Evaluating the similarity rules applied to model experiment of large-scale tuna purse seine

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Abstract. This study primarily evaluated the effects of different small-scales on the model criteria in theory and proved the feasibility of introducing prototype netting and Tauti’s law to construct the large-scale purse seine model net. It was concluded that difference of scale of twine diameter/mesh size will not affect the model law. An experiment of testing with the gear model based on the Tauti’s law and sea trial of full-scale fishing gear were executed. Due to the restriction of Tauti’s law applied to purse seine gear model test, this study modified the model criteria by introducing the shooting speed into the scale to form segmented conversion law. In the shooting process, shooting speed is the main factor determining the sinking depth and speed of the gear. After shooting, gravity and drag are the main factors controlling gear submergence in this case where Tauti’s law was able to keep the similarity. The comparison of sinking depth and speed between prototype net and model net indicated that the corrected conversion law could accurately and practically applied to tuna purse seine model test.

1. Introduction

Considering the advantages associated with the alternative experiment that test conditions are controllable, parameters are measurable, as well as low cost, model test has always been the primary method for investigation of fishing gear [1]. To enable the model results to reflect the status of prototype as exactly as possible, a number of previous researchers have proposed various laws used for model test, such as Tauti’s law [2], Dickson’s law [3] and Christensen’s law [4]. Currently, the most commonly used law in the model test remains either Tauti’s law or Dickson’s law, or some minor improvements on these basis [5-9]. In terms of different fishing gears however, relatively suitable criteria needs to be chosen in accordance with their operational characteristics, such as viscosity similarity law maintaining equivalence of Reynolds number (Re), gravity similarity law maintaining equivalence of Froude number (Fr), and Tauti’s law maintaining fishing gear mechanic similarity. For stationary fishing gears such as set net or cage, as gravity serves as the dominant force, gravity similarity law should be mainly considered; while for towed fishing gears such as trawl net, as the resistance generated by viscosity and the gravity-related force act on the fishing gear simultaneously, influence of Reynolds number and Froude number should be taken into account for both [10]. Considering the dissatisfaction for both
variables to be equivalent between prototype of model, and the influence imposed that is weak under the circumstance, it appears to be more accurate to apply Tauti’s law.

As an example, tuna purse seine is one of the largest fishing gears targeting for pelagic fish. The difficulty of building a model net lies in the fact that firstly, it is impossible to satisfy full geometric similarity. Furthermore, the scale effect caused by the bi-scales method (i.e., the linear scale ratio of fishing gear outline and mesh size/twine diameter) is currently unclear, which is reflected in the difference in speed, time and force. Secondly, the material of seine net is usually made by polyamide or polyester, which has a large specific weight resulting in sinking vertically in the water rapidly. The gravity of the fishing gear and fluid, as well as the inertia force that dominate the movement of the fishing gear should be considered for establishing the model criterion. Thirdly, the shooting process is completed under the vessel’s traction at high setting speed (usually more than 10 knots) such that the net wall will sink down under gravity and move forward as dragged by the auxiliary boat. However, the difference between the purse seine and the above-mentioned fishing gears is that its shape and acting force are time-dependent and the conditions in association with fishing operation (shooting speed and direction) have the significant impact on the fishing gear dynamics. On this account, it is necessary to improve the model law based on parameters in the operation.

The premise for model net and physical net to achieve the similarity is that they should first meet geometric similarity. However, just like other objects with porous structure, it is difficult to make model net following the geometric similarity law. Although the introduction of the bi-scales method can solve such difficulty in certain extent, the scale effect caused by the introduction of small scale (scale for twine diameter and mesh size) is not well defined. It was suggested that if scale of outline dimension is not identical to scale of twine diameter and mesh size, the scale of mesh size and twine diameter should be at least identical [11]. Such practice, compared with full geometric similarity, can reduce scale effect (error caused by similarity law). It was believed that it is unnecessary to meet geometric similarity between mesh size and twine diameter if maintaining geometric similarity of total dimension of the net panel [12]. They have proved the feasibility of using the original net panel as model net in the experiment.

In order to allow the model test results to be accurately reversed to the actual situation, this study firstly adopted Tauti’s law in the experiment of tuna purse seine model. We made an improvement on the applicability of the law by comparing with the measured data in the sea trial. The model conversion criterion was modified by introducing the shooting speed into the scale. Results can provide thoughts for selecting other model laws for purse seine model test in the future, and establishing laws for tuna purse seine model test that can be used to conduct new structural design and optimization of physical net.

2. Materials and Methods

2.1. Dimension of prototype and model net

We used seine gear equipped by tuna purse seiner Jin Hui No.6 operating in the EEZ of Western and Central Pacific Ocean (WCPO) as the prototype. The float line and lead line are measured 1664.5 m and 1809 m long, respectively. Vertical stretched height of the net panel reaches 311.1 m. All materials of the net panel are made by polyamide (PA) with braided thread. Weight of the lead line is estimated 26 t (in the air) and mass of the netting gear (in the air, excluding the purse line) is about 30 t. Purse line is made by the hard wire of about 3000m long. Along lead line is arranged with 121 purse rings, which are attached to the lead line in Y shape. Each purse ring in the air is measured 6 kg. Net panel specification and netting gear structure of the purse seine are shown in Fig. 1 and Table 1.
Table 1. Specifications of corresponding sections (referring to Fig. 1)

| Section | Netting material | Specification of twine | Mesh size (mm) | Dimension of netting (T×N) |
|---------|------------------|------------------------|----------------|-----------------------------|
| A1      | PA               | 32×16                  | 127            | 120×180                     |
| A2      | PA               | 32×16                  | 127            | 120×300                     |
| A3      | PA               | 32×16                  | 127            | 120×480                     |
| A4      | PA               | 32×16                  | 127            | 120×650                     |
| B       | PA               | 32×16                  | 135            | 16270×10                    |
| C       | PA               | 20×16                  | 90             | (840×122)×3                 |
| D1      | PA               | 16×16                  | 90             | (840×122)×3                 |
| D2      | PA               | 16×16                  | 90             | (840×122)×2                 |
| E       | PA               | 14×16                  | 90             | (840×122)×6                 |
| F1      | PA               | 12×16                  | 90             | 840×122                     |
| F2      | PA               | 12×16                  | 90             | 840×122                     |
| G1      | PA               | 10×16                  | 90             | (840×122)×10                |
| G2      | PA               | 10×16                  | 90             | 840×122                     |
| H1      | PA               | 8×16                   | 90             | (840×122)×4                 |
| H2      | PA               | 8×16                   | 90             | 840×122                     |
| I       | PA               | 6×16                   | 105            | (720×122)×17                |
| J       | PA               | 6×16                   | 105            | (720×100)×4                 |
| K       | PA               | 6×16                   | 105            | (720×100)×4                 |
| L       | PA               | 12×16                  | 127            | 15500×85                    |
| M1      | PA               | 8×16                   | 105            | 1440×100                    |
| M2      | PA               | 8×16                   | 105            | 2160×100                    |
| N1      | PA               | 6×16                   | 105            | 2160×100                    |
| N2      | PA               | 6×16                   | 105            | 720×100                     |
| O1      | PA               | 5×16                   | 105            | (720×122)×17                |
| O2      | PA               | 5×16                   | 105            | (720×100)×24                |
| P1      | PA               | 6×16                   | 210            | 6850×50                     |
| P2      | PA               | 6×16                   | 210            | 8296×50                     |
| P3      | PA               | 6×16                   | 210            | (360×80)×10                 |
| P4      | PA               | 6×16                   | 210            | (360×50)×2                  |
| P5      | PA               | 6×16                   | 210            | (360×50)×8                  |
| P6      | PA               | 6×16                   | 210            | (360×50)×9                  |
| Q1      | PA               | 8×16                   | 210            | 8300×50                     |
| Q2      | PA               | 8×16                   | 210            | 6850×50                     |
| Q3      | PA               | 8×16                   | 210            | 1440×50                     |
| Q4      | PA               | 8×16                   | 210            | 720×50                      |
| R1      | PA               | 6×16                   | 260            | (580×80)×20                 |
| R2      | PA               | 6×16                   | 260            | (580×80)×22                 |
| R3      | PA               | 6×16                   | 260            | (580×80)×216                |
| S1      | PA               | 32×16                  | 300            | 100×160                     |
| S2      | PA               | 32×16                  | 300            | 100×240                     |
| S3      | PA               | 32×16                  | 300            | 100×340                     |
| S4      | PA               | 32×16                  | 300            | 100×480                     |
| S5      | PA               | 32×16                  | 300            | 100×620                     |
| T       | PA               | 10×16                  | 105            | 2880×100                    |
| U       | PA               | 12×16                  | 120            | 18300×50                    |
| V       | PA               | 24×16                  | 135            | 16270×10                    |
| W1      | PA               | 10×16                  | 210            | 720×50                      |
| W2      | PA               | 10×16                  | 210            | 1440×50                     |
Figure 1. Schematic configuration of full-scale tuna purse seine gear, amounting to 29 sections, each with a breadth of 75.6 m (50 K). Letters indicate netting panels of different mesh sizes or twine thickness and numbers below the letters indicate strip number.

Model net was fabricated based on Tauti’s law with large scale (outline dimension) $\lambda$ 20:1 and small scale (twine diameter/mesh size) $\lambda'$ 1:1. Net panel of the model purse seine was measured 109 m long and 15.6 m high, respectively. Float line and lead line was measured 80.9 m and 98 m, respectively. Total buoyancy was configured as 2022 N (25 N/m) and weight for the lead line was 65 kg (0.663 kg/m). Hanging ratio of the model net was consistent with that of prototype.

Net panel specification and structure of the model net are shown in Fig. 2 and Table 2. Due the large size and complication in the structure of net, there is only half mesh as to longitudinal meshes of the net panel at some parts such as area B, Q and V by calculation. To simplify the fabrication of the model net, net panel part O, Q and R (account for 74% of total area) are adopted for building the model net such that can keep most similarity with prototype.

Figure 2. Sketch drawing of model tuna purse seine.
Table 2. Specifications of corresponding sections (referring to Fig. 3)

| Section of net | Netting material | Specification of twine | Mesh size (mm) | Dimension of netting (T×N) |
|----------------|-----------------|-----------------------|----------------|-----------------------------|
| A              | PA              | 5×16                  | 105            | 1038×16                     |
| B              | PA              | 8×16                  | 210            | 519×5                       |
| C              | PA              | 5×16                  | 105            | 80×90                       |
| D              | PA              | 6×16                  | 260            | 387×46                      |
| E              | PA              | 5×16                  | 105            | 15×38, 14×11                |
| F              | PA              | 8×16                  | 210            | 12×45, 12×24, 12×12         |
| G              | PA              | 8×16                  | 210            | 519×5                       |
| H              | PA              | 5×16                  | 105            | 1038×6                      |

Float line: PA rope, diameter: 14 mm, length: 80 m
Lead line: PA rope, diameter: 8 mm, diameter: 80 m
Chain: Iron, diameter: 3 mm/5 mm, length: 48 m/50 m
Purse line: PVD rope, diameter: 16 mm, length: 200 m

2.2. Fabrication material and procedure
Three specifications of net panel of the prototype are adopted, which are respectively PA-30 tex×5×16, R 2450tex-105mm; PA-30 tex×6×16, R 2860tex-260mm and PA-30 tex×8×16, R 3950tex-210mm. Net panels of different parts are all laced using double-twine half-mesh seaming, with lacing ratio A:B = 2:1, B:C = 1:2, B:D = 5:4, C:D = 5:2, D:G = 4:5, G:H = 1:2, C:G = 2:1, respectively. For D part, there were 10 longitudinal meshes and 56 transverse meshes cut off on the bottom-left side, while 10 longitudinal meshes and 72 transverse meshes cut off on the bottom-right side.

Rope of float line used PA-14 mm and purse line PVD-16 mm. Two float specifications are adopted, cylindrical (160 mm long with a diameter of 123 mm) and spherical (diameter of 87 mm). Three kinds of chains are adopted with specification of 3 mm, 4 mm and 5 mm in diameter, respectively. Bridle was fabricated using 4 mm diameter chains with 14 in number, each of which was measured 4 m long. Interval of both ends of the bridle was 5 m. The horizontal distance between the last bridle and the terminal of net was 6.5 m. Purse rings used steel rings, with each one 10 mm in diameter.

2.3. Model test and sea trial
Model test was carried out on the Qiandao lake of China with the mean depth of the lake 31 m. Test location was selected in the area where the flow is weak and water depth is above 25 m. According to Tauti’s law, the basic gravity force of the lead line of the model net is 0.663 kg/m. A total of three tests were conducted in order to eliminate the influence of error. The encircling time of the three tests generally lasted for about 70 s.

Sea trial was carried out in conjunction with large-scale tuna purse seine fishing vessel operating in the EEZ of Papua New Guinea. In order to eliminate the impact of current factors on the data, four sets where there was weak current were selected to compare with the results of model test. The mean encircling time for four sets lasted for about 680 s.

The sinking depth of the gear was measured using temperature-depth meter (TDR-2050) produced by RBR Co. Ltd (Canada). The instrument has a measurement depth range of 10-740 m with the accuracy 0.05% of full scale, and the resolution 0.001% of full scale.

3. Results
During the shooting of purse seine fishing, shooting operation had a significant effect on the sinking performance of the net. Part of the net panels in submersion was constrained by the unsubmerged one, which led to the netting gear unable to sink freely if the net was set in a low speed. We thus introduced shooting speed as the quantitative index so as to correct the conversion law suitable for purse seine model test.

According to Tauti’s law, shooting speed scale in theory shall be λ’1/2, namely, the actual shooting speed and the shooting speed in model test are equal. In actual experiment, the shooting speed of model...
net is only about half of that of sea trial. Table 3 listed the sub-rule for different processes of setting as the sub-rule for different processes.

Table 3. Scale ratio details of Tauti’s law and corrected model rule.

| Section of net | Netting material | Specification of twine | Mesh size (mm) | Dimension of netting (T×N) |
|----------------|------------------|------------------------|----------------|---------------------------|
| A              | PA               | 5×16                   | 105            | 1038×16                   |
| B              | PA               | 8×16                   | 210            | 519×5                     |
| C              | PA               | 5×16                   | 105            | 80×90                     |
| D              | PA               | 6×16                   | 260            | 387×46                    |
| E              | PA               | 5×16                   | 105            | 15×38, 14×11              |
| F              | PA               | 8×16                   | 210            | 12×45, 12×24, 12×12       |
| G              | PA               | 8×16                   | 210            | 519×5                     |
| H              | PA               | 5×16                   | 105            | 1038×6                    |

Float line: PA rope, diameter: 14 mm, length: 80 m
Lead line: PA rope, diameter: 8 mm, diameter: 80 m
Chain: Iron, diameter: 3 mm/5 mm, length: 48 m/50 m
Purse line: PVD rope, diameter: 16 mm, length: 200 m

Depth scale, time scale and speed scale of model net obtained according to Tauti’s law are 20:1, 20:1 and 1:1, respectively. After correction, the above scales were converted to 20:1, 10:1 and 2:1 during the shooting and 20:1, 20:1 and 1:1 after the shooting. Fig. 3 showed that the difference between the depth of the model net according to Tauti’s law and the measured depth in sea trial was significant. However, the measured depth after correction remained close with that of prototype.

Figure 3. Sinking depth of model nets with the increase of elapsed time and the comparison of converted sinking depth according to Tauti’s criteria, corrected criteria and measured data.

Fig. 4 showed the comparison of sinking velocity between prototype and model net according to Tauti’s law. Speed scale was considerably deviate from that in the model rule, ranging from 2:1 during shooting to 1:2 after shooting. Fig. 5 showed the comparison of sinking velocity between prototype and model net according to corrected rules. During the shooting, speed scale was close to 2:1 and 1:1 after the shooting, basically in good line with the speed scale in the law.
4. Discussion
Adopting the same scale ratio is the requirement for geometric similarity in the model law. Due to inconvenience in the fabrication process, small scale was adopted in the ratio of twine diameter and twine length. However, the selection of small scale ratio is a problem to be addressed in the model rule. Quantitative assessment is required in terms of the fact that the small scale ratio is closer to the large scale ratio will result in the reduction of scale effect caused by similarity law. It was proved by this study that the use of different small scale ratios has no effect on the normal projected area of net panel. Furthermore, since setting speed of the purse seine gear is relatively small (generally 0–0.5 m/s), the hydrodynamic coefficients could be thought to be in the “subcritical zone” against Reynolds number. Thus, difference of hydrodynamic force coefficient between the prototype and model net could be ignored. No matter how much the value of the small scale ratio is taken, the hydrodynamic force of the
model net remains proportional. On the other hand, as there are a great number of complicated procedures for the fabrication of twine, fabricating model net with net panel of prototype net will save both time and effort.

The second problem for model test is how to make different assumptions for different fishing gears, so as to correct the model law. Prior study investigated the applicability of Tauti’s law and gravity similarity law by combining analysis and test, deriving the mass correction formula and stiffness correction formula of gravity similarity law in the design of net panel model [13]. The validation of formulas was verified from the perspective of acting force and deformation. Fredriksson (2001) considered the change of drag coefficient based on Morison formula, and thus designed net panel model by correcting twine projected area [14]. In addition, drag coefficient of trawl model net was corrected through approximating the drag coefficient to the function of Reynolds number, and compared the various model laws after correction with the full-scale trawl [15]. After conversion, drag and opening expansion height of net mouth of both were in good agreement. In terms of the differences of purse seine gear during fishing process, our study proposed segmented law by correcting Tauti’s law. In the shooting process, shooting speed is the main factor determining the sinking depth and speed of the gear, such that the index, shooting speed, was introduced into the law. After shooting, gravity and drag are the main factors controlling gear submergence in this case where Tauti’s law was able to keep the similarity. The accuracy of the corrected conversion law is proved by comparing the measured data in the sea trial with the model experiment.

In this study, Tauti’s law was adopted for model test on tuna purse seine, and the result showed that there was significant difference between the sinking depth and speed obtained by model and the prototype net. Despite consistent between both after correcting the law for conversion based on the shooting speed, no further theoretical analysis or verification is made towards the internal relationship between this parameter and the formula. As a tentative study, this paper demonstrated that by conducting test with Tauti’s law and correcting the conversion formula, model net can reflect the performance of physical net to a certain extent. However, this did not completely prove that Tauti’s law is the optimal model law for tuna purse seine. Future research on Froude law that considers the fluid gravity should be applied for model test. Furthermore, test conditions should be improved so that they are closer to the actual operation process, as well as increasing sample numbers to enhance the credibility of the contrastive results.

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