INTRODUCTION

In order to design or improve fishing nets, many model tests have been conducted. It is necessary to apply both Reynolds’ law and Froude’s law simultaneously to achieve a dynamic similarity between a prototype and its model moved in fluid. However, it is difficult to effectively carry out model testing in a water tank. Various easy methods have been adopted including several modeling rules and these have been used for the model testing of fishing nets.1-5

Tauti1 presented a practicable theory of model rules for fishing nets by assuming the drag of the net varies proportionally with the square of the velocity of water flow, while Dickson2 proposed a modeling rule of fishing nets based on Froude’s law. In both of these modeling rules, geometrical similarity can be achieved if the ratio of the twine diameter to bar length \( \frac{d}{l} \) and the mesh angle (the half angle between two adjacent bars) of the full-scale are equal to the model net. When model testing for large-scale trawl nets and set nets, the length scale should become considerably smaller. Therefore, it is necessary to choose netting material with very thin twine that is used to make extremely flexible model nets. For this case, the drag coefficient of the model net is usually larger than the value of the full-scale net, and the model net cannot be kept in a dynamic similarity to the full-scale net. Yamamoto et al.6 evaluated a scale effect by drag measurement of plane nets, and it was indicated that by taking account of the \( Cd \) effect on the drags, Tauti’s law is more practical for model experiment. Chow7 examined four trawl models with a different scale according to Tauti’s law, and showed the drag of the small-scale net converted to the full-scale net was larger than the measured value. Further, the smaller the scale model the larger the converted drag of net. As noted above, Fridman4 pointed out that in model testing of fishing nets, the Reynolds number \( Rd \) should become considerably smaller.

For this paper we assumed that the drag coefficient of the net was a function of the Reynolds number based on the twine diameter used experimentally. Three different scale models: 1/12, 1/20 and 1/50 of a midwater trawl net of 61 m in total length were made according to the modified Tauti’s law and Froude’s law, and the full-scale and model experiment were carried out. Consequently, the difference between the converted drags of full-scale by three scale models and measured values was within 10%. Each of these modified modeling rules is effective for the model test of trawl nets.

SUMMARY: For design or improvement of fishing nets, a model test based on Tauti’s law or Froude’s law is well executed. However, because these modeling rules are based on the proportion of the drag of the net to the square of water velocity, the converted drag of the net from the result of model testing is considerably large compared with the observed value. In this study, Tauti’s law and Froude’s law were corrected considering the drag coefficient of the net to the Reynolds number based on the twine diameter used experimentally. Three different scale models: 1/12, 1/20 and 1/50 of a midwater trawl net of 61 m in total length were made according to the modified Tauti’s law and Froude’s law, and the full-scale and model experiment were carried out. Consequently, the difference between the converted drags of full-scale by three scale models and measured values was within 10%. Each of these modified modeling rules is effective for the model test of trawl nets.

KEY WORDS: drag coefficient, model test, Reynolds number, similarity law, trawl net.

Original Article

Effects of drag coefficient of netting for dynamic similarity on model testing of trawl nets

FUXIANG HU,* KO MATUDA AND TADASHI TOKAI

Department of Marine Science and Technology, Tokyo University of Fisheries, Minato, Tokyo 108-8477, Japan

SUMMARY: For design or improvement of fishing nets, a model test based on Tauti’s law or Froude’s law is well executed. However, because these modeling rules are based on the proportion of the drag of the net to the square of water velocity, the converted drag of the net from the result of model testing is considerably large compared with the observed value. In this study, Tauti’s law and Froude’s law were corrected considering the drag coefficient of the net to the Reynolds number based on the twine diameter used experimentally. Three different scale models: 1/12, 1/20 and 1/50 of a midwater trawl net of 61 m in total length were made according to the modified Tauti’s law and Froude’s law, and the full-scale and model experiment were carried out. Consequently, the difference between the converted drags of full-scale by three scale models and measured values was within 10%. Each of these modified modeling rules is effective for the model test of trawl nets.

KEY WORDS: drag coefficient, model test, Reynolds number, similarity law, trawl net.
scale experiments. In order to confirm the validity of the modified Tauti’s and Froude’s laws, the model tests and full-scale experiments for a mid-water trawl were examined. The obtained results were compared with those of Tauti’s and Froude’s model laws.

THEORETICAL CONSIDERATION

In physical model testing when length, time, and force are generally adopted as typical physical factors then three basic model scales can be as follows:

<table>
<thead>
<tr>
<th>Scale</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>( \lambda = \frac{L_m}{L_f} )</td>
</tr>
<tr>
<td>Time</td>
<td>( \tau = \frac{t_m}{t_f} )</td>
</tr>
<tr>
<td>Force</td>
<td>( \kappa = \frac{F_m}{F_f} )</td>
</tr>
</tbody>
</table>

where \( L, t \) and \( F \) are a characteristic length, time and force, the subscripts \( m \) and \( f \) indicate model and full scale, respectively. The velocity scale is derived by the length and time scale:

\[
\frac{v_m}{v_f} = \frac{\lambda}{\tau},
\]

where \( v \) is the characteristic speed.

When the full scale and the model are moved in water, those movements are chiefly controlled by inertia, gravity and viscous force. However, it is considered that the viscous force can be disregarded if the twine used for the model net is not very thin.5 The ratio of inertia force (\( \kappa_i \)) is shown by:

\[
\kappa_i = \frac{\rho_m l_m^3 l_m}{t_m^2} \left( \frac{\rho_f L_f^3 L_f}{t_f^2} \right) = \frac{\rho_m \lambda^4}{\rho_f \tau^2}.
\]

where \( \rho_m \) and \( \rho_f \) are the densities of the fluid of the model and the full scale, respectively. Moreover, since the difference of the acceleration due to gravity in the experimented location is very small, the ratio of gravity (\( \kappa_g \)) is given by:

\[
\kappa_g = \frac{\rho_m l_m^3}{\rho_f L_f^3} = \frac{\rho_m \lambda^3}{\rho_f}.
\]

Since each force scales must be equal, from Eqns 4, 5 and 6 the velocity scale is given by:

\[
\frac{v_m}{v_f} = \lambda^{\frac{1}{2}}.
\]

Equation 7 is known as Froude’s model law among hydraulic engineers.

Drag and apparent weight in water of the netting

Various authors have derived theoretical or experimental expressions to calculate the drag of plane netting. Tauti8 derived a theoretical expression of the drag of plane netting in a flow with the assumption that the bar and the knot for the mesh of the netting independently produced a hydrodynamic resistance:

\[
R = \frac{1}{2} \rho C_D V^2 S d \left[ a_1(\phi, \theta) + a_2(\phi, \theta) \frac{d}{l} \right],
\]

where \( V \) is the speed of the approaching flow, \( \rho \) the density of fluid, \( C_D \) the drag coefficient of the netting, \( S \) the area of the considered section of the netting, \( d \) the twine diameter of the netting, \( l \) the bar length of mesh, \( a_1(\phi, \theta) \) and \( a_2(\phi, \theta) \) are the function of the mesh angle (\( \phi \)) and the attack angle of the netting to the flow (\( \theta \)), respectively. If the geometrical similarity is kept between the full scale and its model, the mesh angle and the attack angle of the netting in the full-scale and model net must be equal to each other in a corresponding portion, that is:

\[
\phi_m = \phi_f \quad \text{and} \quad \theta_m = \theta_f.
\]

Therefore, the coefficient \( a_1(\phi, \theta) \) and \( a_2(\phi, \theta) \) for a model net may be equal to that for a full-scale net. Setting the scale of the twine diameter (or mesh size) as:

\[
\frac{d_m}{d_f} = \frac{l_m}{l_f} = M.
\]

From Eqns 8 and 9, the drag force scale of the netting for model and full scale can be shown as:

\[
\frac{R_m}{R_f} = \frac{\rho_m C_{Dm} V_m^2 l_m^2}{\rho_f C_{Df} V_f^2 l_f^2} = \frac{\rho_m C_{Dm} V_m^2}{\rho_f C_{Df} V_f^2} \lambda^2.
\]

Next, we consider the case where the apparent weight of the netting in water is not negligible. It may be important in cases where the characteristic velocity is relatively slow; for example, stationary or non-drag gears such as set nets, gill nets, and purse seines. The apparent weight in water (\( w \)) of the considered section of the netting can be shown as:

\[
w = b_1(\phi) S d(\rho_c - \rho) g \frac{d}{l} \left[ 1 + b_2 \frac{d}{l} \right],
\]

where \( b_1(\phi) \) is a function of the mesh angle, \( \rho_c \) the density of material and \( b_2 \) a constant due to the kind of knot. From Eqns 9, 10, and 12, the scale of apparent weight in water of the netting is shown by:
from Eqs 6 and 11 the force scale can be expressed as follows:

$$\frac{\rho_mC_{dm}V_m^2}{\rho_fC_{df}V_f^2} = \frac{\rho_m}{\rho_f}\lambda^n. \quad (16)$$

Hence, substituting Eqs 10 and 15 into Eqn 16 the velocity scale can be obtained:

$$\frac{V_m}{V_f} = \left[\frac{M^n\lambda}{\lambda^n}\right]. \quad (17)$$

When $n = 0$ in Eqn 17, it gives the velocity scale Eqn 7. Consequently, Froude’s model law is obtained.

Next, when the relative speed to water of the fishing gear is slow such as for set nets, gill nets and purse seines, the apparent weight in water cannot be disregarded. Thus, the drag force scale must be equal to the apparent weight scale of netting for the model net to be dynamically similar to the full scale. Therefore, from Eqs 12 and 13 we have:

$$\frac{\rho_mC_{dm}V_m^2}{\rho_fC_{df}V_f^2} = \frac{(\rho_{sm}-\rho_m)}{(\rho_{sf}-\rho_f)}\lambda^n. \quad (18)$$

Hence, substituting Eqn 15 into Eqn 18, a velocity scale different from Eqn 17 is obtained:

$$\frac{V_m}{V_f} = \left[\frac{M^n + W/P}{\lambda^n}\right]^{-n}. \quad (19)$$

where

$$\frac{(\rho_{sm}-\rho_m)}{(\rho_{sf}-\rho_f)} = W, \quad (20)$$

$$\frac{\rho_m}{\rho_f} = P. \quad (21)$$

The force scale is obtained from the left or right-hand side of Eqn 18:

$$\frac{F_m}{F_f} = \frac{MW}{P}\lambda^n. \quad (22)$$

When the power $n$ of $R_d$ at the drag coefficient of the netting $n = 0$, the velocity scale Eqn 19 is simplified as follows:

$$\frac{V_m}{V_f} = \left[\frac{MW}{P}\right]^{-n}. \quad (23)$$

This is of the Tauti’s model law with the force scale Eqn 22.

**EXPERIMENTAL RESULTS AND DISCUSSION**

The results obtained from the model and the full-scale experiments are described to examine the validity of the modified modeling rules. Full-scale experiments of a midwater trawl were carried out in the Sea of Japan using the T/RV Shinya-Maru of Tokyo University of Fisheries.$^{10}$ The model nets of
three different scales: 1/12, 1/20, and 1/50 were made with polyethylene twine of high strength. Moreover, the mean twine diameter used in the 1/12 and 1/20 scale model nets was the same at 0.441 mm (Table 1). The 1/12 model experiment was carried out in Tateyama Bay, the 1/20 model in a towing tank of the National Research Institute of Fisheries Engineering and the 1/50 model in a circulating water tank of Tokyo University of Fisheries. Drags of all models and the full-scale net were obtained from measured tension of the hand rope with the underwater tension meter, and the net-mouth heights of the full-scale and 1/50 model were measured, respectively.

The results for the converted drag of the full-scale net from the model experiment for the three scale model nets (1/12, 1/20, and 1/50) according to Tauti’s law, and the measured drag of the full-scale net are presented in Fig. 1. The converted drags from the three scale nets were larger than the measured value for the full-scale net by 46%, 49%, and 55%, respectively. But, the differences between the three various scale models were small. It is considered that the differences in the twine diameter of the three model nets are very small. Using Froude’s law as well, the drag of the net from the 1/50 scale model test was overestimated by 70% (Fig. 2). Consequently, the estimated drags from the model tests according to these modeling rules are considerably larger than the observed values.

The drag of the trawl net is expressed by the following equation by Hu and Matuda: 11

\[ R = \frac{1}{2} \rho C_{DN} S_T V^2, \]  

(24)

where \( S_T \) is the total area of the twine, and \( C_{DN} \) the drag coefficient of the trawl net. The drag coeffi-

Table 1  Details of full-scale and model nets used in the experiments

<table>
<thead>
<tr>
<th></th>
<th>Full-scale net</th>
<th>Model net No. 1</th>
<th>Model net No. 2</th>
<th>Model net No. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length scale ( \lambda )</td>
<td>–</td>
<td>1/12</td>
<td>1/20</td>
<td>1/50</td>
</tr>
<tr>
<td>Twine diameter scale ( M )</td>
<td>–</td>
<td>1/6.85</td>
<td>1/6.85</td>
<td>1/4.82</td>
</tr>
<tr>
<td>Total length (m)</td>
<td>61.12</td>
<td>5.094</td>
<td>3.057</td>
<td>1.223</td>
</tr>
<tr>
<td>Twine diameter (mm)(^1)</td>
<td>3.058</td>
<td>0.441</td>
<td>0.441</td>
<td>0.646</td>
</tr>
<tr>
<td>Bar length (mm)(^1)</td>
<td>170.8</td>
<td>24.2</td>
<td>24.2</td>
<td>35.1</td>
</tr>
<tr>
<td>Total area of twine (m(^2))</td>
<td>92.82</td>
<td>0.622</td>
<td>0.234</td>
<td>0.039</td>
</tr>
<tr>
<td>Material</td>
<td>Polyethylene</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)Twine diameter and bar length are weighted mean values by the twine area of each panel.

![Fig. 1](image1.png)  
**Fig. 1** Comparison between the converted drags with three scale models by Tauti’s law and observed values of a midwater trawl net.

![Fig. 2](image2.png)  
**Fig. 2** Comparison between the converted drags from a 1/50 scale model by Froude’s law and observed values of a midwater trawl net.
of the Reynolds number based on the twine diameter, and the drag coefficients were observed to decrease in the range of the Reynolds number which contains three model nets and the full-scale net as shown in Fig. 3. Here, the relation of the drag coefficient of the net to the Reynolds number is expressed by:

\[ C_{DN} = 0.891 R_d^{-0.146}. \]  

Equation 25 gives the drag coefficient of the trawl net, but the power function of the Reynolds' number corresponds to \( n \) of Eqn 14. Here, Tauti's

![Fig. 3 Relationship of the drag coefficient of the net to Reynolds number based on the twine diameter.](image1)

![Fig. 4 Comparison between the converted drags by the modified Tauti's law and observed values of a midwater trawl net.](image2)

![Fig. 5 Comparison between the converted drags by the modified Froude's law and observed values of a midwater trawl net.](image3)

![Fig. 6 Comparison between the converted heights of net-mouth with a 1/50 scale model by the modified Tauti's and Froude's laws, and the observed values of a midwater trawl net.](image4)
law and Froude’s law were corrected from Eqn 25 as $n=0.15$ for each velocity scale of Eqns 17 and 19. The converted drags from the model nets by the modified Tauti’s law are compared with the observed values in Fig. 4. As for the presumed drag of three model nets with a different scale, the averaged difference was smaller by about 10% than the observed values. The difference between the converted drag for the model net of scale 1/50 by the modified Froude’s law and the observed drag was only 9% as for the results by the modified Tauti’s law (Fig. 5). As for the heights of net-mouth, the presumed values of 1/50 scale model net by the modified Tauti’s law and Froude’s law correspond well with the measured value (Fig. 6).

As noted above, the model rules of the trawl nets were restructured in the present paper in consideration of the drag coefficient of the net depending on the Reynolds number based on the twine diameter. The validity was confirmed by experimental results using the midwater trawl net. A scale effect on the model testing of the fishing nets has been discussed.\(^6\),\(^7\),\(^12\) It seems to include both the length scale effect and the twine diameter (or mesh size) scale effect. Length scale effect often depends on a technical factor (e.g. when the length scale is too small it becomes very difficult to make the model net exact); consequently, it considerably influences the converted values. Miyazaki\(^12\) doubted whether the drag coefficient of netting is always constant in Tauti’s law, and Yamamoto et al.\(^6\) also confirmed that the drag coefficient was expressed as a function of Reynolds number based on twine diameter by the plane netting experiment. In this paper, sea trials and model testing were executed with the midwater trawl net. The effect of drag coefficient thought to originate in twine diameter scale was examined, and Tauti’s law and Froude’s law were corrected. In particular, fishing nets are very flexible structures because they are made with twine. To ensure the law of similarity the physical phenomenon caused in the full scale must be able to be reproduced exactly from the result of model testing. However, it is also very important to be able to easily make the model net. It is preferable in future model testing to use the modified Tauti’s law in consideration of the effect of the drag coefficient.

REFERENCES