flow field around the fishing net calculated by the numerical model at various incoming velocities is obtained.
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NOMENCLATURE

\( a \) \quad Bar length

Area \quad Area of an unit netting

\( B \) \quad Non-dimensional refraction coefficient

\( C \) \quad Constant

\( C_i \) \quad Non-dimensional force coefficient

\( C_F \) \quad Pressure coefficient

\( d_k \) \quad Knot diameter

\( d_t \) \quad Twine diameter

\( E, F \) \quad Complete Elliptic Function of first and second kind

\( F_c \) \quad Force arising from the bars alone

\( F_{ci} \) \quad Force arising from the bars alone in \( i \) direction

\( F_i \) \quad Force in \( i \) direction

\( G \) \quad Green's function

\( K \) \quad Pressure drop coefficient

\( \mathbf{n} \) \quad Normal unit vector on the surface of the control domain, which is pointing outward.

\( n_x, n_R \) \quad Component of normal unit vector in horizontal and radial direction

\( \Delta P_i \) \quad Pressure drop in \( i \) direction

\( \Delta P_n \) \quad Pressure drop in normal direction

\( P_0 \) \quad Undisturbed static pressure

\( R_1 \) \quad Radius of the control domain

\( r \) \quad Distance between point P and Q

\( U_X, U_Y \) \quad Velocity component in X and Y direction

\( u \) \quad Velocity on the surface
\( V \) \( \quad \) Free stream velocity

\( V_n \) \( \quad \) Velocity in normal direction

\( V_{s1}, V_{s2} \) \( \quad \) Tangential velocity on the outside and inside surface of the net

\( V_{x1}, V_{x2} \) \( \quad \) Velocity component in X direction on the outside and inside surface of the net

\( V_{y1}, V_{y2} \) \( \quad \) Velocity component in Y direction on the outside and inside surface of the net

\( X, Y, Z \) \( \quad \) coordinate axes

\( x, R \) \( \quad \) Horizontal and radial measurement of point Q

\( x_p, R_p \) \( \quad \) Horizontal and radial measurement of point P

\( \alpha \) \( \quad \) Angle of incidence

\( \alpha_s \) \( \quad \) Half setting angle

\( \phi \) \( \quad \) Velocity potential

\( \phi_n \) \( \quad \) Velocity potential derivative

\( \phi_{\text{Region 1}} \) \( \quad \) Velocity potential on the outside surface of the net

\( \phi_{\text{Region 2}} \) \( \quad \) Velocity potential on the inside surface of the net

\( \phi_{\text{Diff}} \) \( \quad \) Velocity potential difference across the net

\( \theta \) \( \quad \) Angular measurement from Y axis

\( \Omega \) \( \quad \) Constant

\( \rho \) \( \quad \) Water density

\( \Gamma \) \( \quad \) Circulation

\( \delta \) \( \quad \) Skew angle

\( \delta_{ij} \) \( \quad \) Kronecker delta
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CHAPTER 1

INTRODUCTION

1.1 METHOD OF FISHING

The ocean is a giant resource which provides vitally important supplies such as food, minerals and petroleum. Mankind has developed a heavy dependence on the fishing industry to meet its daily food requirements from the ocean.

Although there are many different means of harvesting fish, trawling is one of the principal methods used by fishing fleets throughout the world. Large quantities of ground fish and pelagic species are harvested on both coast of Canada by bottom and mid-water trawling methods described as follows:

i) Bottom Trawling

Bottom trawling consists of towing a cone shaped net along the ocean bottom. "Doors" or "Otterboards" attached to cables between the vessel and the net serve to keep the mouth of the net horizontally open while the net is making its tow along the ocean bottom. (Figure 1.1.1)

ii) Mid-Water Trawling

Mid-water trawling is similar to bottom trawling, but generally involves towing a much larger net at a selected depth above the ocean floor. (Figure 1.1.2)

A typical fishing net is made up of several components. These are: (Figure 1.1.3)

i) the net bag
ii) the codend
iii) lines
iv) ground warps
v) floats
vi) doors
vii) towing warps

Also included with the net bag are wing bridles, bridle lines, rib lines, a footrope, a headline and a hanging line. In Figure 1.1.4, a sample drawing of the trawling net is shown.

Only recently, after the oil crisis of 1973 pushed the price of fuel up, have researchers started to work on the methods to improve the cost efficiency of the fishing operation. Since about 80% of the entire fuel consumption during a fishing operation is used during the towing of the net, it is beneficial to cut down the fuel consumption during this phase in order to reduce the price of fishing.

1.2 LITERATURE REVIEW

Most of the research work to determine the drag of the fishing net is done experimentally. These experiments are conducted either in towing tanks, flume tanks, or full scale testing at sea. The results are then used to develop empirical formulas.

Some of the early research to determine the drag of sheet netting parallel to water flow was done by Konagaya and Kawakami (1971) [1]. From this data, these researchers developed an
empirical formula to determine drag on a sheet net.

A series of tank tests on conical nets were carried out by Yinggi Zhou [2]. Zhou also developed a method to predict the drag force of the conical net.

A study of the water velocity distribution inside a conical net body was conducted by Higo and Mouri (1975) [3]. The water velocity inside the net was defined as a percentage of the upstream velocity of water entering the net. The researchers found that the water velocity inside the net varied from 94% to 111% upstream velocity.

Ferro and Stewart (1981) [4], reported that the drag of a net can be estimated by the simple formula below:

\[ \text{Drag} = m \, V^n \]  

(1.2.1)

In the equation above, \( V \) is the upstream water speed, \( m \) and \( n \) are constants, which are a function of the net geometry. The values of \( n \) are significantly less than 2 in all cases. Similar formulas were derived by Imaí and Marín (1978) [5], Mangunsukarto and Fuwa (1978) [6] and also Higo and Mouri (1975) [3].

Dickson (1980) [7] developed an alternative method to predict the drag of the fishing net. His method includes the calculation of drag caused by the netting bars and knots in a towing net. His method provides a good agreement with measurements of the drag of full scale trawls at sea. Similar work has been done by Wileman and Hansen (1988) [8].
Dudko, Swiniarski, Przybyszewski, Kwidzinski, Nowakowski and Sendlak (1982) [9], reported the resistance of a net is practically independent of the elliptical base oblateness at the mouth within a range of 0.25 to 1.0. In other words, the drag of a net with elliptical mouth shape should have a similar resistance value compared to a net of circular mouth shape having the same perimeter.

Extensive research work has been carried out at the Department of Mechanical Engineering of U.B.C. The thrust of this work has been in the design of fishing nets, optimization of fishing gear, and the prediction of drag on a trawl net. A computer algorithm which predicts the drag of a net based on the method developed by Kowalski and Giannotti (1974) [10] was written by Wang. The predicted results were confirmed experimentally by Calisal, McIlwaine, Wang and Fung (1984) [11].

It has been determined that for a typical commercial fishing net, the drag of the codend may account for approximately 15% of the drag of the entire net. Also, since the codend has a cylindrical shape, each succeeding mesh along the codend lies in the wake of the previous mesh. This geometry causes the flow fields near and around the codend section to be much more complicated than any other section of the net.

1.3 PURPOSE OF THE PRESENT RESEARCH

A more detailed examination of the flow condition in and around the fishing net is necessary to understand the mechanism
associated with the drag force. The equations used in the prediction of the drag require the speed of the upstream flow, but not the velocity of the fluid around the net. The previously developed drag equations suggest that the net drag is proportional to the square of the upstream velocity. A 10% error in velocity will mean about 20% error in the prediction of drag.

The goal of this thesis is to develop a numerical procedure which can predict the flow field surrounding the net.
2.1 INTRODUCTION

A fishing net is a very porous, flexible structure. It is usually made up of several panels with different mesh geometry. The mesh geometry can be described by the following four parameters: (Figure 2.1.1)

i) twine diameter, \( d_t \).
ii) knot diameter, \( d_k \).
iii) bar length, \( a \).
iv) half setting angle, \( \alpha_s \), which is defined as the half angle between the adjacent bars of an undeformed mesh.

The materials used to make the twine are usually polyethylene, polyester, nylon or new nylon. Each material has different material properties associated with it, e.g. stiffness, water absorption ability, etc.

The twine is either braided or twisted. Hence, the surface texture of the twine is extremely irregular. In other words, the surface is very rough.

During trawling operation, the fishing net is towed by one or two fishing vessels at a speed of two to four knots. The shape of the net while it is being towed under water is more or less conical with an elliptical mouth opening. The trawling operation causes the net to be put under a stress which cause meshes to
stretch lengthwise. This mesh stretching causes the twine diameter to reduce. Also, because of the geometry of the net, the netting solidity increases towards the aft end. Netting solidity is defined as the ratio of the open area to the total area of the netting. Figure 2.1.2 shows the shape of a typical trawl net model being tested in the flume tank.

2.2 MOTION OF THE FLUID THROUGH THE NET

While a net is being towed, water flows through the meshes. Since the net or its elements acts as disturbance, a wake is formed downstream while the upstream flow remains uniform. As the water passes through the net, the static pressure is reduced and the streamlines are deflected. While the component of velocity in the direction normal to the net's surface is kept constant, a discontinuity of the velocity in the direction tangential to the net's profile on the two sides is expected.

2.3 NUMERICAL MODEL

In order to numerically model the fluid flow through a net, a number of assumptions are made. Generally, the flow upstream of the net can be assumed to be uniform and irrotational, while in the region surrounding the net and downstream of the net, the flow is assumed rotational because of the vortex shedding from the circular twines.

One can model the net and fluid interaction by imagining the net to act as a continuous distribution of sources and vortices of very weak strength in the approaching uniform flow.
Hence, the entire flow field can be visualized as made up of irrotational and rotational flow. An additional assumption can also be made here. The rotational flow in the downstream region can be ignored because of low solidity of fishing nets. Therefore, the entire flow field can be represented by a potential function, $\Phi$. This potential function must satisfy the continuity equation for incompressible flow:

$$\nabla^2 \Phi = 0$$  \hspace{1cm} (2.3.1)

which is known as the Laplace Equation.

Where,

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

$\Phi$ = Potential value at any point

The Laplace Equation can be solved with the appropriate boundary conditions. Any function which satisfies the Laplace Equation is a harmonic function.

2.4 BOUNDARY CONDITIONS

The conditions that the numerical model must satisfy are listed as below:

i) Continuity equation across the net and the boundaries of the control domains.

ii) The velocity along the net’s profile in the direction normal to the surfaces on two sides must be equal.

iii) Discontinuity of the velocity potential across the net, or discontinuity of the velocity component tangential to the net geometry is permitted.
CHAPTER 3
MATHEMATICAL FORMULATION OF BOUNDARY ELEMENT METHOD

3.1 SOLUTION METHODS OF THE LAPLACE EQUATION

There are numerous methods available to solve the Laplace Equation with the appropriate boundary conditions.

For a simple geometry, analytical methods can be applied without many difficulties. The Finite Element or Finite Difference Method is normally used when a more complicated geometry is encountered. However, the computational cost involved in these two methods are very expensive due to the large matrix size involved. Besides these methods, the Boundary Element Method (BEM) is an additional choice. This method has an advantage because of the considerably smaller matrix size it requires compared to the Finite Element Method or Finite Difference Method. However, a disadvantage of the method is that the BEM results in a full matrix to be solved.

3.2 ASSUMPTIONS

Before the Boundary Element Method can be applied to the fishing net problem, certain assumptions have to be made. These assumptions are listed below:

i) The potential flow theory can be applied by neglecting the rotational flow field in the region surrounding the net, as well as downstream of the net, because of the weak rotational solenoid field caused by the net.
ii) According to Dudko, Swiniarski, Przybyszewski, Kwidzinski, Nowakowski and Sendlak (1982) [9], although the net has an elliptical cone shape when it is towed underwater, it can be treated as an axisymmetric cone shape having the same perimeter at the mouth.

3.3 GENERAL FORMULATION OF THE BOUNDARY ELEMENT METHOD

Due to the axisymmetric property of the problem, ring elements are chosen to represent the geometry of the net. The variation of the potential value along each element is independent of the geometric angle of the element.

Consider a cylindrical control domain with radius, \( R_1 \), and the coordinate system as shown in Figure 3.3.1. Any arbitrary point can be defined by \((x, y, z)\) or \((x, R, \theta)\), where angle, \( \theta \), is measured from the Y axis. The coordinate systems are related by:

\[
\begin{align*}
  y &= R \cos \theta \\
  z &= R \sin \theta
\end{align*}
\]  

Equation (3.3.1)

Point \( P \) is called the "point of interest", it is the point where the potential is to be calculated. Point \( Q \) is the "running point", it is a running parameter when computing the potential value at \( P \). While point \( P \) can be located inside, outside, or on the boundary of the control domain, point \( Q \) is always located on the surface of the control domain.

Let point \( P \) be described by \((x_p, R_p, 0)\) and point \( Q \) be defined by \((x, R \cos \theta, R \sin \theta)\). The distance, \( r \), between \( P \) and \( Q \)
is obtained by:
\[ r = \sqrt{(x - x_p)^2 + (R \cos \theta - R_p)^2 + (R \sin \theta)^2} \]  
(3.3.2)

The normal unit vector pointing out of the control domain surface, \( \mathbf{n} \), is described by:
\[ \mathbf{n} = (n_x, n_y \cos \theta, n_z \sin \theta) \]  
(3.3.3)

Brebbia (1978) [12], suggests a solution to the Laplace Equation using Green's identity, which is given below:
\[ C \Omega \Phi(P) + \int_{S_t} \Phi(Q) \frac{\partial G(P,Q)}{\partial n} \, dS = \int_{S_t} G(P,Q) \frac{\partial \Phi(P,Q)}{\partial n} \, dS \]  
(3.3.4)

Where \( C \) is a constant equal to 1 in three dimensional cases, and is equal to 1/2 in two dimensional problems. When \( P \) is located inside the control domain, \( \Omega \) is set to \( 4\pi \) and when \( P \) is outside the control domain, \( \Omega \) is set to zero. If \( P \) is at the boundary, \( \Omega \) is equal to \( 2\pi \). \( G \) is known as the Green's Function, and is defined as \( 1/r \) in three dimensional problems and \( \ln(1/r) \) in two dimensional problems. \( S_t \) is the total surface area of the control domain.

To perform the area integration of Equation (3.3.4), a numerical computation is generally used. A discretization procedure is employed to discretize the entire boundary into a series of ring elements.

There are a variety of elements that can be chosen, they are:

i) Constant element
The potential and the potential derivative are assumed to be constant over the element.

ii) Linear element

The variation of the potential and the potential derivative are assumed to be linear within each element.

In the analysis conducted in this thesis, a constant element is chosen in order to simplify the computation. The mid-point of each element is defined as the node point.

For a three dimensional application with point \( P \) located on the boundary, Equation (3.3.4) can be rewritten as:

\[
2\pi\Phi(P) + \int_{S_t} \Phi(Q) \frac{\partial}{\partial n} \left( \frac{1}{r} \right) \, dS = \int_{S_t} \frac{\partial \Phi(Q)}{\partial n} \left( \frac{1}{r^2} \right) \, dS \quad (3.3.5)
\]

Suppose the entire surface of the control domain is composed of \( N \) ring elements. There is one equation similar to the above equation for each element where \( P \) is located. The whole system can be represented in a form of a matrix equation with the size of \( N \times N \) elements on the left hand side as well as the right hand side. This matrix equation can be represented as: (see Appendix A)

\[
[A_{ij}] \begin{bmatrix} \Phi_j \end{bmatrix} = [B_{ij}] \begin{bmatrix} \Phi_n, j \end{bmatrix} \quad (3.3.6)
\]

Where,

\[ i = 1, \ldots, N \]
\[ j = 1, \ldots, N \]

Note that only \( \Phi \) or \( \Phi_n \) has to be prescribed as a boundary
condition on the surface of the control domain. Hence, there are \( N \) unknowns in the matrix equation mentioned above. Reordering the equations in such a way that all the unknowns are on the left hand side, Equation (3.3.6) can be rewritten in the form shown below:

\[
A \mathbf{X} = \mathbf{B} \quad (3.3.7)
\]

Where \( \mathbf{X} \) is the vector of unknowns \( \Phi \) and \( \Phi_n \).

Using the relationship of \( r \) in Equation (3.3.2), Equation (3.3.5) can be rewritten as: (see Appendix B)

\[
2\pi\Phi(P) + \int_{0}^{R} \Phi(Q) \left[ -\frac{4}{(a-b)\sqrt{a+b}} \frac{E(\frac{\pi}{2},\delta) ((x-x_P)R_{x} + R_{n}^{2})}{(a-b)\sqrt{a+b}} \\
+ \frac{2n_{r}}{\sqrt{a+b}} \left[ \frac{a E(\frac{\pi}{2},\delta)}{a-b} - F(\frac{\pi}{2},\delta) \right] \right] dl \\
= \int_{0}^{R} \frac{\partial \Phi(Q)}{\partial n} \frac{4R F(\frac{\pi}{2},\delta)}{(a+b)^{1/2}} dl \quad (3.3.8)
\]

Where,

\[
E(\frac{\pi}{2},\delta) = \text{Complete Elliptic Function of first kind} \\
F(\frac{\pi}{2},\delta) = \text{Complete Elliptic Function of second kind} \\
\delta = \sqrt{\frac{2a}{a+b}}
\]

Using the above formulation with the application of the constant element, the flow field around a sphere with a radius of 1.0 m inside a cylindrical control domain is solved. Due to the axisymmetric shape of the sphere and the control volume, only a quarter of the domain is needed in the calculation, as shown in
Figure 3.3.2. For this analysis, the velocity at upstream boundary is taken to be 1 m/s.

The velocity field inside the control domain as computed by the BEM is graphically illustrated as in Figure 3.3.3.

The velocity along the downstream boundary of the control domain, shown as line CD on Figure 3.3.2, has been calculated using the BEM, and is graphically illustrated in Figure 3.3.4. The results are compared with results obtained from the general analytical formula which is derived from the potential flow theory of uniform flow past a sphere:

\[ U_x = V \left[ \frac{1}{2} \left( \frac{r_1}{r} \right)^3 + 1 \right] \]  

(3.3.9)

Where,

- \( U_x \) = Horizontal velocity at the node point along CD
- \( r_1 \) = Radius of the node point
- \( r \) = Radius of the sphere

From the figure, the maximum difference of the velocity along CD between the results obtained from the BEM and Equation (3.3.9) is around 7%, except at the elements near the corners of the control domain. This discrepancy at the corners is believed to be caused by the numerical inaccuracy occurring as the boundary experiences a sudden change of geometry. Brebbia (1978) [12] suggests this problem can be improved by assuming there are two points very close to each other which belongs to different boundaries as shown in Figure 3.3.5. By doing so, each element can have a different potential or potential derivative.
Figure 3.3.6 shows the pressure coefficient, $C_p$, along the surface of the sphere. The results obtained from the BEM are compared with the results from the following analytical formula, which is also derived from the potential theory:

$$C_p = 1 - \frac{9}{4} \sin^2 \psi$$  \hspace{1cm} (3.3.10)

Where,

$\psi$ = Angular measurement of the node point on the surface of the sphere with the X axis.

In Figure 3.3.6, the maximum difference of $C_p$ between the two methods is around 23%. This is due to the velocities along the surface of the sphere being over predicted by the BEM. In order to improve the accuracy of the results, a smaller element size is recommended by Chan (1984) [13].
4.1 WAKE MODEL

Due to the disturbance of the net, a discontinuity of potential occurs across the net. This discontinuity leads to a wake being formed at the downstream flow field. The discontinuity of the potential generally depends on the geometry of the mesh, the net material, the fluid properties, and the velocity as well.

However, in order to simplify the problem, the investigation of the dependence of this discontinuity along the net's profile will not be carried out. Alternatively, the discontinuity of the potential across the net will be represented by a function which is based on the coordinates of the net itself. The objectives here are to verify the applicability of the Boundary Element Method to this problem, and to investigate whether an irrotational wake model can be constructed using this procedure.

It is convenient to represent the flow fields in and outside the net as two distinct regions. As shown in Figure 4.1.1, the region outside the net is named Region 1, and the region inside the net is named Region 2. A cylindrical outer boundary, with radius $R_1$, is chosen to define the global control volume. This global control volume contains a smaller control domain, Region 2, which represents the internal region of the net. The net is represented by the control boundary, AB, dividing
the two regions. A discontinuity of the velocity in tangential direction, as well as a discontinuity of pressure on the two sides of the net is permitted.

4.2 BOUNDARY CONDITIONS

Before solving the Laplace Equation, the boundary conditions enforced in the problem are:

i) Assume the potential value along the downstream boundary, \( s_1 \), is constant, and it can be represented by any arbitrary constant value;
\[ \Phi = 1.0 \]

ii) Assume the order of magnitude of the velocity in the direction normal to the surface of the outer control domain, \( s_2 \), is small compared with the velocity in the tangential direction. Therefore, a non-permeable boundary condition can be assumed, i.e.
\[ \Phi_n = 0.0 \]

iii) Assume the potential derivative along the upstream boundary, \( s_3 \), is a negative incoming velocity, i.e.
\[ \Phi_n = -v \]

iv) There is no discontinuity of potential along the artificial boundary, \( s_4 \), i.e.
\[ \Phi_{\text{Region 1}} - \Phi_{\text{Region 2}} = 0.0 \]

v) The boundary condition along the net, \( s_5 \), can be represented by the potential difference across the net. This potential difference can be represented by a function, i.e.
\[ \Phi_{\text{Region 1}} - \Phi_{\text{Region 2}} \neq 0.0 \]
4.3 MATHEMATICAL FORMULATION

In this problem, there are two different control domains, where the common boundaries of these two regions are AB and BC. One equation, similar to Equation (3.3.5), can be written for each region. For Region 1, the following equation is obtained:

(See Appendix C)

\[
2\pi\Phi(P) + \int_{0}^{R_1} \Phi(Q) \left[ -4 E\left(\frac{\pi}{2}, \delta\right) \frac{(x - x_p)R_n x + R^2n_R}{(a - b)\sqrt{a + b}} \right. \\
+ \frac{2 \nu_R}{\sqrt{a + b}} \left[ \frac{a E\left(\frac{\pi}{2}, \delta\right)}{a - b} - F\left(\frac{\pi}{2}, \delta\right) \right] \right] \, dy \\
+ \int_{0}^{L} \Phi(Q) \left[ -4 E\left(\frac{\pi}{2}, \delta\right) \frac{(x - x_p)R_n x + R^2n_R}{(a - b)\sqrt{a + b}} \right] \\
+ \frac{2 \nu_R}{\sqrt{a + b}} \left[ \frac{a E\left(\frac{\pi}{2}, \delta\right)}{a - b} - F\left(\frac{\pi}{2}, \delta\right) \right] \, dl \\
+ \int_{Y}^{R_1} \Phi(Q) \left[ -4 E\left(\frac{\pi}{2}, \delta\right) \frac{(x - x_p)R_n x + R^2n_R}{(a - b)\sqrt{a + b}} \right] \\
+ \frac{2 \nu_R}{\sqrt{a + b}} \left[ \frac{a E\left(\frac{\pi}{2}, \delta\right)}{a - b} - F\left(\frac{\pi}{2}, \delta\right) \right] \, dy \\
+ \int_{0}^{X_1} \Phi(Q) \left[ -4 E\left(\frac{\pi}{2}, \delta\right) \frac{(x - x_p)R_n x + R^2n_R}{(a - b)\sqrt{a + b}} \right] \\
+ \frac{2 \nu_R}{\sqrt{a + b}} \left[ \frac{a E\left(\frac{\pi}{2}, \delta\right)}{a - b} - F\left(\frac{\pi}{2}, \delta\right) \right] \, dl
\]
Similarly, the following equation is obtained for Region 2,

\[
2\pi\Phi(P) + \int_{x_2}^{x_1} \Phi(Q) \left[ \frac{-4 \, E\left(\frac{\pi}{2}, \delta\right) \left((x - x_2)R_{x_2} + R^2n_n\right)}{(a - b) \sqrt{a + b}} \right] \, dl
+ \frac{2 \, n_R}{\sqrt{a + b}} \left[ \frac{a \, E\left(\frac{\pi}{2}, \delta\right)}{a - b} - F\left(\frac{\pi}{2}, \delta\right) \right] \, dl
+ \int_{x_1}^0 \Phi(Q) \left[ \frac{-4 \, E\left(\frac{\pi}{2}, \delta\right) \left((x - x_1)R_{x_1} + R^2n_n\right)}{(a - b) \sqrt{a + b}} \right] \, dl
\]
\[
+ \frac{2 n_R}{\sqrt{a + b}} \left[ \frac{a E(\frac{\pi}{2}, \delta)}{a - b} - F(\frac{\pi}{2}, \delta) \right] \, dl
\]

\[
+ \int_0^y \Phi(Q) \left[ -\frac{4 E(\frac{\pi}{2}, \delta) ((x - x_f)R_n + R^2n)}{(a - b) \sqrt{a + b}} \right] \, dy
\]

\[
+ \frac{2 n_R}{\sqrt{a + b}} \left[ \frac{a E(\frac{\pi}{2}, \delta)}{a - b} - F(\frac{\pi}{2}, \delta) \right] \, dy
\]

\[
= \int_{x_2}^{x_1} \frac{\partial \Phi(Q)}{\partial n} \frac{4 R F(\frac{\pi}{2}, \delta)}{(a + b)^{1/2}} \, dl
\]

\[
+ \int_{x_1}^{0} \frac{\partial \Phi(Q)}{\partial n} \frac{4 R F(\frac{\pi}{2}, \delta)}{(a + b)^{1/2}} \, dl
\]

\[
+ \int_y^0 \frac{\partial \Phi(Q)}{\partial n} \frac{4 R F(\frac{\pi}{2}, \delta)}{(a + b)^{1/2}} \, dy
\]

Equations (4.3.1) and (4.3.2) can be written in a matrix equation form similar to Equation (3.3.6). These matrix equations are listed below:

\[
\begin{bmatrix}
C_{ij}
\end{bmatrix}
\begin{bmatrix}
\Phi_j
\end{bmatrix}
= \begin{bmatrix}
D_{ij}
\end{bmatrix}
\begin{bmatrix}
\Phi_n, j
\end{bmatrix}
\] (4.3.3)

\[
\begin{bmatrix}
E_{ij}
\end{bmatrix}
\begin{bmatrix}
\Phi_j
\end{bmatrix}
= \begin{bmatrix}
F_{ij}
\end{bmatrix}
\begin{bmatrix}
\Phi_n, j
\end{bmatrix}
\] (4.3.4)

Since there are common boundaries between the two regions, a method of matching the \( \Phi \) and \( \Phi_n \) must be employed in order to solve the above matrix equations.
4.4 MATCHING TECHNIQUE

The control domain is discretized into a total of $N_{T1}$ elements on Region 1, and a total of $N_{T2}$ elements on Region 2, while along the common boundaries, AC, there are a total of $N_C$ elements. This setup is illustrated on Figure 4.1.1.

For Region 1, there are $N_{T1}$ plus $N_C$ unknowns, and for Region 2, there are $N_{T2}$ plus $N_C$ unknowns. However, the $N_C$ unknowns are common to both regions. Therefore, the total number of unknowns of $\Phi$ and $\Phi_n$ is equal to the sum of $N_{T1}$, $N_{T2}$ and $2N_C$.

After combining the two matrix equations, (4.3.3) and (4.3.4), the combined matrix equation is reordered in such a way that the $\Phi$ and $\Phi_n$ values along the common boundaries are matched. The following matrix equation is obtained: (see Appendix D)

\[
\begin{bmatrix}
N_{T1} & N_{T2} \\
N_{T2} & N_C \\
N_C & N_{T1}
\end{bmatrix}
\begin{bmatrix}
G_{i,j} & -D_{i,j} \\
E_{i,j} & -F_{i,j} \\
1 & 1
\end{bmatrix}
\begin{bmatrix}
\Phi_j \\
\Phi_n \\
\Phi_{n,n}
\end{bmatrix}
= 
\begin{bmatrix}
N_{T1} + N_{T2} + N_C \\
D_{i,j} \\
F_{i,j}
\end{bmatrix}
\begin{bmatrix}
\Phi_j \\
\Phi_n \\
\Phi_{n,n}
\end{bmatrix}
\]

(4.3.5)

According to the boundary conditions set out in 4.2, the column vector on the left hand side of Equation (4.3.5) consists of the prescribed potential values as well as the unknowns. Hence, it is required that the matrix be rearranged in such a way that all the unknown values are located on the column vector of
the left hand side of Equation (4.3.5). Therefore, an equation similar to Equation (3.3.7) can be obtained:

$$AX = B$$
CHAPTER 5
RESULTS OF IRROTATIONAL WAKE MODEL

5.1 INTRODUCTION

In this chapter, the results of the six test cases are discussed. Three of the test cases are without discontinuity of potential across the boundary AB, shown in Figure 4.1.1. The other three test cases have a discontinuity in potential across the boundary.

Three profiles of AB are investigated, these are:

i) vertical

ii) 90 degrees arc

iii) 60 degrees with X axis

Each of the profiles mentioned above is tested with and without a potential discontinuity across the boundary AB. The upstream velocity is taken to be 2 m/s for all test cases.

The reason to include the test cases without the potential difference across the boundary AB is to ensure that the computer program is correct before it is applied to the later analysis.

5.2 RESULTS WITHOUT POTENTIAL DISCONTINUITY

The results of $\Phi$ and $\Phi_n$ computed by the Boundary Element Method for the vertical, 90 degrees arc, and 60 degrees boundary profiles are graphically illustrated in Figures 5.2.1, 5.2.4 and 5.2.7 respectively. Also included in these figures, are the velocity vectors inside the control domains. Comparison of the
normal velocity along the net with the analytical results of the tested cases are shown in Figures 5.2.2, 5.2.5, and 5.2.8. While comparison of the velocity at the downstream boundary with the analytical results are shown in Figures 5.2.3, 5.2.6 and 5.2.9. All of the results have a very good agreement with the theoretical values, except at the turning points of the boundaries where some numerical inaccuracy has occurred.

5.3 RESULTS WITH POTENTIAL DISCONTINUITY

The functions to represent the potential discontinuity across the boundary AB, are shown below:

i) Vertical

\[ \Phi_{\text{DIFF}} = 0.7 y^2 + 0.3 y + 0.5 \]

ii) 90 degrees arc

\[ \Phi_{\text{DIFF}} = 0.2 x^2 + 0.03 x - 0.01 \]

iii) 60 degrees with X axis

\[ \Phi_{\text{DIFF}} = 1.2 x^2 + 0.6 x \]

Where \( x \) and \( y \) are the X and Y coordinates of the node point of the elements along the boundary.

There is no specific reason to represent the potential discontinuity across the boundary AB in the above formats. As mentioned in the previous chapter, the discontinuity of the potential across the net depends on a large number of parameters. Therefore, it is not impossible to represent the potential difference across the net by the formats stated above or other
Using these functions for the potential discontinuity across the boundary, the BEM was used to determine the $\Phi$ values, the $\Phi_n$ values, and the velocity vectors for the control domains with a vertical, 90 degrees arc, and 60 degrees domain boundary. These results are plotted and shown in Figures 5.3.1, 5.3.2 and 5.3.3 respectively. From each of the three cases, one can notice the formation of a wake at the downstream end as shown in each figure. Also in Figures 5.3.1 and 5.3.3, one can notice that vortex like flows are formed in the flow field in addition to the formation of a wake.

5.4 DISCUSSION

Even though there is a lack of analytical or experimental results to compare with, one can conclude from the graphical results that if a proper description of the potential discontinuity along the net is known, then the BEM can be used to successfully simulate the flow fields near and around the net.

In the next chapter, the representation of the potential discontinuity across the net is investigated.
6.1 THE DETERMINATION OF FORCES ACTING ON THE NET

Through private communication between Crewe, P. of British Hovercraft Corporation and Dr. S.M. Calisal of the Mechanical Engineering Department, U.B.C., the forces acting on a unit of netting, (i.e. 1 knot and 4 half bars) as shown in Figure 6.1.1, are given below:

\[
F_i = \rho a_i d_t V^2 C_i \tag{6.1.1}
\]

where,

- \( F_i \) = Force in the \( i \) direction (i = 1, 2, 3)
- \( \rho \) = Density of water
- \( C_i \) = Non-dimensional force coefficients.

From the analysis of Crewe, the following equation can be derived from Equation (6.1.1): (See Appendix E)

\[
\begin{align*}
F_1 &= 1.03 F_{ct} \rho a_t V^2 \\
F_2 &= 1.03 (F_{cn} \cos \alpha - F_{cs} \sin \alpha) \rho a_t V^2 \\
F_3 &= 1.03 \left\{ (F_{cs} \cos \alpha + F_{cn} \sin \alpha) + \frac{d_t |\sin \alpha|}{3 \ a} \left( \frac{F_k}{d_t} \right)^2 \right\} \rho a_t V^2 
\end{align*} \tag{6.1.2}
\]

Where,

- \( \alpha \) = Angle of incidence
- \( F_{ct} \) = Force arising from the bars alone in \( t \) direction
- \( F_{cn} \) = Force arising from the bars alone in \( n \) direction
\[ F_{cs} = \text{Force arising from the bars alone in } s \text{ direction} \]

### 6.2 Algorithm of Pressure Drop across a Net

After the forces acting on the net are obtained, the pressure drop across the net can be calculated by:

\[ \Delta P_i = \frac{F_i}{\text{Area}} \quad (6.2.1) \]

Where,

- \( \Delta P_i \) = Pressure drop in the \( i \) direction (\( i = 1, 2, 3 \))
- \( \text{Area} \) = Area of a unit netting (i.e. 1 knot and 4 half bars)

The pressure drop across the net in the normal direction, \( \Delta P_n \), can then be obtained as: (See Appendix F)

\[ \Delta P_n = \Delta P_3 \sin \alpha + \Delta P_2 \cos \alpha \quad (6.2.2) \]

Also, the total drag of the net can be represented by the summation of the forces in direction \( i = 3 \), i.e.:

\[ \text{Total Drag} = \sum F_3 \quad (6.2.3) \]

### 6.3 Determination of the Velocity Components

The reduction in static pressure when water passes through the net is usually expressed by a dimensionless pressure drop coefficient, \( K \), which is defined as:

\[ K = \frac{\Delta P_n}{\frac{1}{2} \rho V_n^2} \quad (6.3.1) \]

Where \( V_n \) is the velocity in the normal direction to the net geometry.
Since the net is a very porous structure, to a first degree of approximation, the normal velocity, $V_n$, can be written as:

$$V_n = V \sin \alpha$$

(6.3.2)

Hence, Equation (6.3.1) can then be rewritten as:

$$K = \frac{\Delta P_n}{\frac{1}{2} \rho V^2 \sin^2 \alpha}$$

(6.3.3)

After the pressure drop across the net in the normal direction is obtained from Equation (6.2.2), the pressure drop coefficient, $K$, can be calculated from Equation (6.3.3).

McCarthy (1964) [14] introduced a non-dimensional refraction coefficient, $B$, to describe the relationship between the tangential velocities on both sides of the net. This refraction coefficient is expressed as:

$$B = \frac{V_{s2}}{V_{s1}}$$

(6.3.4)

Where,

$V_{s1}$ = Tangential velocity in front of the net

$V_{s2}$ = Tangential velocity behind the net

He also showed that the pressure drop coefficient, $K$, and the refraction coefficient, $B$, has a relationship expressed as:

$$B = \frac{1.1}{\sqrt{1 + K}}$$

(6.3.5)

If one assumes that the tangential velocity in front of the net can be represented by:

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\[ V_{s1} = V \cos \alpha \quad (6.3.6) \]

Then, from Equation (6.3.4), one obtains,

\[ V_{s2} = B V_{s1} \quad (6.3.7) \]

Once the refraction coefficient, \( B \), is obtained from Equation (6.3.5), the tangential velocity behind the net is readily calculated by Equation (6.3.7).

### 6.4 ALGORITHM FOR REPRESENTING POTENTIAL DISCONTINUITY

Consider a typical element along the net, as shown in Figure 6.4.1. Due to the difference in tangential velocity on the two sides, a circulation can be expected on the element. This circulation, \( \Gamma \), can be represented by:

\[ \Gamma = \oint_c u \, dc \quad (6.4.1) \]

Where \( c \) is the contour of the surface, and \( u \) can be expressed as the gradient of the potential, \( \Phi \). Using the circulation theorem, the integral between any two points, \( A \) and \( B \), on the surface can be written as:

\[ \Gamma = \int_A^B \nabla \Phi \cdot \mathbf{n} \, ds \]

\[ = \int_A^B \frac{\partial \Phi}{\partial x} \, dx + \frac{\partial \Phi}{\partial y} \, dy + \frac{\partial \Phi}{\partial z} \, dz \quad (6.4.2) \]

In this problem, the last term on the right hand side of Equation (6.4.2) can be ignored due to axisymmetry of the net, and so Equation (6.4.2) can be expressed as:

\[ \Gamma = \Phi_B - \Phi_A \quad (6.4.3) \]
Where $\Phi_A$ is the potential at point A, and $\Phi_B$ is the potential at point B. If point A is the node point of the element on the inside surface, and point B is the node point on the outside surface of the same element, then the potential difference, $\Phi_{\text{DIFF}}$, across the element can be related by the circulation, $\Gamma$, on the surfaces of the element as shown in Equation (6.4.3). From Equations (6.4.2) and (6.4.3), the following equation can be obtained:

$$\Phi_{\text{DIFF}} = (V_{x2} - V_{x1}) \Delta x + (V_{y2} - V_{y1}) \Delta y \quad (6.4.4)$$

Where,

$$\Phi_{\text{DIFF}} = \Phi_B - \Phi_A$$

and $V_{x1}$ and $V_{y1}$ are the velocity components on the outside surface, and $V_{x2}$ and $V_{y2}$ are the velocity components on the inside surface of the element, as shown in Figure 6.4.2. Hence, the discontinuity of the potential across the net on each element is readily obtained from Equation (6.4.4).

After the velocity in the normal direction along the net, $V_n$, and the tangential velocities on both sides of the net, $V_{s1}$ and $V_{s2}$, are obtained from the Equation (6.3.2), (6.3.6) and (6.3.7) respectively. Then the velocity components in the normal direction and the tangential direction are related to the velocity components in the X and Y direction by the following equations:

$$\begin{bmatrix} V_{x1} \\ V_{y1} \end{bmatrix} = \begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} V_{s1} \\ V_n \end{bmatrix} \quad (6.4.5)$$
\[
\begin{bmatrix}
V_{x2} \\
V_{y2}
\end{bmatrix} =
\begin{bmatrix}
\cos \alpha & \sin \alpha \\
-\sin \alpha & \cos \alpha
\end{bmatrix}
\begin{bmatrix}
V_{s2} \\
V_{n}
\end{bmatrix}
\] (6.4.6)

By substituting the potential difference, $\Phi_{\text{DIFF}}$, into the combined matrix Equation (4.3.5) with the boundary conditions (i), (ii), (iii) and (iv) found in Section 4.2, a numerical model of the net can be set up.

When the attack angle, $\alpha$, is equal to zero degrees, then the above formulation will break down, as no circulation will form on the element. Hence, the attack angle, $\alpha$, must always be different from zero degrees.

The total drag of the net must be balanced by an equal and opposite force acting on the fluid. This drag force results from the pressure on the upstream and downstream boundaries plus the net rate of flux of momentum across the boundaries. The total drag of the numerical model can be calculated based on the wake model formulation, and is written in the following form:

\[
\text{Total drag} = \int_{D}^{E} (P_{0} + \rho V^{2}) \, dA - \int_{F}^{G} (P_{0} + \rho U_{x}^{2}) \, dA
\]
\[
- \int_{E}^{F} \rho U_{y} \, V \, dA
\] (6.4.7)

Where,

$P_{0}$ = Undisturbed static pressure

$V$ = Incoming velocity at upstream

$U_{x}$ = Velocity component in X direction

$U_{y}$ = Velocity component in Y direction
However, the continuity equation across the boundaries requires that:

\[ \int_D \rho V \, dA + \int_F \rho U_x \, dA = \int_E \rho U_y \, dA \]

(6.4.8)

Hence, Equation (6.4.7) can be rewritten as:

Total Drag = \( \int_F \rho U_x (V - U_x) \, dA \)

(6.4.9)
CHAPTER 7

CONICAL NET EXPERIMENT

7.1 INTRODUCTION

An experiment to determine the flow field inside a conical net, as well as the shape of the net under flowing water has been carried out in the flume tank of the Marine Institute located at St. John's, Newfoundland. The interior view of the establishment is shown in Figure 7.1.1.

The flume tank has a working section 21.5 metres long, 8.0 metres wide, and 4.0 metres in depth. The maximum water velocity of the flume tank is 1.0 metre per second.

The tested conical net is constructed of 4 panels made with braided nylon knotless meshes. The net was mounted on a circular hoop with a diameter of 1.354 metre. Floats were attached to the hoop in order to ensure a neutral buoyancy. As shown in Figure 7.1.2, each panel had 41 meshes at the mouth, 23 meshes at the end, and 72 meshes along the length. The meshes had a bar length of 28.5 mm and the twine diameter was 1.85 mm. The conical net was tested with the water velocity set at 0.4, 0.6, 0.8 and 1.0 m/s.

After the net was tested in the flume tank, it was tested also in the towing tank of British Columbia Research in order to confirm the results of the drag force obtained from the original flume tank tests.
7.2 MEASUREMENT OF THE CONICAL NET PROFILE

During tests in the flume tank at the Marine Institute, the net profile was measured for the various flow velocities. In order to obtain the profile of the conical net at the different test velocities, the net was divided into 10 stations, each station being 8 meshes apart. Then, the coordinates of each station were measured by a coordinate measurement device installed in the flume tank. This device consists of 3 cameras with a cross hair moving along the flume tank.

7.3 MEASUREMENT OF THE VELOCITY INSIDE THE NET

The water velocity inside the net was measured by a propeller type current meter (see Figure 7.3.1). The position of the current meter was measured by the coordinate measurement device. The propeller speed reading of the current meter can be converted to fluid velocity by using the calibration graph of the current meter, which is shown in Figure 7.3.2.

7.4 OBSERVATION OF THE FLOW FIELD AROUND THE NET

In order to observe the flow field close to the netting, "Tell-Tails", which are just pieces of wool tied to the net, were attached to the netting at various positions along the net as shown in Figure 7.4.1. The relative angle of the "Tell-Tails", as well as their relative motions, would indicate what type of flow field exists around the net.
7.5 MEASUREMENT OF THE DRAG FORCE

For the different flow velocities, the total drag force of the conical net, hoop, floats, and the tow line was measured by a force transducer attached to the tow line. The angle of the tow line to the vertical direction was also measured. In order to obtain the drag force of the netting itself, the drag force of the hoop, floats and the tow line must first be measured. This was done by dismounted the netting from the hoop and measuring the drag force on the existing equipment without the net, as well as the angle of the tow line, at the water velocities of 0.4, 0.6, 0.8 and 1.0 m/s. Then the drag force of the netting alone is calculated by subtracted the measured drag force without netting from the total drag force measured with the netting. It is assumed that the interference from the hoop, floats and the tow line is negligible.
CHAPTER 8
RESULTS OF THE CONICAL NET EXPERIMENT

8.1 PROFILE OF THE CONICAL NET

For each of the flow velocities, the coordinates of each station were measured and are listed in Appendix G. Also, the profile of the net at the various tested speeds are graphically plotted in Figure 8.1.1. These plots have been smoothed by a fifth order parametric curve smoothing function to give a smooth profile of the net.

From Figure 8.1.1, one can see that the length of the net becomes longer at a higher velocity, as well as the net becomes more symmetrical. It is believed that at low speeds, the gravity force pulls the net downward, causing the net to become less symmetrical.

From the photographs shown in Figure 8.1.2, the meshes appear more open at the entry of the net and close towards the end of the net.

8.2 FLOW FIELD INSIDE THE NET

The measured water velocities inside the net, as well as the positions of the current meter, are shown in Appendix H.

From the results, it seems that the magnitude of the water velocity inside the net are randomly distributed but consistently less than the incoming velocity by 8.5% to 18.9%. This is
contrary to the report by Higo and Mouri (1975) [3], which states that the velocity inside a conical net ranges from 94% to 111%. These researchers also concluded that the water velocity inside the net is influenced by the relationship between the diameter of the twine and the mesh size. Hence, different mesh sizes and twines will produce different results in the flow field inside the net. This may account for the difference in the results found in the experiment compared to the results of Higo and Mouri.

8.3 FLOW FIELD AROUND THE NET

During the experimental tests, it was observed that the flow was not significantly disturbed by the netting as the water passes through the meshes. From the photographs shown in Figure 8.3.1, the "Tell-Tails" maintain a horizontal position except at the rear part of the net. At this part of the net, a larger degree of turbulence is expected due to the smaller mesh openings.

8.4 DRAG FORCE OF THE CONICAL NET

For the various tested velocities in the flume tank, as well as in the towing tank, the total drag forces of the net, including the netting, hoop, floats and tow line, were measured and listed in Appendix I. Also included in the Appendix I, are the measured drag forces excluding the netting. The angles of the tow line to the vertical direction of both cases for the flume tank experiment, and the calculated drag force of the netting alone from the flume tank, and the towing tank, are also
included.
CHAPTER 9
RESULTS OF THE NUMERICAL NET MODEL

9.1 INTRODUCTION

In this chapter, the numerical net model obtained from the Boundary Element Method is tested by using the profiles obtained during the flume tank testing. The profiles of the net were discretized and used for the input of the net model program. The mesh angle of each element was then calculated by the program itself. The potential difference of each element along the net can then be calculated by Equation (6.4.4).

9.2 RESULTS

The calculated $\Phi$ and $\Phi_n$ values, as well as the velocity vectors inside the control domains at upstream velocities equal to 0.4, 0.6, 0.8 and 1.0 m/s are shown in Figures 9.2.1, 9.2.2, 9.2.3 and 9.2.4 respectively. From the figures, one can observe that the flow field near the region close to the net and at the end of the net is irregular, while in the regions further from the net, the flow field is relatively uniform.

The velocity in the normal direction along the net at the tested speeds, obtained by both Equation (6.3.2) and the BEM, are plotted in Figures 9.2.5, 9.2.6, 9.2.7 and 9.2.8.

The tangential velocity on the inside and outside surfaces of the net obtained by the BEM are compared with the values calculated by Equations (6.3.6) and (6.3.7). These results,
computed at various flow velocities are shown in Figures 9.2.9, 9.2.10, 9.2.11 and 9.2.12.

The pressure drop across the net calculated by the BEM is also compared with the results obtained from Crewe's formulation, and are shown in Figures 9.2.13, 9.2.14, 9.2.15 and 9.2.16.

The drag force obtained from the various empirical methods, the BEM, and the experimental results are shown in Figure 9.2.17.
A numerical model to predict the drag force of a conical net and also to obtain the flow field around the net based on the potential flow theory is developed. This numerical method requires the knowledge of the shape of the net underwater so it can be input into the program. Then the potential difference across the net can be obtained from Equation (6.4.4), which was derived from the forces acting on a unit of netting. A principal assumption is used in this numerical procedure, whereby the normal velocity along the net, and the tangential velocity in front of the net, are approximated by the velocity components of the undistributed flow as stated in Equation (6.3.2) and Equation (6.3.6). This assumption is practical if the net has a very coarse structure. Hence, as the water passes through the net, the water velocity will not increase by a significant amount due to the blockage effect of the meshes.

In Figure 9.2.5, 9.2.6, 9.2.7 and 9.2.8, the normal velocity obtained by BEM along the net is observed to fluctuate, especially near the end of the conical net. Yet it seems that the normal velocity follows the trend of the value from Equation (6.3.2). The tangential velocities on the two surfaces of the net calculated by the BEM are shown in Figure 9.2.9, 9.2.10, 9.2.11 and 9.2.12. From the figures, the tangential velocities exhibit a similar fluctuation problem. The fluctuation behavior of the
pressure drop across the net is shown in Figure 9.2.13, 9.2.14, 9.2.15 and 9.2.16. This fluctuation behavior is the result from the fluctuation phenomenon of the velocity components. Since the pressure drop across the net is the function of the velocity components on the two surfaces of an element along the net, the pressure will fluctuate as the velocity fluctuates.

The fluctuation behavior of the solution is more pronounced at the end of the net, and is a result of the high solidity at that region. At high solidity, the assumption that the water velocity will not change by a significant amount as it passes through the net may not be valid. However, the fluctuation behavior of the solution at the other region may be attributed to the size of the elements or the type of element being used. This problem has also been encountered by Chan (1984) [13]. He suggested a possible explanation which is related to the size and the type of element. When the element size becomes larger, the constant potential or potential derivative can no longer represent the actual value on the surface of the body. This is especially true for an object with complicated geometry. Therefore, in order to suppress the fluctuation phenomenon, a finer element size or more sophisticated type of element is recommended. However, this will result in a longer computation time and require more memory space of the computer.

The drag forces computed by the various methods are shown in Figure 9.2.17. One can observe a large discrepancy between the
results of the BEM and the other methods. It is interesting to point out that the drag value of the conical net tested in the flume tank and the towing tank has a difference of around 30%. For this studied conical net, the Reynolds Number based on a smooth circular cylinder having the same diameter as the twine diameter, for the tested speed range, is about 700 to 1800. From published Reynolds charts, the coefficient of drag for the twine can be assumed constant throughout this speed range. Hence, the drag force of the netting is a function of the surface area of the conical net alone. Based on this argument, the shape of the conical net in the flume tank is different from the towing tank. The only explanation is the difference of the flow field between the towing tank and the flume tank. The flow field of the flume tank is not uniform, the velocity gradient is changing throughout the flume tank. Hence, the shape of the net may change as well. This might affect the flow around the conical net, and lead to a large discrepancy between the results of the drag value between the two tanks. It would be valuable to record the shape of the net in the towing tank and then compare it with the profile from the flume tank.

The reasons of the large discrepancy of the drag value compared with the other methods may be quite complicated. Usually, the researchers carry out a series of experiments for a particular type of fishing net, and then develop a formula or method to predict the drag force based on the experimental data. Since the drag force of the netting and the flow field around a
fishing net are dependent on a large number of parameters, this method of formulation may restrict the applicability of the method to other kinds of fishing nets. The most important parameters are: water velocity, type of material, method of net making, type of knot in the net panel, size of mesh, half setting angle, inclination of net panel to the water flow, and twine diameter. The effect of some of the parameters on the drag force and the flow field around a net is not quite understood by the researchers. A comprehensive method to predict the drag force of the different types of fishing net is almost impossible before the effect of all these parameters is well understood. For example, nets made out of different materials may have different profiles underwater, even though the nets may have the same mesh geometry and same panel geometry. The profile of a net made from a stiffer material may not change the net geometry dramatically compared to a net with a less stiffer material when increasing the towing speed. It is known that the shape of the net definitely will affect the value of the drag force and the flow field around the net. This is because the surface area of the netting, the mesh opening, and the attack angle of each panel are different. In most cases, the mesh opening and the attack angle along the same section are different from place to place. A less stiffer material and a smaller twine diameter may increase the vibration of the twine, and could lead to a higher turbulence level in the flow field. It has similar effect when the mesh size is increased. The level of vibration is dependent on the velocity
as well. The surface roughness of the twine will have an effect on the drag force. As the surface roughness increases, a higher value of the skin friction is usually expected, and a higher level of turbulence generated in the flow field is also expected. Wileman and Hansen (1988) [8] found that an extremely high drag coefficient of the netting when one set of bars lies at a right angle to the water flow. An increase in the drag value is then expected when the meshes are more open in the water since the bars lie more across the water flow. If the material has a higher degree of water absorption ability, the absorbed water may increase the twine diameter significantly. This will result in a higher drag value, and at the same time, may change the net geometry as well.

In addition, the surface of the fishing net in the numerical model is smooth and axisymmetric, the attack angle and the mesh opening are constant along the section. However, in reality, the surface of the net is irregular, the angle of attack and the mesh opening are different throughout the surface of the netting, as shown in Figure 10.1. This may cause a more complicated flow field around the net, and generate a higher turbulence level in the flow field. Due to the irregularity of the surface, a larger surface area of the netting compared with the numerical model is expected. Also, in the calculation of the forces acting on an unit netting for the numerical model, the skew angle, $\theta$, is assumed to be zero degrees. However, in a realistic case, the skew angle will vary continuously through out
the surface of the net. The skew angle of each mesh is entirely dependent on how the net takes shape underwater, and this makes the calculation of the skew angle impossible. If the skew angle is included in the calculation, it could give a higher drag force.

Another error may come from the measurement of the twine diameter. Because of the extremely irregular surface of the twine, a standard methodology to measure the diameter of the twine is not available.

The numerical procedure presented, serves as a means to predict the drag force of a fishing net and the flow field around it from a theoretical point of view. Although it does not include all of the parameters that affect the drag force, it offers a numerical procedure for the calculation of the flow inside, and around, a fishing net. The velocity field obtained from this numerical procedure seems to simulate an actual flow field. Also, the calculated drag values of the net are promising compared to the flume tank results.


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APPENDIX A

TRANSFORMATION OF EQUATION (3.3.5) INTO EQUATION (3.3.6)

Equation (3.3.5):

\[ 2\pi\phi(P) + \int_S \phi(Q) \frac{\partial}{\partial n} \left( \frac{1}{r} \right) dS = \int_S \frac{\partial \phi(Q)}{\partial n} \left( \frac{1}{r} \right) dS \]

The boundary has been discretized into \( N \) elements. The values of the potential and its derivative are assumed to be constant on each element, and are equal to the value at the node point of the element. Equation (3.3.5) rewritten for a given \( i \) point in discretized form is shown below:

\[ 2\pi\phi(i) + \sum_{j=1}^{N} \phi(j) \frac{\partial}{\partial n} \left( \frac{1}{r} \right) dS = \sum_{j=1}^{N} \frac{\partial \phi(Q)}{\partial n} \left( \frac{1}{r} \right) dS \quad (A.1) \]

Hence, one equation similar to Equation (A.1) can be written for each \( i \) node, obtaining \( N \) equations. Therefore, Equation (3.3.5) can be expressed in matrix form as:

\[ \begin{bmatrix} A_{ij} \end{bmatrix} \begin{bmatrix} \phi_j \end{bmatrix} = \begin{bmatrix} B_{ij} \end{bmatrix} \begin{bmatrix} \phi_{n,j} \end{bmatrix} \quad (3.3.6) \]

Where,

\( i = 1, \ldots, N \)

\( j = 1, \ldots, N \)
APPENDIX B

Simplification of Equation (3.3.5) into Equation (3.3.8)

Equation (3.3.5),
\[ 2\pi \Phi(P) + \int_{S_t} \Phi(Q) \frac{1}{r} \frac{\partial}{\partial n}(\frac{1}{r}) \ dS = \int_{S_t} \frac{\partial \Phi(Q)}{\partial n} (-\frac{1}{r}) \ dS \]

Where,
\[ \frac{\partial}{\partial n}(\frac{1}{r}) = -\frac{1}{r^2} \nabla r \cdot \hat{n} \]  \hspace{1cm} (B.1)

From Equation (3.3.2) the distance, \( r \), between \( P \) and \( Q \) is:
\[ r = \sqrt{(x - x_p)^2 + (R \cos \theta - R_p)^2 + (R \sin \theta)^2} \]

and,
\[ \nabla r = \frac{(x - x_p), (R \cos \theta - R_p), (R \sin \theta)}{\sqrt{(x - x_p)^2 + (R \cos \theta - R_p)^2 + (R \sin \theta)^2}} \]  \hspace{1cm} (B.2)

From Equation (3.3.3) a normal unit vector, \( \hat{n} \), is shown as:
\[ \hat{n} = (n_x, n_y \cos \theta, n_y \sin \theta) \]

So Equation (B.2) becomes:
\[ \nabla r \cdot \hat{n} = \frac{(x - x_p)n_x + (R \cos \theta - R_p)n_x \cos \theta + (R \sin \theta)n_x \sin \theta}{\sqrt{(x - x_p)^2 + (R \cos \theta - R_p)^2 + (R \sin \theta)^2}} \]  \hspace{1cm} (B.3)

and,
\[ \frac{\partial}{\partial n}(\frac{1}{r}) = -\left[ \frac{(x - x_p)n_x + (R \cos \theta - R_p)n_x \cos \theta + (R \sin \theta)n_x \sin \theta}{[ (x - x_p)^2 + (R \cos \theta - R_p)^2 + (R \sin \theta)^2 ]^{3/2}} \right] \]
Let \( a = (x - x_\text{p})^2 + R_\text{p}^2 + R^2 \) and \( b = 2 R R_\text{p} \).

Substituting \( a \) and \( b \) into Equation (B.4), it can be rewritten as:

\[
\frac{\partial}{\partial n}\left(\frac{1}{r}\right) = -\left[ \frac{(x - x_\text{p})n_x + R n_R - R_\text{p} n_R \cos \theta}{(a - b \cos \theta)^{3/2}} \right] \]

(B.5)

The second term of Equation (3.3.5) is:

\[
- \int_{S_t} \Phi(Q) \frac{\partial}{\partial n}\left(\frac{1}{r}\right) \, dS
\]

\[
- \int_0^R \Phi(Q) \int_0^{2\pi} - \left[ \frac{(x - x_\text{p})n_x + R n_R - R_\text{p} n_R \cos \theta}{(a - b \cos \theta)^{3/2}} \right] R \, d\theta \, dl
\]

\[
= \int_0^R \Phi(Q) \int_0^{2\pi} - \left[ \frac{(x - x_\text{p})R n_x + R^2n_R - R R_\text{p} n_R \cos \theta}{(a - b \cos \theta)^{3/2}} \right] d\theta \, dl
\]

\[
= \int_0^R \Phi(Q) \int_0^{2\pi} - \left[ \frac{(x - x_\text{p})R n_x + R^2n_R}{(a - b \cos \theta)^{3/2}} + \frac{(a - b \cos \theta - a)n_R}{2 (a - b \cos \theta)^{3/2}} \right] d\theta \, dl
\]

\[
= \int_0^R \Phi(Q) \int_0^{2\pi} - \left[ \frac{(x - x_\text{p})R n_x + R^2n_R}{(a - b \cos \theta)^{3/2}} + \frac{(a - b \cos \theta)n_R}{2 (a - b \cos \theta)^{3/2}} \right] d\theta \, dl
\]
\[ - \frac{a n_R}{2 (a - b \cos \theta)^{3/2}} \] d\theta \ dl

= \int_0^R \Phi(Q) \int_0^{2\pi} \left[ \frac{(x - x_p) R_{n_x} + R_{n_R}^2}{(a - b \cos \theta)^{3/2}} + \frac{n_R}{2 (a - b \cos \theta)^{1/2}} \right] d\theta \ dl

\[ - \frac{a n_R}{2 (a - b \cos \theta)^{3/2}} \] d\theta \ dl

= \int_0^R - 2 \Phi(Q) \int_0^{\pi} \left[ \frac{(x - x_p) R_{n_x} + R_{n_R}^2}{(a - b \cos \theta)^{3/2}} \right] d\theta \ dl

\[ + \frac{n_R}{2 (a - b \cos \theta)^{1/2}} - \frac{a n_R}{2 (a - b \cos \theta)^{3/2}} \]

(B.6)

Since,

\[ \int_0^\pi \frac{d\theta}{(a - b \cos \theta)^{1/2}} = \frac{2}{\sqrt{a + b}} F\left(\frac{\pi}{2}, \delta\right) \]

\[ \int_0^\pi \frac{d\theta}{(a - b \cos \theta)^{3/2}} = \frac{2}{(a - b) \sqrt{a + b}} E\left(-\frac{\pi}{2}, \delta\right) \]

Where,

\[ E\left(-\frac{\pi}{2}, \delta\right) = \text{Complete Elliptic Function of first kind} \]

\[ F\left(-\frac{\pi}{2}, \delta\right) = \text{Complete Elliptic Function of second kind} \]

\[ \delta = \sqrt{\frac{2 \frac{a}{a + b}}{a + b}} \]

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Equation (B.6) becomes,

\[ \int_0^R - 2 \frac{\partial \Phi(Q)}{\partial \mathbf{n}} \left[ -4 E\left( \frac{\pi}{2}, \delta \right) \frac{(x - x_p)R \mathbf{n}_x + R^2 n_R}{(a - b) \sqrt{a + b}} \right] d\mathbf{l} \]

\[ + \frac{2 F\left( -\frac{\pi}{2}, \delta \right) n_R}{2 \sqrt{a + b}} - \frac{2 E\left( -\frac{\pi}{2}, \delta \right) a n_R}{2 (a - b) \sqrt{a + b}} \]

\[ = \int_0^R \Phi(Q) \left[ -4 E\left( \frac{\pi}{2}, \delta \right) \frac{(x - x_p)R \mathbf{n}_x + R^2 n_R}{(a - b) \sqrt{a + b}} \right] d\mathbf{l} \]

\[ + \frac{2 n_R}{\sqrt{a + b}} \left[ \frac{a E\left( \frac{\pi}{2}, \delta \right)}{a - b} - F\left( \frac{\pi}{2}, \delta \right) \right] d\mathbf{l} \]

The right hand side of Equation (3.3.5) is:

\[ = \int_{S_t} \frac{\partial \Phi(Q)}{\partial \mathbf{n}} \left( -\frac{1}{r} \right) dS \]

\[ = \int_0^R \frac{\partial \Phi(Q)}{\partial \mathbf{n}} \left[ 2\pi \frac{R d\theta d\mathbf{l}}{\sqrt{(x - x_p)^2 + (R \cos \theta - R_p)^2 + (R \sin \theta)^2}} \right] \]

\[ + \int_0^R 2 \frac{\partial \Phi(Q)}{\partial \mathbf{n}} \left[ \pi \frac{R d\theta d\mathbf{l}}{(a - b \cos \theta)^{1/2}} \right] \]

\[ - \int_0^R \frac{\partial \Phi(Q)}{\partial \mathbf{n}} \left[ 4 \frac{R F\left( -\frac{\pi}{2}, \delta \right)}{(a + b)^{1/2}} d\mathbf{l} \right] \]
Therefore, Equation (3.3.5) can be rewritten as:

\[
2\pi \Phi(P) + \int_{0}^{R_1} \Phi(Q) \left[ -\frac{4 E\left(\frac{\pi}{2}, \delta\right) ((x - x_p)R x + R^2 n_x)}{(a - b) \sqrt{a + b}} \right.
\]

\[
+ \frac{2 n_R}{\sqrt{a + b}} \left[ \frac{\frac{\pi}{2}}{a - b} \right. - \left. F\left(\frac{\pi}{2}, \delta\right) \right] \right] dl
\]

\[
= \int_{0}^{R_1} \frac{\delta \Phi(Q)}{\delta n} \frac{4 R F\left(\frac{\pi}{2}, \delta\right)}{(a + b)^{3/2}} dl \quad (3.3.8)
\]
APPENDIX C

DERIVATION OF EQUATION (4.3.1) AND (4.3.2)

From Equation (3.3.5),

\[ 2\pi \Phi(P) + \int_{S} \Phi(Q) \frac{\partial}{\partial n} \left( \frac{1}{r} \right) \, dS = \int_{S} \frac{\partial \Phi(Q)}{\partial n} \left( \frac{1}{r} \right) \, dS \]

The entire boundary of Region 1 is made up by \( S_1 \), \( S_2 \), \( S_3 \), \( S_4 \) and \( S_5 \), hence, Equation (3.3.5) can be written as:

\[
2\pi \Phi(P) + \int_{S_1} \Phi(Q) \frac{\partial}{\partial n} \left( \frac{1}{r} \right) \, dS + \int_{S_2} \Phi(Q) \frac{\partial}{\partial n} \left( \frac{1}{r} \right) \, dS \\
+ \int_{S_3} \Phi(Q) \frac{\partial}{\partial n} \left( \frac{1}{r} \right) \, dS + \int_{S_4} \Phi(Q) \frac{\partial}{\partial n} \left( \frac{1}{r} \right) \, dS \\
+ \int_{S_5} \Phi(Q) \frac{\partial}{\partial n} \left( \frac{1}{r} \right) \, dS
\]

\[
= \int_{S_1} \frac{\partial \Phi(Q)}{\partial n} \left( \frac{1}{r} \right) \, dS + \int_{S_2} \frac{\partial \Phi(Q)}{\partial n} \left( \frac{1}{r} \right) \, dS \\
+ \int_{S_3} \frac{\partial \Phi(Q)}{\partial n} \left( \frac{1}{r} \right) \, dS + \int_{S_4} \frac{\partial \Phi(Q)}{\partial n} \left( \frac{1}{r} \right) \, dS \\
+ \int_{S_5} \frac{\partial \Phi(Q)}{\partial n} \left( \frac{1}{r} \right) \, dS \quad (C.1)
\]

From Appendix B, the terms on the left hand side of the above equation with an integral sign has a form of:

\[
\int \Phi(Q) \left[ -4 \frac{E(\frac{\pi}{2},\delta) ((x - x_r)R n_x + R^2 n_z)}{(a - b)\sqrt{a + b}} \\
+ \frac{2 n_r}{\sqrt{a + b}} \left[ \frac{a E(\frac{\pi}{2},\delta)}{a - b} - F(-\frac{\pi}{2},\delta) \right] \right] \, dl
\]

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And the terms on the right hand side has a form of:

\[
\int \frac{\partial \Phi(Q)}{\partial n} \frac{4 R F(\frac{\pi}{2}, \delta)}{(a + b)^{1/2}} \, dl
\]

With the appropriate limits, Equation (C.1) can be written as:

\[
2 \pi \Phi(P) + \int_{0}^{R_1} \Phi(Q) \left[ -4 E(\frac{\pi}{2}, \delta) \frac{((x - x_p) R_{nx} + R_{n_p}^2)}{(a - b)\sqrt{a + b}} \right] dy
\]

\[
+ \int_{L}^{0} \Phi(Q) \left[ -4 E(\frac{\pi}{2}, \delta) \frac{((x - x_p) R_{nx} + R_{n_p}^2)}{(a - b)\sqrt{a + b}} \right] dl
\]

\[
+ \int_{R_1}^{Y} \Phi(Q) \left[ -4 E(\frac{\pi}{2}, \delta) \frac{((x - x_p) R_{nx} + R_{n_p}^2)}{(a - b)\sqrt{a + b}} \right] dy
\]

\[
+ \int_{0}^{X_1} \Phi(Q) \left[ -4 E(\frac{\pi}{2}, \delta) \frac{((x - x_p) R_{nx} + R_{n_p}^2)}{(a - b)\sqrt{a + b}} \right] dl
\]
Similarly, Region 2 is represented by $S_4$, $S_5$, and $S_6$, and the following equation is obtained:

$$2\pi\Phi(P) + \int_{x_1}^{x_2} \Phi(Q) \left[ -\frac{4 E\left(\frac{\pi}{2}, \delta\right) ((x - x_p) R_n + R^2 n_R)}{(a - b)\sqrt{a + b}} \right. \left. + \frac{2 n_R}{\sqrt{a + b}} \left[ \frac{a E\left(\frac{\pi}{2}, \delta\right)}{a - b} - F\left(\frac{\pi}{2}, \delta\right) \right] \right] d\ell$$

$$+ \int_{x_1}^{x_2} \Phi(Q) \left[ -\frac{4 E\left(\frac{\pi}{2}, \delta\right) ((x - x_p) R_n + R^2 n_R)}{(a - b)\sqrt{a + b}} \right. \left. + \frac{2 n_R}{\sqrt{a + b}} \left[ \frac{a E\left(\frac{\pi}{2}, \delta\right)}{a - b} - F\left(\frac{\pi}{2}, \delta\right) \right] \right] d\ell$$

$$+ \int_{x_1}^{x_2} \Phi(Q) \left[ -\frac{4 E\left(\frac{\pi}{2}, \delta\right) ((x - x_p) R_n + R^2 n_R)}{(a - b)\sqrt{a + b}} \right. \left. + \frac{2 n_R}{\sqrt{a + b}} \left[ \frac{a E\left(\frac{\pi}{2}, \delta\right)}{a - b} - F\left(\frac{\pi}{2}, \delta\right) \right] \right] d\ell$$

$$(4.3.1)$$
\[ + \frac{2 \pi}{\sqrt{a+b}} \left[ \frac{a E(-\frac{\pi}{2}, \delta)}{a-b} - F\left(\frac{\pi}{2}, \delta\right) \right] \, dl \]

\[ + \int_0^y \Phi(Q) \left[ - 4 E\left(\frac{\pi}{2}, \delta\right) \frac{(x-x_p) R n_x + R^2 n_\delta}{(a-b)\sqrt{a+b}} \right] \, dy \]

\[ + \frac{2 \pi}{\sqrt{a+b}} \left[ \frac{a E(-\frac{\pi}{2}, \delta)}{a-b} - F\left(\frac{\pi}{2}, \delta\right) \right] \, dy \]

\[ - \int_{x_2}^{x_1} \frac{\partial \Phi(Q)}{\partial n} \frac{4 R F\left(\frac{\pi}{2}, \delta\right)}{(a+b)^{1/2}} \, dl \]

\[ + \int_{x_1}^{0} \frac{\partial \Phi(Q)}{\partial n} \frac{4 R F\left(\frac{\pi}{2}, \delta\right)}{(a+b)^{1/2}} \, dl \]

\[ + \int_{y}^{0} \frac{\partial \Phi(Q)}{\partial n} \frac{4 R F\left(\frac{\pi}{2}, \delta\right)}{(a+b)^{1/2}} \, dy \]  

(4.3.2)
From Equation (4.3.3) and (4.3.4):

\[
\begin{bmatrix}
C_{ij} \\
E_{ij}
\end{bmatrix}
\begin{bmatrix}
\Phi_j \\
\Phi_j
\end{bmatrix}
= 
\begin{bmatrix}
D_{ij} \\
F_{ij}
\end{bmatrix}
\begin{bmatrix}
\Phi_{n,j} \\
\Phi_{n,j}
\end{bmatrix}
\tag{4.3.3}
\]  

Therefore, matrix C and D have a size of \((N_{T1} \times N_{T1})\) and matrix E and F have a size of \((N_{T2} \times N_{T2})\). In Equation (4.3.3), \(i\) and \(j\) are from 1 to \(N_{T1}\), where in Equation (4.3.4), they are 1 to \(N_{T2}\).

According to boundary conditions (iv) and (v) in 4.2, one can move the \(N_1 + N_2 + N_3 + 1\) to \(N_1 + N_2 + N_3 + N_4 + N_5\) columns of matrix D, and 1 to \(N_4 + N_5\) columns of matrix F, to the left hand side. One can also move the corresponding rows of the \(\Phi_n\) of the two regions. Then the two matrix are combined as:
\[
\begin{bmatrix}
N_{T1} & | & N_{T2} & | & -D_{ij} & | & \Phi_j \\
C_{ij} & | & E_{ij} & | & -F_{ij} & | & \Phi_j \\
\tilde{N}_4 & | & 1 & | & -1 & | & \Phi_n \\
\tilde{N}_5 & | & 1 & | & -1 & | & \Phi_n \\
N_4 & | & 1 & | & 1 & | & \Phi_n \\
\end{bmatrix}
\begin{bmatrix}
N_1 + N_2 + N_3 \\
N_6 \\
\end{bmatrix}
= 
\begin{bmatrix}
D_{ij} \\
F_{ij} \\
0 \\
\Phi_{\text{Diff}} \\
0 \\
0 \\
\end{bmatrix}
\begin{bmatrix}
\Phi_n \\
\Phi_n \\
\Phi_n \\
\Phi_n \\
\Phi_n \\
\Phi_n \\
\end{bmatrix}
\]

(4.3.5)

Where \( \Phi_{\text{Diff}} = \Phi_{\text{Region 1}} - \Phi_{\text{Region 2}} \)
The forces $F_i$ in the $i$ direction ($i = 1, 2, 3$) on a unit of netting, (i.e. one knot and four half bars) as shown in Figure 6.1.1, are given by:

$$ F_i = \rho a d_t V^2 C_i $$

(6.1.1)

The force coefficients $C_i$ depend on the following additional parameters: (Figure E.1)

i) The inclination of mesh plane to the flow, $\alpha$.

ii) The half setting angle of the mesh, $\alpha_s$.

iii) The skew angle of the mesh, $\theta$.

iv) Diameter of the knot, $d_k$.

The force coefficients $C_i$ are given as:

$$ C_i = 1.03 F_{c_i} + \delta_{i3} \frac{d_t |\sin \alpha|}{3 a} \left( \frac{d_k}{d_t} \right)^2 $$

(E.1)

Where, $F_{c_i}$ is the $i$'th component of $F_c$, the force arising from the bars alone. and $\delta_{i3}$ is the Kronecker delta ($\delta_{i3} = 1$, if $i = 3$, otherwise, it is set to zero). The second term arises from the knots. The direction of axes 1, 2 and 3 are shown in Figure E.2, and are oriented so that 1 is in the transverse direction, 2 being the vertical direction and 3 is the drag direction.

The force $F_c$ is most simply defined in terms of its components relative to the net plane axes, $n, s,$ and $t$, as shown
in Figure E.2. Angles $\beta_1$ and $\beta_2$ are defined as the angles of the bars to the direction of the motion of the net and are given by:

$$\cos \beta_1 = \cos(\theta + \alpha_s) \cos \alpha$$

$$\sin \beta_1 = +\sqrt{1 - \cos^2 \beta_1}$$

$$\cos \beta_2 = \cos(\theta - \alpha_s) \cos \alpha$$

$$\sin \beta_2 = +\sqrt{1 - \cos^2 \beta_2}$$

(E.2)

The components of $F_c$ are then given by:

$$F_{cn} = \frac{1}{2} \sin \alpha \left( \sin \beta_1 + \sin \beta_2 \right)$$

$$F_{cs} = \frac{1}{2} \cos \alpha \left( \sin^2(\theta + \alpha_s) \sin \beta_1 + \sin^2(\theta - \alpha_s) \sin \beta_2 \right.$$  

$$+ b \left[ \cos^2(\theta + \alpha_s) |\cos \beta_1| + \cos^2(\theta - \alpha_s) |\cos \beta_2| \right] \right)$$

$$F_{ct} = -\frac{1}{2} \cos \alpha \left( \sin(\theta + \alpha_s) \cos(\theta + \alpha_s) \left[ \sin \beta_1 - b |\cos \beta_1| \right] \right.$$  

$$+ \sin(\theta - \alpha_s) \cos(\theta - \alpha_s) \left[ \sin \beta_2 - b |\cos \beta_2| \right] \right)$$

(E.3)

Where $b$ is equal to 0.035, which is determined empirically.

$F_{cn}$, $F_{cs}$ and $F_{ct}$ have to be transformed into the direction of drag, vertical and transverse, which are listed below:

$$F_{c1} = F_{ct}$$

$$F_{c2} = F_{cn} \cos \alpha - F_{cs} \sin \alpha$$

$$F_{c3} = F_{cs} \cos \alpha + F_{cn} \sin \alpha$$

(E.4)
Equation (E.1) can be rewritten as:

\[
C_1 = 1.03 \, F_{ct}
\]

\[
C_2 = 1.03 \left( F_{cn} \cos \alpha - F_{cs} \sin \alpha \right)
\]

\[
C_3 = 1.03 \left( F_{cs} \cos \alpha + F_{cn} \sin \alpha \right) + \frac{d_t |\sin \alpha|}{3 \, a} \left( \frac{d_k}{d_t} \right)^2
\]

(E.5)

After \( C_1 \), \( C_2 \) and \( C_3 \) are calculated, the forces in \( i \) direction can be obtained as:

\[
F_1 = 1.03 \, F_{ct} \, \rho \, a \, d_t \, v^2
\]

\[
F_2 = 1.03 \left( F_{cn} \cos \alpha - F_{cs} \sin \alpha \right) \, \rho \, a \, d_t \, v^2
\]

\[
F_3 = 1.03 \left\{ \left( F_{cs} \cos \alpha + F_{cn} \sin \alpha \right) + \frac{d_t |\sin \alpha|}{3 \, a} \left( \frac{d_k}{d_t} \right)^2 \right\} \, \rho \, a \, d_t \, v^2
\]

(6.1.2)
APPENDIX F

FORMULATION OF THE PRESSURE DIFFERENCE ACROSS THE NET

From Equation (6.2.1):

\[ \Delta P_i = \frac{F_i}{\text{Area}} \]

Where,

\[ \text{Area} = \text{Area of unit netting (i.e. 1 knot and 4 half bars)} \]

and,

\[ \text{Area} = 2a^2 \sin \alpha_s \cos \alpha_s \]  \hspace{1cm} (F.1)

Substituting Equations (6.1.2) and (F.1) into Equation (6.2.1), the pressure drop in \( i \) direction can be rewritten as:

\[ \Delta P_1 = \frac{1.03 \frac{F_{ct}}{\rho} \frac{d_t}{V^2}}{2a \sin \alpha_s \cos \alpha_s} \]

\[ \Delta P_2 = \frac{1.03 \left( \frac{F_{cn}}{\rho} \cos \alpha - \frac{F_{cs}}{\rho} \sin \alpha \right) \frac{d_t}{V^2}}{2a \sin \alpha_s \cos \alpha_s} \]

\[ \Delta P_3 = \frac{1.03 \rho \frac{d_t}{V^2}}{2a \sin \alpha_s \cos \alpha_s} \left\{ \left( \frac{F_{cs}}{\rho} \cos \alpha + \frac{F_{cn}}{\rho} \sin \alpha \right) \right. \]

\[ + \frac{d_t |\sin \alpha|}{3a} \left( \frac{d_k}{d_t} \right)^2 \} \]  \hspace{1cm} (F.2)

Due to the impossible nature in the prediction of the skew angle, \( \theta \), it is assumed to be zero degrees. According to Equation (E.2), \( \theta_1 \) and \( \theta_2 \) must be equal. Therefore, from Equation (E.3), the force in the "t" direction, \( F_{ct} \), must be zero. Hence, the
pressure drop across the net in the direction normal to the netting plane, \( \Delta P_n \), is:

\[
\Delta P_n = \Delta P_3 \sin \alpha + \Delta P_2 \cos \alpha
\]  

(6.2.2)
APPENDIX G

PROFILE OF CONICAL NET

The coordinates of each station of the conical net at various water velocity are listed below. The reference frame of coordinates is shown in Figure G.1.

G.1 WATER VELOCITY = 0.4 m/s

<table>
<thead>
<tr>
<th>STATION #</th>
<th>X (mm)</th>
<th>Y_{ LOWER} (mm)</th>
<th>Y_{ UPPER} (mm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>240</td>
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<td>345</td>
<td>354</td>
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<td>427</td>
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<td>1273</td>
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### G.2 WATER VELOCITY = 0.6 m/s

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<th>X (mm)</th>
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<th>Y_UPPER (mm)</th>
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<td>1813</td>
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<td>1860</td>
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<td>1880</td>
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### G.3 WATER VELOCITY = 0.8 m/s

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<th>Y_UPPER (mm)</th>
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G.4 WATER VELOCITY = 1.0 m/s

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<th>Y_{UPPER} (mm)</th>
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APPENDIX H

VELOCITY MEASUREMENT INSIDE THE CONICAL NET

The water velocities inside the conical net at various velocities are listed below. The conversion of the current meter's reading to velocity is according to the calibration graph shown in Figure 7.3.2. The reference frame of the coordinates is shown in Figure H.1. Also, the water velocities inside the conical net along each section at the different tested speeds are plotted and shown in Figures H.2, H.3, H.4 and H.5.

H.1 INCOMING VELOCITY = 0.4 m/s

<table>
<thead>
<tr>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>Meter Reading</th>
<th>Velocity (m/s)</th>
<th>% Decrease</th>
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<tbody>
<tr>
<td>320</td>
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<td>1341</td>
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<td>70</td>
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<th>% Decrease</th>
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<td>116</td>
<td>0.5226</td>
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### H.3 INCOMING VELOCITY = 0.8 m/s

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<th>Meter Reading</th>
<th>Velocity (m/s)</th>
<th>% Decrease</th>
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<tbody>
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<th>Y (mm)</th>
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<th>% Decrease</th>
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<td>813</td>
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APPENDIX 1

DRAG FORCE FROM EXPERIMENT

I.1 RESULTS FROM THE FLUME TANK EXPERIMENT

The drag forces and angles of the tow line to the vertical direction obtained from the experiments conducted in the flume tank are listed below:

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<thead>
<tr>
<th>Vel. (m/s)</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drag Force (Kgf)</td>
<td>Angle</td>
<td>Drag Force (Kgf)</td>
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<td>3.114</td>
<td>75.64°</td>
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<td>19.635</td>
<td>85.64°</td>
<td>2.793</td>
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Where the drag forces and the angles of Case 1 include the conical netting, hoop, floats and tow line, while Case 2 excludes the netting. The measured drag forces are the drag of the netting itself at different tested velocities and is obtained from the following equation:

\[
\text{Drag}_{\text{Measured}} = \text{Drag}_{\text{Case 1}} \sin (\text{Angle}_{\text{Case 1}}) - \text{Drag}_{\text{Case 2}} \sin (\text{Angle}_{\text{Case 2}}) \quad (I.1)
\]
### 1.2 RESULTS FROM THE TOWING TANK EXPERIMENT

The drag forces obtained from the experiments conducted in the towing tank are listed below:

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<th>Measured</th>
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<td>Drag Force (Kgf)</td>
<td>Drag Force (Kgf)</td>
<td>Drag Force (Kgf)</td>
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</tr>
<tr>
<td>0.8</td>
<td>15.850</td>
<td>2.430</td>
<td>13.420</td>
</tr>
<tr>
<td>1.0</td>
<td>23.900</td>
<td>3.545</td>
<td>20.355</td>
</tr>
</tbody>
</table>

Where the drag forces of Case 1 include the conical netting, hoop, floats and tow line, while Case 2 is excludes the netting. The measured drag forces are the drag of the netting itself at different tested velocities and is obtained from the following equation:

\[
\text{Drag}_{\text{Measured}} = \text{Drag}_{\text{Case 1}} - \text{Drag}_{\text{Case 2}} \quad (1.2)
\]
FIGURE 1.1.1 TRAWLING

FIGURE 1.1.2 MID-WATER TRAWLING
FIGURE 1.1.3 TYPICAL FISHING NET
FIGURE 1.1.4 SAMPLE DRAWING OF THE TRAWLING NET

FIGURE 2.1.1 MESH PARAMETERS
FIGURE 2.1.2 FISHING NET IN FLUME TANK
FIGURE 3.3.1 COORDINATE SYSTEM FOR RING ELEMENT

FIGURE 3.3.2 CONTROL DOMAIN FOR THE SPHERE
FIGURE 3.3.3 FLOW FIELD AROUND A SPHERE

UPSTREAM VELOCITY = 1.0 M/S
FIGURE 3.3.4 VELOCITY ALONG THE DOWNSTREAM BOUNDARY OF THE CONTROL DOMAIN
FIGURE 3.3.5 ELEMENTS AT CORNER
FIGURE 3.3.6 COEFFICIENT OF PRESSURE $C_p$, ALONG THE SURFACE OF A SPHERE
FIGURE 4.1.1 CONTROL DOMAINS FOR THE NUMERICAL MODEL OF FISHING NET
FIGURE 5.2.1 FLOW FIELD OF A VERTICAL BOUNDARY
WITHOUT POTENTIAL DIFFERENCE
UPSTREAM VELOCITY = 2.0 M/S
FIGURE 5.2.2 NORMAL VELOCITY ALONG VERTICAL BOUNDARY
WITHOUT POTENTIAL DIFFERENCE
UPSTREAM VELOCITY = 2.0 M/S

Legend
○ ANALYTICAL
× BEM

FIGURE 5.2.3 VELOCITY ALONG DOWNSTREAM BOUNDARY
WITHOUT POTENTIAL DIFFERENCE
VELOCITY POTENTIAL

NORMAL VELOCITY

VELOCITY POTENTIAL

VELOCITY POTENTIAL ON THE OUTSIDE SURFACE

NORMAL VELOCITY ON THE OUTSIDE SURFACE

VELOCITY POTENTIAL ON THE INSIDE SURFACE

NORMAL VELOCITY ON THE INSIDE SURFACE

FIGURE 5.2.4 FLOW FIELD OF A 90 DEGREES ARC BOUNDARY

WITHOUT POTENTIAL DIFFERENCE

UPSTREAM VELOCITY = 2.0 M/s
UPSTREAM VELOCITY = 2.0 M/S

Legend

○ ANALYTICAL
× BEM

FIGURE 5.2.5 NORMAL VELOCITY ALONG 90 DEGREES ARC
WITHOUT POTENTIAL DIFFERENCE
UPSTREAM VELOCITY = 2.0 M/S

Legend
  O ANALYTICAL
  X BEM

FIGURE 5.2.6 VELOCITY ALONG DOWNSTREAM BOUNDARY

WITHOUT POTENTIAL DIFFERENCE
FIGURE 5.2.7 FLOW FIELD OF A 60 DEGREES BOUNDARY
WITHOUT POTENTIAL DIFFERENCE
UPSTREAM VELOCITY = 2.0 M/S
UPSTREAM VELOCITY = 2.0 M/S

FIGURE 5.2.8 NORMAL VELOCITY ALONG 60 DEGREES BOUNDARY
WITHOUT POTENTIAL DIFFERENCE
FIGURE 5.2.9 VELOCITY ALONG DOWNSTREAM BOUNDARY

WITHOUT POTENTIAL DIFFERENCE
FIGURE 5.3.1 FLOW FIELD OF A VERTICAL BOUNDARY
WITH POTENTIAL DIFFERENCE
UPSTREAM VELOCITY = 2.0 m/s
FIGURE 5.3.2 FLOW FIELD OF A 90 DEGREES ARC BOUNDARY WITH POTENTIAL DIFFERENCE

UPSTREAM VELOCITY = 2.0 M/S
VELOCITY POTENTIAL

NORMAL VELOCITY

VELOCITY POTENTIAL ON THE OUTSIDE SURFACE

NORMAL VELOCITY ON THE OUTSIDE SURFACE

VELOCITY POTENTIAL ON THE INSIDE SURFACE

NORMAL VELOCITY ON THE INSIDE SURFACE

FIGURE 5.3.3 FLOW FIELD OF 60 DEGREES BOUNDARY WITH POTENTIAL DIFFERENCE

UPSTREAM VELOCITY = 2.0 m/s
Figure 6.1.1 An Unit Netting

Figure 6.4.1 An Element Along The Net
FIGURE 6.4.2 VELOCITY COMPONENTS ON THE SURFACE OF THE NET
FIGURE 7.1.1 FLUME TANK AT MARINE INSTITUTE
FIGURE 7.1.2 GEOMETRY OF CONICAL NET PANEL
FIGURE 7.3.1 PROPELLER TYPE CURRENT METER
Current Meter Calibration Graph

Regression Equation: \[ y = -5.2756 + 232.0778x \quad R = 1.00 \]

FIGURE 7.3.2 CALIBRATION GRAPH OF CURRENT METER
FIGURE 7.4.1 TELL-TAILS ATTACHED TO THE CONICAL NET
FIGURE 8.1.1 PROFILE OF THE CONICAL NET AT VARIOUS WATER SPEED
FIGURE 8.1.2 MESH OPENING ALONG THE CONICAL NET
FIGURE 8.3.1 TELL-TAILS AT VARIOUS POSITION OF THE CONICAL NET
FIGURE 9.2.1 FLOW FIELD AROUND THE CONICAL NET AT 0.4 M/S
FIGURE 9.2.2 FLOW FIELD AROUND THE CONICAL NET AT 0.6 M/S
Figure 9.2.3 Flow field around the conical net at 0.8 m/s
FIGURE 9.2.4 FLOW FIELD AROUND THE CONICAL NET AT 1.0 M/S
FIGURE 9.2.5 NORMAL VELOCITY ALONG THE NET AT 0.4 M/S
FIGURE 9.2.6 NORMAL VELOCITY ALONG THE NET AT 0.6 M/S
FIGURE 9.2.7 NORMAL VELOCITY ALONG THE NET AT 0.8 M/S
FIGURE 9.2.8 NORMAL VELOCITY ALONG THE NET AT 1.0 M/S
FIGURE 9.2.9 TANGENTIAL VELOCITY ALONG THE NET AT 0.4 M/S
FIGURE 9.2.10 TANGENTIAL VELOCITY ALONG THE NET AT 0.6 M/S
FIGURE 9.2.11 TANGENTIAL VELOCITY ALONG THE NET AT 0.8 M/S
FIGURE 9.2.12 TANGENTIAL VELOCITY ALONG THE NET AT 1.0 M/S

Legend
- **EQUATION 6.3.6 (INSIDE)**
- **BEM (INSIDE)**
- **EQUATION 6.3.7 (OUTSIDE)**
- **BEM (OUTSIDE)**
FIGURE 9.2.13 PRESSURE DROP ACROSS THE NET AT 0.4 M/S
FIGURE 9.2.14 PRESSURE DROP ACROSS THE NET AT 0.6 M/S
FIGURE 9.2.15 PRESSURE DROP ACROSS THE NET AT 0.8 M/S

Legend
CREWE
BEM
FIGURE 9.2.16 PRESSURE DROP ACROSS THE NET AT 1.0 M/S
FIGURE 9.2.17 COMPARISON OF DRAG FORCES
FIGURE 10.1 SURFACE OF CONICAL NET UNDER TEST
FIGURE E.1 MESH PLANE PARAMETERS
FIGURE E.2 DEFINITION OF THE AXIS
FIGURE G.1 REFERENCE FRAME OF COORDINATE FOR PROFILE MEASUREMENT
FIGURE H.1 REFERENCE FRAME OF COORDINATE FOR VELOCITY MEASUREMENT
FIGURE 4.2 WATER VELOCITY INSIDE THE NET AT 0.4 M/S
FIGURE H.3 WATER VELOCITY INSIDE THE NET AT 0.6 M/S
FIGURE H.4 WATER VELOCITY INSIDE THE NET AT 0.8 M/S
FIGURE H.5 WATER VELOCITY INSIDE THE NET AT 1.0 M/S