

曳網索へのカテナリー理論適用に関する基礎的研究

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Verification of the catenary-application to the warp of a towing net

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Abstract : Many methods have been used for the shape approximation of the warp of a trawl. Catenary approximation is one of them. However, as many studies about catenary approximation of a warp have been carried out aboard vessels, it is difficult to standardize experimental conditions. We verified the catenary-application to the warp of a towing net under various conditions using a circulating water tank. We used cord weighted with lead weights and a cone net as the actual warp and a towing net. In the tank, we took photographs of the cord in the flow, changing the length and the weight of the cord and the velocity of the flow. From the photograph we measured the depth of the net. We also calculated the depth by the catenary and compared it against the measured depth. After rectifying for the effect of the billowing of the cord by the flow, the variance between the measured depth and the calculated depth became about 2 %. Therefore it is considered that the current verification of the catenary-application to the warp of a towing net is appropriate.

Key words : catenary, catenary-application, warp, towing net, trawl, circulating water tank, hyperbolic function.

Introduction

For the efficient operation of a trawl, it is important to know the depth of a net and the length of warp which is reeled out to set the net at certain depth. Nowadays, many kinds of instruments are in use in order to measure the depth of a trawl net. However it is useful if the depth of a net and the length of warp can be independently calculated. Many methods have been used for the shape approximation of a warp.¹⁻⁴⁾ Catenary approximation is one of them. However, in studies about the catenary approximation for warps, as the equation of the catenary curve involves a hyperbolic function previously it has been difficult to calculate the shape. For example, they had to use a computer or transform the catenary into some other equation, which requires much processing.⁵⁻⁸⁾ Furthermore, as previous studies examined using an actual ship it was difficult to assess various controlled conditions.⁸⁾ In such studies, although the measured values are very valuable, setting of

the experiment conditions is difficult. On the other hand, experiment using a circulating water tank sometimes shows difference from the actual value. However, setting of the experimental conditions is easy and it makes it possible to confirm the measurement in detail. By using a circulating water tank it is possible to precisely measure parameters affecting net hydrodynamics which then allows comparison with actual ship derived data. Consequently, as the first step, we verified the catenary-application to the warp of a towing net under various conditions using a circulating water tank.

Catenary curve and warp of trawl

When a piece of flexible rope is supported at two points: I and II, the rope hangs down in a perpendicular plane which involves the points due to gravity. Let's determine the shape of this curve, which is called a catenary.

Consider a balance of an arc with length S from the

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lowest point of a curve A to any particular point P(x,y) along the curve in Fig. 1. Suppose that the tensile force at point A and P are T_0 and T respectively, and an angle between a tangential line to this curve drawn at point P and x axis is ϕ . Forces acting on the arc AP are T_0 , T , and the weight of the rope between A and P : wS (w is the weight per unit length of the rope). These three forces maintain the shape of the arc.

The force T can be broken down into a horizontal component and a vertical component. That is, T can be expressed $T \cos \phi + T \sin \phi$.

But since T_0 has only a horizontal component and wS has only a vertical component,

$$T \cos \phi = T_0, T \sin \phi = wS$$

$$\therefore \tan \phi = \frac{wS}{T_0}$$

Suppose that T_0 is equal to wa ,⁹⁾ that is

$$T_0 = wa \tag{1}$$

$$\tan \phi = \frac{wS}{T_0} = \frac{wS}{wa} = \frac{S}{a}$$

$$\therefore S = a \tan \phi \tag{2}$$

As Fig. 1 shows, a indicates the length of AO.

When we solve equation (2) in relationship to x and y ,⁹⁾ the equation (3) and (4) are finally derived as a catenary curve which is the shape of the rope that hangs down between two points : I and II.

$$S = \frac{a}{2} (e^{\frac{x}{a}} - e^{-\frac{x}{a}}) = a \sinh \frac{x}{a} \tag{3}$$

$$y = \frac{a}{2} (e^{\frac{x}{a}} + e^{-\frac{x}{a}}) = a \cosh \frac{x}{a} \tag{4}$$

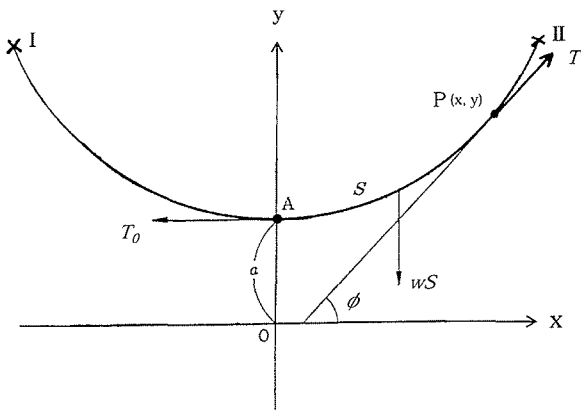
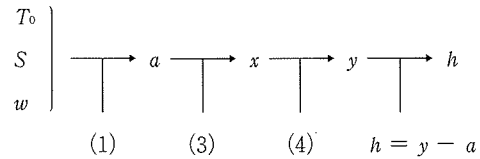


Fig. 1. A coordinate axis in the case of a piece of flexible rope which is supported at two points: I and II.

Next, let's consider the case of correspondence of this catenary curve to the warp of a towing net. Fig. 2 shows the case of approximation of the catenary curve to the warp of a towing net in the sea. In the figure, the length of warp is S , drag force on a net is T_0 , water depth is h , horizontal distance is x .

In this study, T_0 , S , and w are given as known data. In order to calculate the water depth (h), these data are substituted for above equations. The algorithm can be represented as a flow chart as follows. Present scientific electronic calculators are commonly equipped with a hyperbolic function.¹⁰⁾ Therefore these calculations can be done with relative ease.



Experimental method

We used the circulating water tank of National Fisheries University. It is a tank of horizontal circulating type with one impeller. Dimensions of the whole tank are 13.6m in length, 5.1m in width, 1.9m in height with a water capacity of about 50 m³. Dimensions of the observation channel are 6m in length, 2.2m in width, 1.2m in height, where we are able to generate the maximum velocity of steady flow 1.2m/s by a remote controlled operator.

Figure 3 shows a view of the experimental apparatus from the top of the tank. According to the characteristics of the tank, which were previously examined,¹¹⁾ we set up

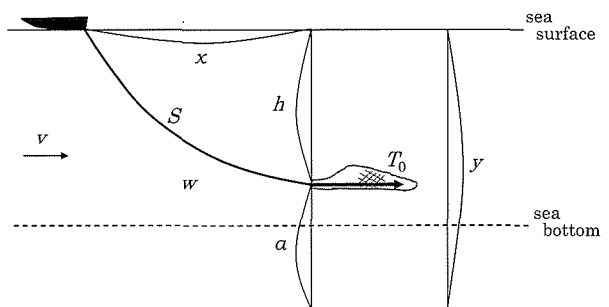


Fig. 2. Application of catenary to the warp of a trawl. The dashed line which shows the sea bottom is different from the abscissa in Fig. 1.

a three component load cell (LSM-20KBS, Kyowa Dengyo Co.) at a point in the observation channel. The point was shifted 20 cm to the channel wall from the center of the channel, which had the least velocity change in the water depth direction. We attached a piece of cord weighted with lead weights, which we regarded as the warp, to the lower end of a support rod of the three component load cell. Hereafter we call the cord “lead cord”. The lower end of the support rod equates to the stern of the trawl in Fig. 2. We further attached a cone net, which we regarded as the trawl net, to the end of the lead cord. The cone net used was a flock remover of a domestic washing machine. We made its specific gravity 1.0. In this study, we are going

to compare the measured depth of the end of the lead cord with the calculated depth by the catenary. Therefore we took a photograph of the point of the end of the lead cord in the flow using a digital camera ; Optio33LF (PENTAX), effective pixels is 3.2M. We also adjusted the position of the three component load cell upstream and downstream in order to set the end of the lead cord at the center section where the velocity distribution of the channel had been measured.

The lead cord is a piece of nylon thread 0.5mm in diameter inserted through many small pieces of lead. We made the length of the lead cord five (S1 ~S5) as shown in Table 1 . We also changed the weight per unit length of

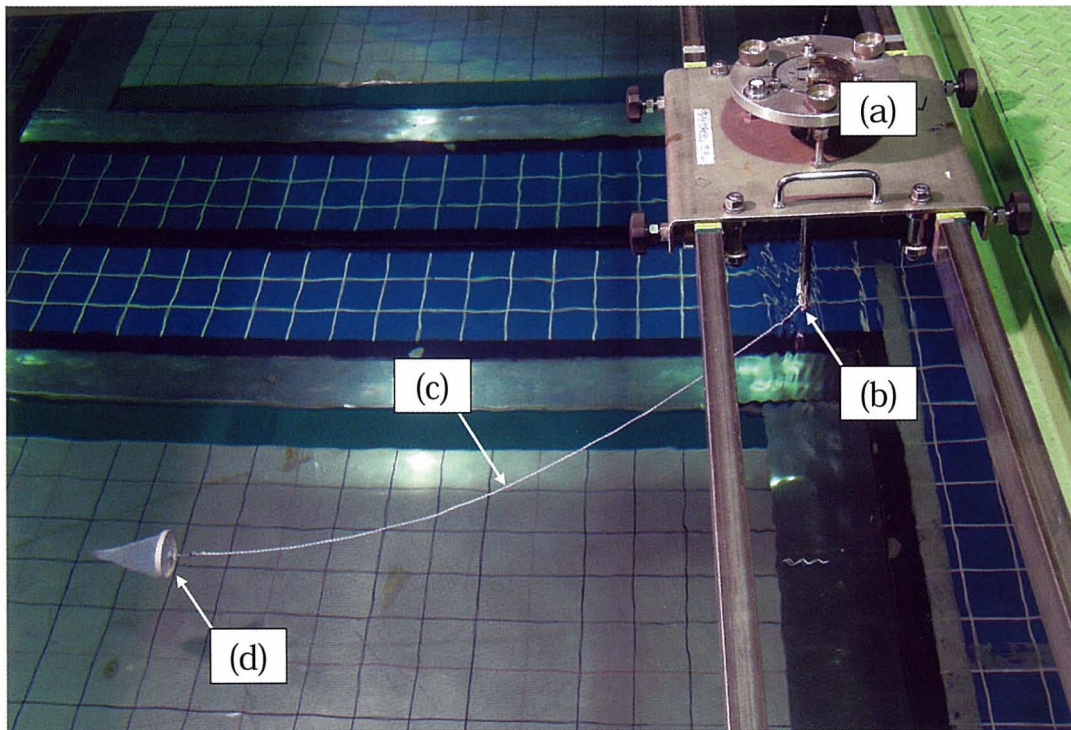


Fig. 3 . View of experimental apparatus from the top of the circulating water tank. (a) three component load cell (b) lower end of a support rod (c) lead cord (d) cone net

Table 1 Properties of the lead cord : string with many small pieces of lead weights

	Length(m)		Weight per unit length (g/m)	Diameter of lead weights (mm)	Length of lead weights (mm)	Number of lead weights per 10 cm
S1	0.75	w1	9.0	1.12	5.4	16
S2	1.00	w2	11.5	1.19	5.3	16
S3	1.25	w3	13.5	1.73	5.2	16
S4	1.50	w4	17.9	1.81	5.3	17
S5	1.75	w5	23.2	2.10	5.2	17

the cord five ($w_1 \sim w_5$) for each length. In total, we used 25 pieces of the lead cord. We changed the velocity at 5 ~ 7 speed levels in range of 5.7~38.9cm/s for each cord.

Figure 4 shows the photographing of the position of the lead cord end by a digital camera using a LED lamp. The distance between the lens on the camera and the glass of the tank is about 85cm. In order to get exact measurements of the position of the end of the lead cord, we applied the photograph on the screen of image-editing software and measured the position of the end of the lead cord, that is, the depth. At the measurement, considering the size of the cone net (10cm in diameter), we stood a scale 15cm apart from the end of the lead cord to the tank wall as shown in Fig. 4. When we stood the scale apart from the cord, however, there may be some reading errors according to the position of the lens. We have to set the lens and the end of the cord at the same level in order to avoid the reading errors. Therefore, we attached a LED on the top of the camera and set up the position of the camera to overlap the red light of the LED which was reflected in the glass of the tank with the end of the lead cord.

In order to confirm the accuracy of reading of the photo, we hung a small sinker (target) in the water without flow

and stood a scale at two points (just the point of the target; position of 0 cm and the point of 15cm behind the target) to take photos. It is considered that no reading errors occurred by the discrepancy of the position of the camera at the position of 0 cm. We compared the depth of the target measurements at six distances between at 0 cm (which is considered to be the true depth) and at 15cm behind the target.

In this water tank, there are slight changes of velocity at each measuring point. The point of the end of the cord that is the depth of the cone net changes according to the change of velocity. Therefore we previously investigated the relation between the inverter frequency of the motor of the tank and the velocity at each measuring point. Then we got the velocity value which affected to the cone net from the aforesaid relation.

On the other hand, for the accurate drag force on the cone net is needed at the catenary-application. We measured the drag force on the cone net using the three component load cell besides taking photos. It was supposed that the drag force might change because of clogging of the meshes of the cone net. Then we measured the drag force three times; at the beginning, midway and the end of the experiment. We got the drag force for each S1 ~S5 and

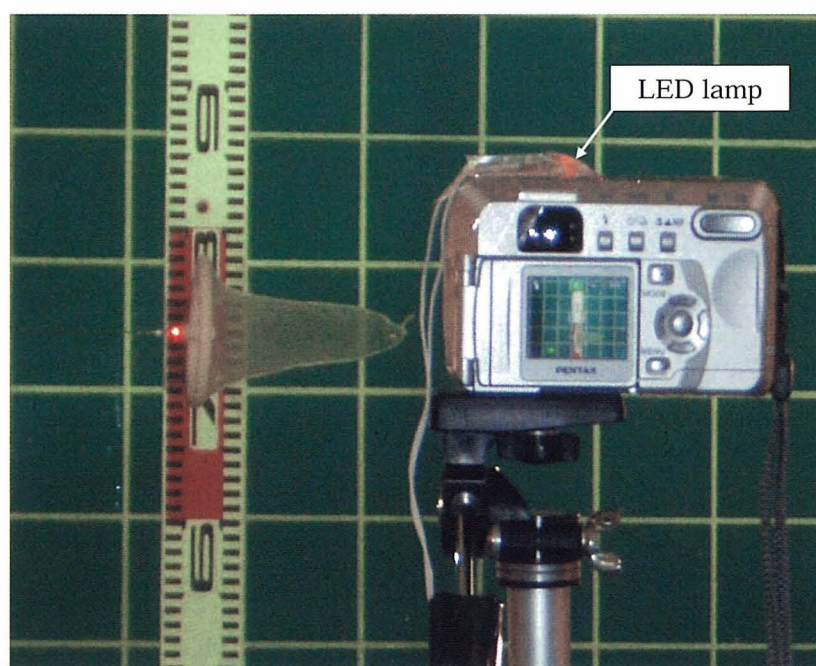


Fig. 4. Photographing of the position of the lead cord end by a digital camera using a LED lamp.

w 1 ~ w 5 , assuming the value to be T_0 , we substituted them into catenary with S and w . After that, we calculated the depth and compared it with measured depth by taking photo.

Results and discussion

Figure 5 shows the results of the taking photos of a small sinker (target) at two points (position of 0 cm and 15cm) changing the depth to six distances. The measurement at position of 0 cm is plotted on the abscissa and at position of 15cm is plotted on the ordinate. It clearly showed a linear relation between both measurements. Furthermore, as the regression coefficient of the straight line indicates 1.0, we decided that there is no difference in the measurement in the case of standing the scale 15 cm behind the end of the lead cord. We made the reading value from the photo actual measurement value without any correction.

Results of measurements about inverter frequency and velocity at eight measuring points at intervals of 10cm at the water depth ; 20~90 cm at the center section of the channel showed that the velocity was proportional to the inverter frequency respectively. We derived linear

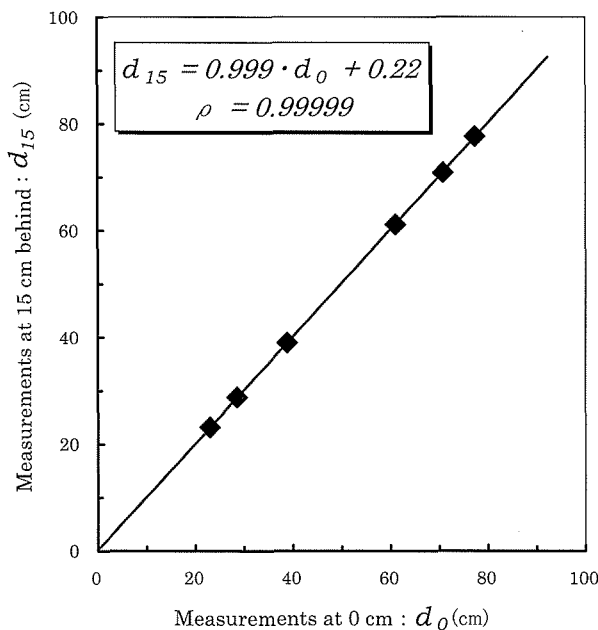


Fig. 5 . Relationship between measurements at 0 cm and measurements at 15 cm behind a target. ρ means the coefficient of correlation.

equations which showed relationship between frequency and velocity at each measuring point. Then at each measured depth, using the equation near the depth, we derived the velocity on the cone net substituting the frequency into the equation respectively.

There was a linear relation between the squared value of the velocity on the abscissa and the drag force on the cone net on the ordinate. Therefore, as described above, we derived the velocity from the frequency at first, and secondly the drag force namely T_0 from the velocity, at last the depth; calculated value, by substituting into catenary. The temporal change of the drag force was not measured.

Originally, for the catenary, the external force on the cord is only the weight of the cord which affects vertically as referred to earlier. But in this study (the same as for the warp of a trawl), we should consider the flowing water pressure as another external force on the cord. That is the effect of billowing of the cord by the flow. Therefore, as shown in Fig. 6 , we let the cord be straight as a matter of convenience, and considered the flowing water pressure ; F_0 acting on the cord. Namely, we made the measured diameter of lead of the cord (see Table 1) the diameter of the cord. We considered the velocity ; $V \sin \theta$ acting on the cord. For this velocity, we used the average velocity of the corresponding depth. We used the drag coefficient $C_D = 1.2$ regarding the cord as infinite length cylinder. Then the lift component ; $F_L (= F_0 \cos \theta)$ acts to decrease of weight of the cord and the drag component ; $F_D (= F_0 \sin \theta)$ acts to increase of drag force on the cone net. Furthermore we newly let " $w - F_L/S$ " the weight per unit length of cord and " $T_0 + F_D$ " the drag of the cone net. Figure 7 shows the results of measured value by taking photo and calculated value of the depth for the five lengths of the lead cord for the weight per unit length of the cord (w 1 ~ w 5) for

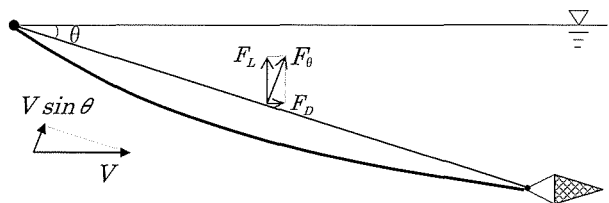


Fig. 6 . Normal force exerted on the cord which is assumed to be a straight line. The force is resolved into the drag component and the lift component.

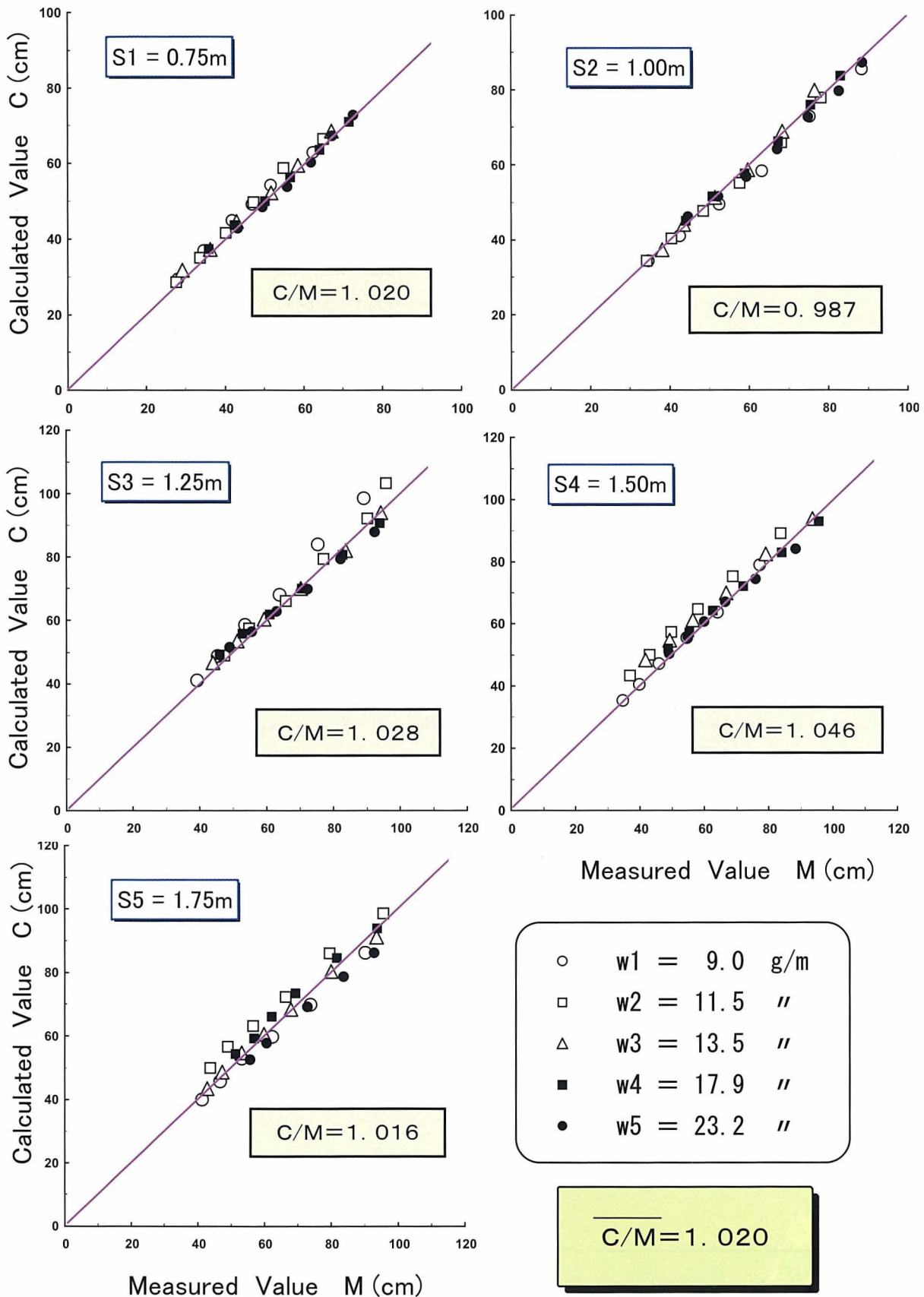


Fig. 7. Relationship between the measured value (M) by taking photo and the calculated value (C) by catenary of the depth for the five lengths of the lead cord for the weight per unit length of the cord ($w_1 \sim w_5$) for each length. The calculated value is resolved by incorporating the effect of the billowing of the cord by the flow. The straight line shows $M=C$.

each length. The measured value : M is plotted on the abscissa and the calculated value : C is plotted on the ordinate. The straight line in the figure shows $C=M$. If the measured value is approximate to the calculated value, it is plotted near the straight line. We showed the average value of the ratio of calculated value to measured value : C/M on the bottom-right corner. If both values are the same, C/M becomes 1.0 and the variance between C and M must be 0 %. From Fig. 7, the ratio varies a little with S increasing; however there are no distinct changes of C/M for the difference of the length and weight of the cord.

Consequently, the average of C/M becomes 1.02 which makes the variance between C and M less than 2 %. It is considered that the current verification of the catenary-application to the warp of a towing net is appropriate.

This time, we rectified the decrease of the weight caused by the billowing of the cord without considering of the weight of the cone net. However in the actual trawl, the weight of the net must be considered. Therefore in the actual case, maybe we don't have to rectify the decrease of weight caused by the billowing of the cord.

Incidentally, the average of C/M without considering the effect of the billowing becomes 1.07 which makes the variance between C and M 7 %. That means we might be able to calculate the depth within a few percentage in the actual case. In that calculation, as shown in the flow chart, they can be done with relative ease using a scientific electronic calculator. We also show the effectivity of using the scientific electronic calculator in the approximate calculation of the catenary for the application to the warp of a towing net.

Anyway, in future, we hope to discuss the case of considering the weight of the net including otter boards and furthermore verify this method of estimating the catenary relationship using actual ship derived data.

Conclusion

Using an experiment in a circulating water tank we verified the catenary-application to the warp of a towing net under various conditions. We also suggested the effectivity of using the scientific electronic calculator in the approximate calculation of the catenary.

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曳網索へのカタナリー理論適用に関する基礎的研究

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曳網索の形状近似の一つにカタナリー近似があるが、これまで十分な検証がなされていない。そこで本研究では、回流水槽を用い、いろいろな条件下での水深測定を行い、曳網索へのカタナリー理論適用の検証を行った。実際の曳網の代わりに抵抗体を、曳網索の代わりに鉛付きコードを用いた。回流水槽において、流れをかけたときのコードの形状を、写真撮影により調べた。カタナリーの式を用いて算出した水深の計算値 C を、コード先端の水深の測定値 M と比較した。コードの吹かれによる影響を補正して計算した結果、 C/M の平均値は1.02となり、両者の差は2%となった。したがって、曳網索へのカタナリー理論適用の有効性が認められたといえる。