BEHAVIOUR OF SWEEP LINE WITH HEAVY BALL*

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It is usual, in Japanese ground trawling, to connect a sweep line and a tow rope by a length of heavy chain. This chain is commonly considered to serve for the increase of the sweeping efficiency of gear as well as the prevention of departure of sweep line from the sea bottom.

In order to get informations about the effect of chain on sweep line, a fundamental study is developed in a simple case that a heavy ball is attached to a uniform rope.

Theoretical Consideration

A uniform flexible rope A-B-C is laid at first on a horizontal sand plane in such a form that its parts $\overline{AB}$ and $\overline{BC}$ are bent at a point B making a right angle, and a heavy ball is attached to the rope at a distance L along the line $\overline{AB}$ measured

Fig. 1. Form of sweep line fitted with heavy ball in layout and in motion.

from the point B (Fig. 1). If the free end C of rope is pulled slowly to a definite direction $\overline{BC}$, there appears a sharp bend at a point P along the rope to which the ball is attached. With increase of towed distance of rope end C, the bend will

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disappear and the pattern of rope will become one smooth curve, since the tension acting on rope at the point P becomes sufficiently large as compared with the resistance of the ball.

Referring to Fig. 1, take the y -axis along the direction of the part $\overline{AB}$ of originally laid rope and choose the origin at the point O where the curve $\widehat{OP}$ comes in contact with the y -axis. Denote by R_s the frictional resistance of the ball, and let T_p and T_q be the tensions acting on the respective parts of rope $\widehat{OP}$ and $\widehat{PR}$ at the point P. θ_p and θ_q be the angles of the directions of tension T_p and T_q relative to the y -axis, respectively, and γ the angle between the directions of T_p and R_s . Resolution of these forces into the directions of T_p and its normal gives,

$$T_p + R_s \cos \gamma = T_q \cos (\theta_q - \theta_p), \quad (1)$$

$$R_s \sin \gamma = T_q \sin (\theta_q - \theta_p). \quad (2)$$

Separately from the above circumstances, we consider a form assumed by a uniform rope, omitted the ball. The originally laid form of rope is deformed to a smooth curve by towing the free end of rope, as mentioned in the references.^{1,2)} On this smooth curve $\widehat{OR}$ of rope carrying no ball, we now choose points P and Q at the respective points where the directions of rope make angles θ_p and θ_q relative to the y -axis. Here, imagine that the tensions acting on rope at the points P and Q, at an instant of towing, just become T_p and T_q , respectively. The form assumed by the parts of rope, $\widehat{OP}$ and $\widehat{QR}$, thus obtained should be geometrically congruent with that of the parts of rope, $\widehat{OP}$ and $\widehat{PR}$, shown in Fig. 1, since the mechanical relations by which the form of rope is governed must be the same as in the references.^{1,2)} In other words, the form of rope in Fig. 1 may be regarded as that obtained by the following procedure: cut off the part $\widehat{PQ}$ from the whole curve $\widehat{OR}$ and remove the curve $\widehat{QR}$ keeping the angle of the direction of T_q relative to the y -axis to θ_q in such a manner that the point Q just comes to the point P of the curve $\widehat{OP}$. Accordingly, we have the following relation, in accordance with the equation (3) of the reference:¹⁾

$$\frac{T_q}{T_p} = e^{\kappa(\theta_q - \theta_p)}, \quad (3)$$

where $\kappa = K_t/K_n$, denoting by K_t and K_n the tangential and the normal component of frictional force per unit length of rope.

Substitution of the equation (3) into the relations (1) and (2) gives

$$\cot \gamma = \cot (\theta_q - \theta_p) - e^{-\kappa(\theta_q - \theta_p)} \operatorname{cosec} (\theta_q - \theta_p), \quad (4)$$

$$(R_s/T_p)^2 = e^{2\kappa(\theta_q - \theta_p)} - 2e^{\kappa(\theta_q - \theta_p)} \cos (\theta_q - \theta_p) + 1. \quad (5)$$

Moreover, denote by s_1 the arc length of the curve $\widehat{OP}$, x_1 and y_1 its projections to the x - and the y -axis, and let s_2 , x_2 and y_2 be the corresponding quantities of the curve $\widehat{PR}$. Then, the following relations may be obtained by the reference to Fig. 1,

$$X+Y-S=l, \quad (6)$$

$$Y-s_1=L, \quad (7)$$

in which $S=s_1+s_2$, $X=x_1+x_2$, $Y=y_1+y_2$ and l is the towed distance of the rope end C. In accordance with the equations (4), (5) and (6) of the reference,¹⁾ S , X , Y and s_1 are expressed as:

$$S=\frac{T_p}{K_n} \frac{1}{\kappa} (e^{\kappa(\pi/2-\theta_p)} - e^{\kappa(\theta_q-\theta_p)} - e^{\kappa\theta_p} + 1), \quad (8)$$

$$X=\frac{T_p}{K_n} \frac{1}{\kappa^2+1} [\kappa e^{\kappa(\pi/2-\theta_p)} - e^{\kappa(\theta_q-\theta_p)} (\kappa \sin \theta_q - \cos \theta_q) + (\kappa \sin \theta_p - \cos \theta_p) + e^{-\kappa\theta_p}], \quad (9)$$

$$Y=\frac{T_p}{K_n} \frac{1}{\kappa^2+1} [e^{\kappa(\pi/2-\theta_p)} - e^{\kappa(\theta_q-\theta_p)} (\kappa \cos \theta_q + \sin \theta_q) + (\kappa \cos \theta_p + \sin \theta_p) - \kappa e^{-\kappa\theta_p}], \quad (10)$$

$$s_1=\frac{T_p}{K_n} \frac{1}{\kappa} (1 - e^{-\kappa\theta_p}). \quad (11)$$

It is seen at once from the equations (4) and (5) that the value of γ and the ratio R_s/T_p are functions of $(\theta_q-\theta_p)$, if the value of κ is known. Division of the

Fig. 2. Isopleths of R_s/T_p and L/l for $\kappa=0.85$. Broken line shows relation of θ_q versus θ_p for $L=10$ cm. and $R_s=2.11$ gr.

equation (7) by (6), in consideration of the equations (8)~(11), eliminates T_p/K_n and gives the ratio L/l as a function of two variables θ_p and θ_q . In Fig. 2 is shown the isopleth of L/l together with that of R_s/T_p , letting $\kappa=0.85$. This value of κ corresponds to that given from experimental conditions, as will be seen later. From the figure, the ratio R_s/T_p is determined as a function of θ_p for a definite value of θ_q . Combining the equation (7) and the relation between R_s/T_p and θ_p for arbitrary θ_q and giving the value of R_s , we can obtain the relation of θ_q versus θ_p for a given value of L ($\neq 0$) by trial and error. In a special case of $L=0$, it holds that $L/l=0$. In consequence, the curve $L/l=0$ determines the values of R_s/T_p and θ_q as functions of θ_p . Thus, we can obtain the relations of R_s/T_p versus θ_p and θ_q versus θ_p for an arbitrary value of L . In the figure the curves of $L=0$, and 10 cm. are illustrated: the curve of $L=10$ cm. is calculated with substitution of $R_s=2.11$ gr. which is given by experimental condition.

From the data given above the values of S , X and Y , characteristic for the pattern of rope, can be calculated as functions of θ_p . Since, moreover, the towed distance l can also be obtained as a function of θ_p in terms of the equation (6), S , X and Y are reversely expressed as functions of l . The tension T_t acting on rope at the point R is

$$T_t = T_p e^{\kappa(\pi/2 - \theta_p)},$$

and the tension $T_c [= T_t + K_t \times \overline{RC}]$ acting on rope at the end C is also calculated as a function of l , since the linear part $\overline{RC}$ is calculated as a function of l . Thus, we can predict how the form and tension of rope under consideration vary with the towed distance.

Experimental

An arrangement of experimental apparatus employed was illustrated schematically in the reference.³⁾ A uniform nylon twine of 3 mm. in diameter, whose values of K_t and K_n are 0.0440 and 0.0517 gr./cm. respectively, was laid on a horizontal plane of dry sand in such a form as shown in Fig. 1, letting $\overline{AB}=90$ cm. and $\overline{BC}=100$ cm. A small lead ball whose frictional resistance is 2.11 gr. was attached to the twine at the point B ($L=0$) in one of duplicate experiments, and, in the other, at the point of $L=10$ cm. Then the free end C of the twine was towed to the direction $\overline{BC}$ as far as 30 cm. in the speed range of 0.7 to 1.0 cm./sec. At a regular interval 5 cm. of towing, the towing force was measured and simultaneously the form of twine was photographed from the top.

Results and Discussion

In the case of $L=0$ cm., the ball starts to move as soon as the twine end C is pulled. Accordingly, as mentioned in the theoretical, the values of S , X and Y are

determined as functions of l throughout the whole course of towing.

In the case of $L=10$ cm., however, the ball does not start to move so immediately. The behaviour of twine can be divided into three stages as follows: (1) from the beginning of towing to the propagation of the deformation of rope into the point P, (2) thereafter to the moment when the ball starts to move, and (3) after the time when the ball has moved. The data for the behaviour in the first stage are available from the references,^{1,2)} from which l is known to be about 5 cm. when the deformation of rope propagates to the point P. Moreover, Fig.2 gives the value of θ_p ($\approx 56^\circ$) at the moment when the ball starts to move. The value of l , at this instant, is calculated to be about 8 cm. In the second stage that $5 < l < 8$, i.e. $0 < \theta_q < 56^\circ$, since the ball retains its initial position, $\theta_p = 0^\circ$ and $y_2 = 10$ cm. Hence, the following relation is obtained,

$$y_2 (=10) = -\frac{T_p}{\kappa_n} \frac{1}{\kappa^2 + 1} [e^{\kappa\pi/2} - e^{\kappa\theta_q}(\kappa \cos \theta_q + \sin \theta_q)] .$$

It is seen that the above expression gives the relation of T_p and θ_q in $0 < \theta_q < 56^\circ$.

By the use of this relation, the values of s_2 and x_2 , are also calculated as functions of θ_q , and, alternatively, are expressed as functions of l . In the range $l > 8$, S , X

Fig. 3-a. Characteristic values, S , X and Y , of sweep line plotted against towed distance l , for $L=0$ cm. $\circ$: Experimental; —: Theoretical.

Fig. 3-b. Similar plots as in Fig. 3-a for $L=10$ cm. $\bullet$: Experimental; —: Theoretical

and Y are determined with the aid of Fig. 2 and the relation (6). In Figs. 3-a and 3-b are plotted the values of S , X and Y as functions of l in the respective case of $L=0$ and 10 cm., together with their observed ones.

In Fig. 4 the calculated and the observed values of T_e are plotted against l .

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Fig. 4. Tension T_e as a function of towed distance l . $\circ$, $\bullet$: Experimental values for $L=0$ and 10 cm., respectively; —: Theoretical.

References

- 1) SUZUKI, O.: *Bull. Jap. Soc. Sci. Fish.*, **28**, 985-987 (1962).
- 2) ———: *ibid.*, **28**, 988-991 (1962).
- 3) KAWAKAMI, T. and O. SUZUKI: *ibid.*, **25**, 413-416 (1959).