釣獲過程におけるスケトウダラの流体力学的解析

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A Hydrodynamical Analysis of Hooking Process of Walleye Pollock *Theragra chalcogramma*[*1]

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The rush and jerk motions in relation to hooking were analyzed hydrodynamically with fish behaviour restricted by a snood, in order to gain a mechanical understanding of the hooking process.

The rush was similar to a rapid starting performance and its kinematic stages are divisible into two. At the first stage, the fish changes its form from a stretched straight to an L-(or C-) shape by moving its tail and anterior parts laterally. The second was the propulsive stage where the fish moved its tail laterally at a high speed. During this stage, the calculated mean of practical thrust was 8.1 N. If it were not for the snood, the speed and distance that would have been covered at the end of this stage would be 5.6 m/s and 37 cm, respectively.

The first stage of the jerk motion was similar to the first stage of the rush. However at the second stage, the fish changed its form either by straightening out or reversing to a C-shape by moving mainly the anterior part. The length of this stroke was approximately 1/3 times the body length.

The distance covered and the stroke are very important factors in understanding the hooking process which includes a complicated interaction between the gear and the fish. This process must be considered at the gear designing stage.

The catching process of longline gear depends on the interaction between the fish and gear. The operating condition of longline gear is considered to be roughly static, thus hooking depends highly on fish motions. A hydrodynamical study of fish motions in relation to hooking is necessary in explaining the hooking mechanism and in improving the hooking performance of a gear.

Fish response to the longline has been examined in the laboratory[1,2)] and in the field.[3,4)] The results showed that the hooking occurred in connection with strong responses such as the rush or jerk motion with one behaviour or several sequential behaviours. The analysis of fish steadily swimming in a straight line has been conducted by Lighthill[5-7)] and Wu.[8,9)] As another approach, the treatment of the hydrofoil or wing to analyze power output by fish has been conducted by Chopra and Kambe.[10)] Recent works have been directed toward to clarify the hydrodynamics parameters in swimming, such as wave length, its period, and propel efficiency.[11-13)] In most cases, fish reactions to longline gear are considered to be the unsteady activity, including rapid start or stop and turning. These motions may be treated by a modification of a basic model.[14-17)] However, up to now, there are few investigations regarding these motions and hydrodynamical analysis of fish motion restricted by a snood.

Therefore, the objectives of the present study are as follows: 1) describe the rush and jerk motions observed in fish; 2) determine which of these motions are classified by fish behaviour investigators and fit them into their respective hydrodynamical models as developed by hydrodynamicists; 3) to know the distance covered and stroke of these motions (rush and jerk); 4) and finally, the relationship between the hydrodynamics parameters and hooking are also discussed.

Analysis

The materials and methods used in this experiment have been fully described in a previous paper.[1)] Hence, only a brief overview of the analytical method is given below. Fig. 1 is the lateral view of a walleye pollock. A model fish chosen in the study of rushing motion was the largest in the samples (52 cm and 850 gw). The

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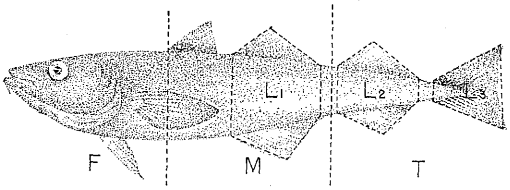

Fig. 1. Lateral view of a walleye pollock. The fish body is divided into three equal length parts, the letters of F, M and T stand for the fore part, the middle part and the tail part, respectively. The letters L_1, L_2 and L_3 stand for the first paired fins, the second paired fins and the tail fin, respectively.

fish used in the jerk motion study is about 47 cm, 630 gw in length and weight. The VTR frames used in the analysis of the motions were selected when the fish was swimming horizontally.

The instantaneous force (F) acting on the fish was calculated using the formula given by Weihs[14)] in his study on fish turning motions,

$$F=-\frac{\partial}{\partial t}\int_0^l mw\boldsymbol{n}\mathrm{d}a-\sum_{i=1}^{k} L_i \qquad (1)$$

where l is the fish length, m is the added mass of a cross section per unit length, w is the velocity component of $\boldsymbol{n}$ at that cross section, and $\boldsymbol{n}$ is a unit vector perpendicular to the center line. Also L is the force caused by momentum shedding from the fins and lens-shaped sections of the fish, and k is the number of the section.

In calculating the values of the first term of Eq. (1), the following procedures were used. In every frame, the time interval between frames was 1/30 s, the position coordinate (x, y) of arbitrary 30 points along the center line of the fish body from the tip of the caudal fin to the top of the head was read by means of a superimposed VTR image on a microcomputer (PC-286V) display. The obtained position coordinates were interpolated by a spline function and the fish length was calculated using the interpolated line. After which, 30 equally spaced points $a(x, y)$ were identified along the body line, from the tip of the caudal fin ($a=0$) to the top of the head ($a=l$). The error between the real length and the calculated one was less than 5% and has been neglected.

The velocity $u(a, t)$ of an identified segment was obtained by comparing three successive frames to the identified points on the center line of the fish. We write

$$u_n(a, t)=\frac{a(x, y)_{n+1}-a(x, y)_{n-1}}{2\Delta t} \qquad (2)$$

where n is the frame number and Δt is 1/30 s. The velocity of a segment is separated into normal and tangential components relative to the centerline. The added mass of the cross section which is elliptical and the combination of elliptical shapes and lines, can be written as[6)]

$$m=\frac{\pi}{4}\rho d^2\beta \qquad (3)$$

where ρ is the density of sea water (1026 kg/m^3), d is the depth of the cross section, and β is the coefficient which varies 0.8–1, depending upon the shape of the section.

In calculating the second term of Eq. (1), for convenience, the sections which generate the momentum shedding forces were divided into 3 parts (see Fig. 1). The first part (L_1) consisted of the second dorsal fin and the first pectoral fin, with an aspect ratio ($A\!\!\!R$) of 1.96, and area(S) of 91.8 cm^2. The second part (L_2) consisted of the third dorsal fin and the second pectoral fin ($A\!\!\!R$: 1.61; S: 54.8 cm^2) and the third part (L_3) is the caudal fin ($A\!\!\!R$: 2.07; S: 35.3 cm^2). The areas of the fins were calculated on the assumption that they were fully erect, as observed by Eaton *et al.*.[18)] The momentum shedding is given by[14,19)]

$$L=\frac{1}{2}\rho Su^2C_L \qquad (4)$$

where C_L is the lift coefficient and is calculated by $(\pi/2)A\!\!\!R\alpha$; α is the angle of attack.

Results

Rush

The mechanics of a rush motion was basically the same as those of the rapid start as described by Weihs[15)] and Webb.[16)] The rush motion could also be divided into three stage, but in this case, the kinematic stage could not be clearly identified because of the existence of a snood. Hence here we examined the relationship between the fish motion and the fishing gear (Fig. 2).

(a) First stage: The fish changes its form from a stretched straight to an L-(or C-) shape by moving its tail and head laterally (frames 1 to 10). In this stage, the lumped forces generated at the forepart and tail part causing the momentum change are approximately on the same direction and they are balanced by the force generated at the middle part of the body having a high added mass.

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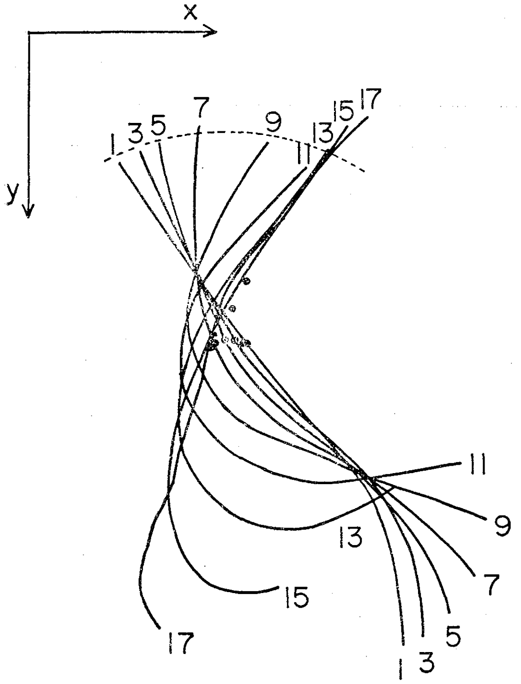

Fig. 2. Successive position of the body center line of the walleye pollock during rush. Numbers indicate frame number. Time interval of a frame is 1/30 s. The center of the mass is shown by the closed circles. Broken line shows the limitation of the snood when it is fully stretched.

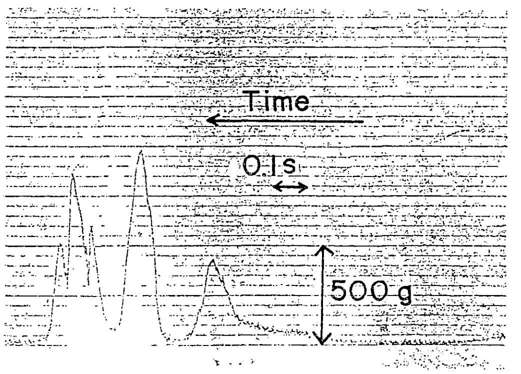

Fig. 3. Direct measured tension on snood during rush using strain gauges.

momentum on the forepart in Table 1, we found deceleration at frame 6 and acceleration at frames 8 and 9. This is an evidence that the first restriction by the snood occurs at frame 7, as is clearly seen in Fig. 2. Recorded tension on the snood at this moment corresponds to the first peak in Fig. 3.

At the end of the first stage, the shedding forces generated by the tail fin become dominant, so that the center of mass starts to accelerate in the direction perpendicular to the original course.

(b) Second stage: The tail fin moves perpendicularly to the original axis of the fish at a high speed, and the forepart moves ahead tangentially with the center of mass moving accordingly (frames 11 to 17). From frame 13 of this stage, the fish is restricted again by the snood, and the tension at this moment can be seen as the second peak in Fig. 3.

During this stage, fins of the second part (L_2) contributed significantly to the propulsive forces because these fins were subtended at a small angle of attack to its direction of motion. This plays an important role in compensating the discontinuity in thrust caused by the change in the direction of the caudal fin movements (frames 11, 12).

The strong restriction on the fish body leads to a forced pitching movement and the body line delineated abnormally (frame 17). The final stage could not be described here because the scaling error becomes large due to the vertical movement of the body. The third peak in Fig. 3 was considered as another rush motion.

Jerk

Fig. 4 shows the centerline of the walleye pollock observed during the jerk motion. As in the case of the rush motion, it can also be divided

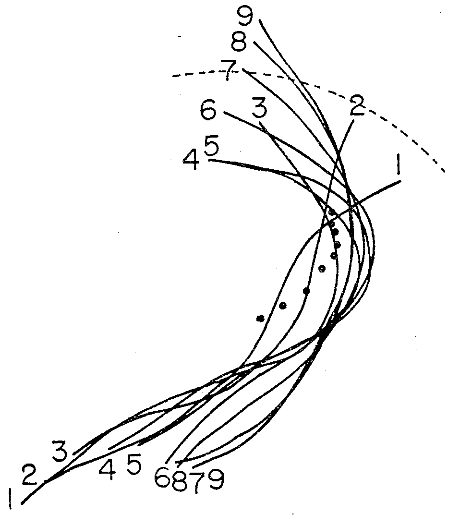

Fig. 4. Successive position of the body center line of the walleye pollock during jerk. Numbers indicate frame number with 1/30 s time interval. The center of the mass is shown by the closed circles. Broken line shows the limitation of the snood when it is fully stretched.

Table 1. Forces calculated from the Eq. (1) during rush of walleye pollock *Theragra chalcogramma*

Frame[*2] no.		Momentum changes[*1]			Shedding forces[*1]			Resultant forces
		F[*3]	M[*3]	T[*3]	L_1[*3]	L_2[*3]	L_3[*3]	
1	x[*2]				0	−0.4	0	−0.4
	y				0	−0.6	0	−0.6
2	x	0.2	0.2	−0.2	0	0	−0.2	0
	y	−0.1	−0.2	−0.1	0	0	−0.4	−0.8
3	x	0.2	0.4	0.3	−0.1	−0.1	−0.4	0.3
	y	−0.2	−0.4	0	−0.1	0	−0.7	−1.4
4	x	−0.6	0.4	0.2	0	0	−0.7	−0.7
	y	0.2	−0.5	0.2	−0.3	0	−0.6	−1.0
5	x	−0.4	0.4	−0.3	0	0	−1.0	−1.3
	y	0.1	−0.2	0.7	−0.5	0	−0.8	−0.7
6	x	0.5	0.9	−0.1	−0.1	−0.2	−1.4	−0.4
	y	−0.3	−0.6	0.7	−0.7	0.1	−0.8	−1.6
7	x	0	1.1	0.4	−0.1	0	−2.2	−0.8
	y	−0.5	−0.7	0.6	−1.3	0	−0.6	−2.5
8	x	−1.2	0.5	0.6	−0.2	0	−2.7	−3.0
	y	−0.5	−0.5	0.3	−1.3	0	−0.3	−2.3
9	x	−0.7	0	0.8	−0.5	0	−2.8	−3.2
	y	−0.4	−0.1	−0.8	−1.8	−0.1	0.5	−2.7
10	x	−0.3	−1.1	0.7	−1.2	−0.2	−2.4	−4.5
	y	−0.3	0.4	−2.4	−2.8	−0.6	1.4	−4.3
11	x	−0.3	−1.1	−0.1	−0.7	−0.8	−0.5	−3.5
	y	−0.1	0.6	−3.0	−3.0	−1.6	1.6	−5.5
12	x	0.4	−1.5	−0.8	−1.0	−2.8	−0.3	−6.0
	y	0.2	1.0	−2.1	−4.7	−3.7	−0.6	−9.9
13	x	0.8	−2.8	0.3	0.2	−2.5	−2.7	−6.7
	y	0.5	0.8	0.9	−0.9	−6.6	−2.5	−7.8
14	x	0.8	−1.0	1.4	0.4	−1.1	−3.3	−2.8
	y	0.6	0.2	2.0	0	−8.4	−4.0	−9.6
15	x	0.3	1.8	0.5	−0.1	1.7	−3.1	1.1
	y	0.3	0.6	0.8	0	−6.3	−5.2	−9.8
16	x	0	2.6	−1.6	−1.0	0.4	−1.5	−1.1
	y	0	1.1	1.0	−0.8	−0.1	−8.0	−6.8
17	x				0.2	−1.7	−0.2	−1.7
	y				0	−1.4	0.3	−1.1

[*1] Momentum changes and shedding forces are calculated from the first and second term of the Eq. (1), respectively.

[*2] The frame numbers and coordinate system are the same as used in Fig. 2.

[*3] The letters F, M, T, L_1, L_2, and L_3 are shown in Fig. 1.

into stages:

(a) First stage: The fish changes its form from a stretched straight to a C-shape by moving its head and tail laterally (frames 1 to 4). The kinematic feature of this stage was fundamentally the same as in the first stage of the rush. The movement of the center of mass was small.

(b) Second stage: At this stage, the fish changes its body form either to a stretched straight or to a reversed C-shape (frames 5 to 9). Several repetitions of these motions are as a jerk series. But in this case, the restriction by the snood (from frame 8) disturbs the fish to straighten out fully. The tension was recorded (Fig. 5), at the moment the fish was hooked. Unlike in the rush motion, the movement here is largely by the anterior part. The hydrodynamical disadvantage of the movement by the anterior part was pointed out by Lighthill.[5)]

The cross section of the walleye pollock at the anterior is elliptical (rounded edged) which flattens and becomes sharp towards the posterior end. Correspondingly, the body structure changes from being stiff to flexible. This is similar to a hybrid oscilIator model which is stiffness-dominated at the anterior part and resistance-dominated at the posterior part as discussed by Bright.[20)]

An observation of the actual fish movement

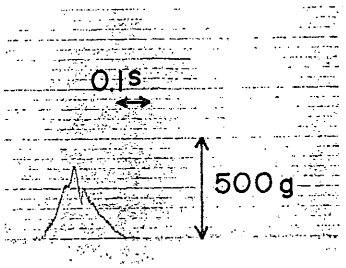

Fig. 5. Direct measured tension on snood during jerk using strain gauges.

showed that the amplitude of the anterior part was larger than that of the posterior part (Fig. 4). The reason for this can be considered as follows. The main objective of the jerk motion seems to pull the bait off the hook, as the previous paper[1] pointed out. The frequency of this movement increased just after the bait was sucked into the mouth and naturally the movement of the head dominated. This motion can also be explained from the viewpoint of hydrodynamics. Considering that the edge of the cross section of the posterior part is sharp, this part is expected to have a large drag coefficient to the normal component of the centerline of the body. Hence by oscillating at a smaller amplitude it will be able to sustain a longitudinal balance. Of course, this sharp edged vorticity will be shed, and this shedding force will contribute to the movement of the center of mass, however, in this case it was very small.

The final stage can not be described here because the fish remains motionless due to being hooked.

Discussion

As mentioned above, the diameterical difference in the mechanics of the rush and jerk motions become evident in the second stage. Accordingly, the second stage of these movements is discussed in detail here.

The mean thrust during the rush motion (frames 13 to 16) must be equal to the sum of the body drag (D_b), induced drag (D_i) on the fin parts and mean snood tension which was measured directly taking into account loss. This loss was mainly due to the elongation of the snood, the ring used as the tensionmeter and mouth cavity of the fish, and although very small, bending of the pipe used as the mainline, but since the experimental setup is considered to be sturdy, the loss would be negligible. The body drag (D_b) is given by[11,12]

$$D_b=\frac{1}{2}\rho A u^2\times 1.2C_f \tag{5}$$

where A is the surface area of the fish (0.05 m^2), u is the volocity of the fish (0.3 m/s; mean value of frames 13 to 16) and C_f is the frictional drag coefficient, which varies whether the flow is laminar ($1.328\,\mathrm{Re}^{-0.5}$) or turbulent ($0.074\,\mathrm{Re}^{-0.2}$). In this calculation, the laminar drag coefficient was used. As expected, the contribution of D_b was very small (0.01 N) and can be disregarded. On the other hand, induced drag (D_i) is given by[19,21]

$$D_i=\frac{1}{2}L\alpha \tag{6}$$

where L is the force caused by momentum shedding and α is the angle of attack. The mean value of D_i for frames 13 to 16 was $x=3.7$ N and $y=-0.9$ N (refer to Fig. 2 for coordinate system).

The mean thrust of the x and y components, taking into account D_i, were 1.3 N and -9.5 N, respectively. The component of the anterior part axis (practical thrust) was 8.1 N. This force must be balanced by the tension on the snood. The measured mean tension was determined to be about 5 N and considering the directional cosine of the fish body axis, it is estimated to be about 5.5 N. The difference between 8.1 N and 5.5 N was probably due to the loss mentioned above.

If it were not for the snood, since the fish body received an impulsive force (8.1 N) during a short time of 4/30 s, the speed and distance covered at the end of the second stage should be predictable by the law of momentum conservation. Here, it is assumed that the body drag at any instant can be calculated from Eq. (5), using the turbulent drag coefficient. Under this condition, momentum conservation becomes

$$(F-D_b)t=M(u-u_0) \tag{7}$$

where M is the body mass taking into account the added mass taken as 1.2 times the body mass,[16,23] and considering that $u_0=0$, then the speed attained at the end of the second stage is 5.6 m/s. This value agreed well with 8.5 l/s obtained by Webb.[16]

The distance (x) covered during this period can be calculated from the standard Newtonian mechanics

$$u^2=u_0^2+2ax \tag{8}$$

where $u_0=0$ and, since the mean acceleration rate

(a) was 42 m/s^2, x was about 37 cm.

Since at every stage of the jerk motion, the movement of the center of mass was very small, the length of the stroke depended only on the lunging capabilities of the fish body. The stroke length included the amplitude of the head shaking from side to side, and was estimated to be about 1/3 times the body length of the walleye pollock.

The stroke or distance covered at any kinematic stage is a very important factor in determining whether the hooking conditions as described in a previous paper[1)] could be satisfied or not. The first condition of hooking is that tension is exerted on the snood. This can be easily satisfied by a movement which has a long stroke, such as a rush motion. The second condition is the proper orientation of the point of the hook to ensure a fast penetration into the mouth cavity, while the first condition is being satisfied. In other words, hooking should take place instantaneously at any kinematic stage of these movements if the above conditions are to be satisfied.

To clearly illustrate the hooking mechanism, it is important to know the direction in which the snood was stretched and the moving angle of the head to the body axis. It is therefore valid to classify the behaviour catalog dealing with each kinematic stage. For example, the decision as to whether a kinematic stage belongs to the rush or the jerk motions should be based upon whether the direction of movement of the head is longitudinal or tangential. Using this classification scheme, the first stage of a rush motion can be considered as a jerk. At this stage the first condition of hooking was satisfied, but the second condition was not. Similarly in the second stage, which was classified as a rush, the second condition of hooking was not satisfied. In both cases, as discussed in a previous paper[1)] and ealier suggested by Huse,* when the angle between the direction of the stretched snood and the forepart axis of the fish body was small, it would be difficult to satisfy the second condition when the traditional J-hook was used. In contrast, at the second stage of the jerk motion both conditions were fully satisfied. Based on the observation of the hooking process, the typical behavioural sequence was bite-jerk-rush-jerk-hooking.[1)] Of course, this depended on the configuration of the hook, length of the snood and the degree of fixedness of the mainline.

There are various longline rigging methods according to the target species and method of operation. In designing the longline gear, the snood length is of particular importance not only in determining the method of handling the gear but also because it affects the hooking rate. As for the hooking rate, Park[23)] has reported that shortening of the snoods due to entangling reduces the hooking rate. Recently, Bjordal[24)] pointed out based on several practical operations that a reduced snood length decreases the catch rates. In modern mechanized longline gear, snoods of 30–50 cm are widely used for the fish with a subcarangiform mode of swimming such as cod or walleye pollock. Such fishes have more flexible bodies than carangiform mode fish, and have a high acceleration performance. These seem to be the reason why hooking is possible using a relatively short snood. Practically, the required force (tension on the snood) to hook a fish is far smaller than the force exerted by the fish at any kinematic stage of the rush and jerk motions.[1)] From this experiment, it seems that there is a minimum snood length that will enable the fish to move at the first stage of the rush or jerk motions.

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