

A Hydrodynamic Study of Active Drag in Swimming*

Hideki TAKAGI**, Yukimaru SHIMIZU***
and Norihisa KODAN****

The purpose of this study is to measure active drag, which is dynamic drag acting on a self-propelling swimmer in water. We developed a new measurement device, which was capable of measuring active drag without disturbing natural swimming in a circulating water channel. Four collegiate skilled swimmers volunteered to participate in this study. The subjects were asked to swim front crawl and to keep the predetermined stroke frequency within a range of 0 m/s to 1.8 m/s flow velocity. The active drag was estimated by means of the relationship between residual thrust (thrust minus the resistance) and passive drag (static drag acting on a prone position swimmer). As a result of these development, it was possible to measure active drag more precisely than before, and to obtain the experimental equation that predicted the active drag within a range of Reynolds number equaled the actual swimming velocity.

Key Words: Flow Measurement, Fluid Force, Bio-Fluid Mechanics, Propulsion, Sports-Engineering, Swimming, Human

1. Introduction

In recent times, mechanical engineering has been used frequently for practical research involved in sports and exercise. Methodology and knowledge of engineering contributed remarkably to develop the equipment and facilities, and to analyze human movements in sports and exercise. For examples in swimming, a low-resistance swimsuit has been developed, it has been contributing to improve the record. It is expected that applied sports engineering will develop more widely in the future. However, there have not been many researchers who analyzed swimming movement by the engineering approach. Especially, the few studies that have been conducted involved a hydrodynamical approach^{(1),(2)} to active drag (dynamic drag acting on a self-propelling swimmer)

except for the several pioneering studies⁽³⁾⁻⁽⁶⁾. Taneda⁽⁷⁾ pointed out that the difficulty of measuring active drag prevented progress of the research. To measure active drag accurately, whole pressure and friction distribution of the swimmer must be measured without disturbing the natural swimming movement. The measurement of active drag was difficult therefore when there was no established method to measure it accurately. Even though there have been some studies reported the procedure for analyzing active drag, an accuracy of data collecting has been in problem.

The purpose of this study was to develop a device and methodology that were capable of measuring active drag accurately, and to obtain the experimental equation that can predict the active drag within a range of Reynolds number equaled the actual swimming velocity.

Nomenclature

A_s : Body surface area (m^2)
 C_{Da} : Active drag coefficient
 C_{Dk} : Kinetic drag coefficient
 C_{Dp} : Passive drag coefficient
 Da : Active drag (N)
 Dk : Kinetic drag (N)
 Dp : Passive drag (N)

* Received 24th September, 1998. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 64, No. 618, B (1997), p. 405-411 (Received 21st May, 1997)

** Faculty of Education, Mie University, 1515 Kamihama, Tsu 514-8507, Japan. E-mail: takagi@edu.mie-u.ac.jp

*** Faculty of Engineering, Mie University, 1515 Kamihama, Tsu 514-8507, Japan

**** NKK Co. Ltd., 1 Kumozukoukan-cho, Tsu 514-0393, Japan

- Fr : Froude number $= U/(gH)^{0.5}$
 F_{\max} , $F_{3/4}$, $F_{1/2}$, $F_{1/3}$: Stroke frequencies for maximum effort, 3/4, 1/2, 1/3 strokes respectively
 g : Acceleration due to gravity (m/s^2)
 H : Body height (m)
 Re : Reynolds number $= HU/\nu$
 Tr : Residual thrust (N)
 T_0 : Original thrust when $U=0$ (N)
 U : Flow velocity (m/s)
 U_0 : Achievable swimming velocity when $Tr=0$ (m/s)
 V : Body volume (m^3)
 W : Body weight (kg)
 ρ : Density of water (kg/m^3)
 ν : Kinematic viscosity of water (m^2/s)

2. Experimental Apparatus and Method

2.1 Subject

Four collegiate skilled swimmers, with a competitive career ranging from 5 to 17 years volunteered to participate in this study. All subjects submitted written consent. We measured physical characteristics (e.g., height, weight), and estimated the body surface area As using the following Nagamine's⁽⁸⁾ function.

$$As = 0.007246(100H)^{0.725} W^{0.425} \quad (1)$$

The body volume V was estimated by dividing the weight by the mean body density of a 20 years old male ($1.03 \times 10^3 \text{ kg/m}^3$). All physical characteristics are shown in Table 1.

2.2 Test apparatus

The measurement of the active drag was conducted in the circulating water channel (CWC) in NKK Corporation and the schematic view of the CWC is shown in Fig. 1. This CWC was controlled by a microcomputer for solving peculiar problems such as an unbalanced flow distribution, an incline in the water surface, and an occurrence of regular wave⁽⁹⁾. This system allowed error to be minimized between two experimental conditions (i.e. towing through the still water and fixing in the moving water). The measuring device of the active drag is shown in Fig. 2. This device was designed to measure forces only in the swimming direction regardless of yawing, pitching, and rolling movements of the swimmers. Four aluminum pipes (diameter, 30 mm; wall thickness, 3 mm) were connected by a universal joint on both ends. One end of this structure was fixed to the upper part of the CWC and the other end to a stabilizing plate. These structures allowed the stabilizing plate to maintain a vertical position perpendicular to the flow, so the four pipes could maintain a parallelogram without twisting. The load cell was set under the stabilizing plate and it could move a little back and

forth with a spring system and the rigid structure prevented the natural stroking. The apparatus was suspended from the ceiling, so that the weight of the device could not influence the swimmer.

Forces acting on the swimmer using the spring system that was similar to the present study were measured by Clarys⁽¹⁰⁾, however the yawing, pitching

Table 1 Individual data describing age, career, height, weight and body surface area

Subjects	Sex	Age (yrs.)	Height H (m)	Weight W (kg)	Body Surface Area As (m^2)	Volume V (m^3)
A	Male	22	1.70	68.00	1.81	0.066
B	Male	21	1.68	60.00	1.70	0.058
C	Male	21	1.72	65.00	1.78	0.063
D	Male	20	1.72	53.00	1.64	0.051
Averaged Value		21.0	1.71	61.50	1.73	0.060
Standard Deviation		0.8	0.02	6.56	0.08	0.006

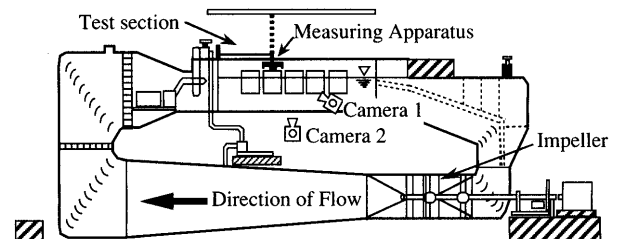
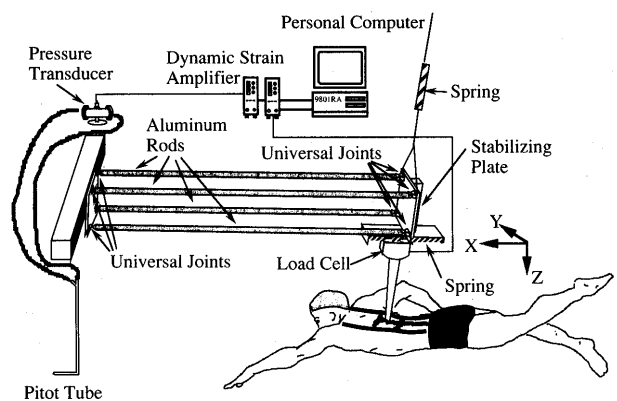
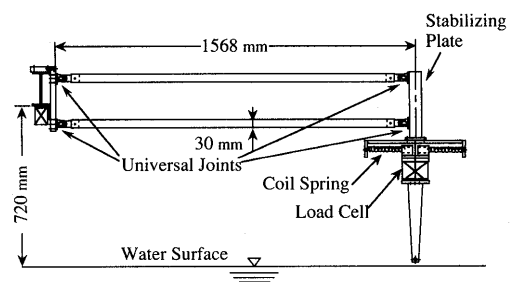


Fig. 1 Schematic side view of the circulating water channel

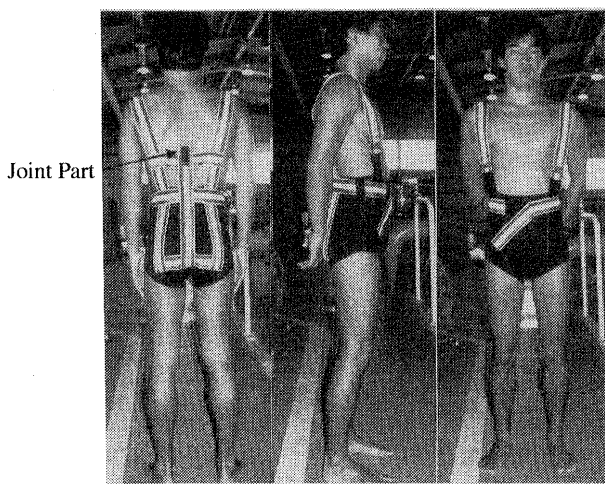


(a) Bird's-eye View



(b) Side View

Fig. 2 Measuring apparatus



(a) Back View (b) Side View (c) Front View

Fig. 3 Special harness for swimmer

and rolling movements of the swimmer were not considered in Clarys' measurement. Hence, it was difficult for the swimmer to swim in a free-swimming condition. In comparison to Clarys' study, we designed specially adapted structure to measure the forces precisely without disturbing natural swimming.

Three directional views of the harness are shown in Fig. 3. The harness was designed to fit the swimmer and to transmit the propelling force generated by the swimmer or the resistance received from the flow to the load cell. The lower part of harness was made by modifying a wet suit and the upper part was shaped with nylon belts. The load cell was connected by a rod to the harness. The harness could be adjusted to fit each subject and did not prevent the swimmer from natural swimming.

2.3 Data collecting

Two kinds of experiments were conducted in this study. First, the subjects were attached to the measurement device and asked to keep a gliding position (streamlining the body in prone position, see Fig. 4 (a)) in the CWC. The passive drag Dp was measured for a period of 10 seconds at each flow velocity stage, which increased from 0 m/s to 1.6 m/s at 0.2 m/s intervals.

The second experiment was designed by modifying the performance examination procedure for a screw in shipbuilding engineering. The subjects were attached to the device and asked to swim front crawl at four pre-determined stroke frequencies (see Fig. 4 (b)). The residual thrust Tr , thrust minus the active drag Da , was measured for 10 seconds at each flow velocity, which increased from 0 m/s at 0.2 m/s intervals until the value of the residual thrust Tr indicated a negative value. The four stroke frequencies were determined according to the following procedure:

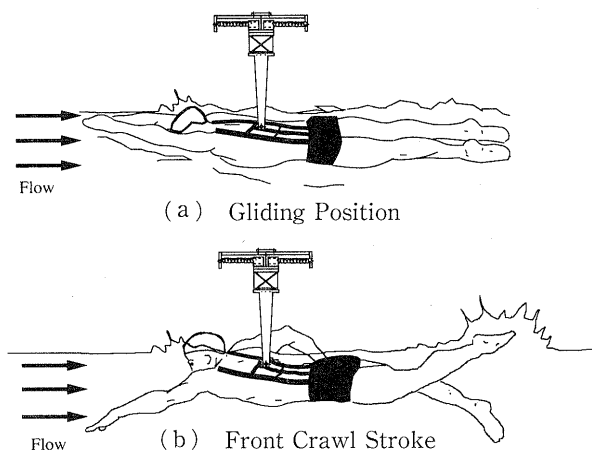


Fig. 4 Two types of the swimming position

First, the number of alternate strokes counted during ten seconds of a maximal effort in the CWC was used to determine the maximum frequency (F_{max}). We then defined three quarters of F_{max} as $F_{3/4}$, half of F_{max} as $F_{1/2}$ and one third of F_{max} as $F_{1/3}$. After determining the stroke frequencies, the subjects were asked to swim at an even stroke frequency regardless of a change of flow velocity. During the experiments, subjects' stroke frequencies were constantly checked by VTR image. If their stroke frequency was different from the required frequency, the subjects were asked to retest. There was sufficient rest between the trials for the subjects to recover.

On each velocity stage for both measurements of the passive drag Dp and active drag Da , the 10-second output signal of the load cell was digitized after amplification and low-pass filtering (5 Hz) and processed with a microcomputer (sample frequency 10 Hz). To confirm the flow velocity, a pitot tube was set on the upper stream point, where it had no influence on the swimmer and the flow velocity U was continuously monitored.

3. Results and Discussion

3.1 Passive drag results

During the passive drag measurement, the whole body sank in the water, even though the back of the head appeared slightly above the water surface and the posture of the subject was kept level regardless of increasing the flow velocity. The mean attack angle of the body with respect to the horizontal level (an angle between the line that went through the shoulder and hip, and the horizontal line) was $25.4^\circ \pm 3.9^\circ$. There was little variance between subjects (within 5 percentages).

A sample output of the passive drag Dp for Sub. C is shown in Fig. 5. The Dp changed dynamically at the beginning of the measuring period, but it became stable on 4 seconds later and then changed

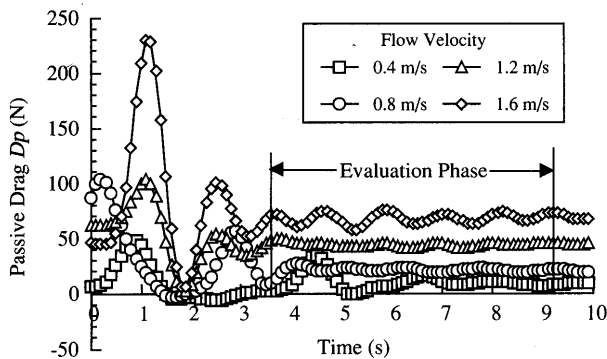


Fig. 5 Typical example of the D_p data in the gliding position (Sub. C)

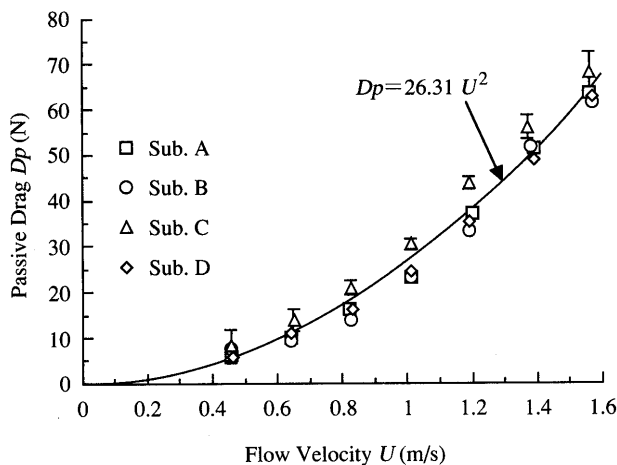


Fig. 6 Average D_p as a function of the flow velocity U

periodically with small amplitude. The violently changing data at the beginning were discarded, while the relatively stable data for the “evaluation phase” (from 4 to 9 seconds later) were used to calculate an average D_p at each flow velocity stage.

The relation between the D_p and the flow velocity U of each subject and the regression curve is shown in Fig. 6. The standard deviations of the measured data for Sub. C are also described in the Fig. 6. The measured data matched well with a quadratic regression curve.

To discuss the D_p hydrodynamically, the D_p was transformed to the coefficient C_{Dp} , a dimensionless variable, using Eq. (2). In this calculation, the body surface area A_s was adopted as the representative area, because the frontal cross-sectional area was not steady during swimming. Moreover, the flow velocity was changed into the Reynolds number Re using the Eq. (3). The height H was adopted as the representative length.

$$C_{Dp} = \frac{D_p}{0.5 \rho A_s U^2} \quad (2)$$

$$Re = \frac{HU}{\nu} \quad (3)$$

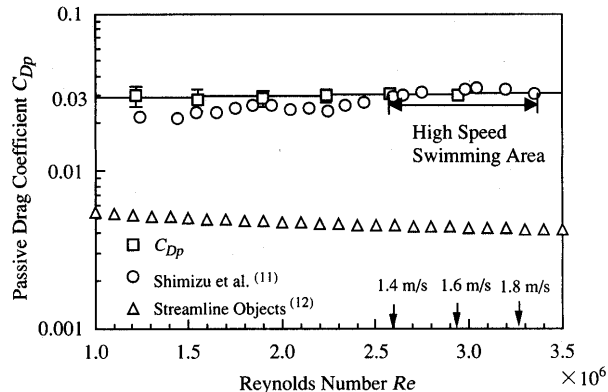


Fig. 7 Passive drag coefficient C_{Dp} as a function of Reynolds Number Re

The relation between the mean C_{Dp} and the Re is shown in Fig. 7. To examine validity of the C_{Dp} , result of Shimizu et al.⁽¹¹⁾ and theoretical drag coefficient⁽¹²⁾ of a streamlined object were indicated in the Fig. 7. Shimizu et al. measured the fluid drag of human body model when it was towed through the water. The theoretical drag coefficient values were obtained by calculating drag acting on the streamlined long and narrow object (length/width=6) that is similar to the human body. Even though the within-subjects variance of C_{Dp} was small in the lower Re ($Re < 2.5 \times 10^6$), when taking a general view of the C_{Dp} , the mean C_{Dp} values were almost stabilized and equal to about 0.03. In comparison to the theoretical drag coefficient, the theoretical value indicated much smaller (1/5), and it was almost constant in the range of $1.0 \times 10^6 < Re < 3.5 \times 10^6$. On the other hand, the drag coefficient of human model was somewhat lower than the C_{Dp} in the range of $Re < 2.5 \times 10^6$, and it was changing with the Re . However, in the range of $2.6 \times 10^6 < Re < 3.4 \times 10^6$, the data of Shimizu et al. were stabilized almost equal to the C_{Dp} . If it is assumed that the C_{Dp} is steady and equal to 0.03 in the selected Re range, $2.6 \times 10^6 < Re < 3.4 \times 10^6$, within all examined Re range, the following expression for D_p is determined with the use of Eq. (2).

$$D_p = \frac{0.03}{2} \rho A_s U^2 = 0.015 \rho A_s U^2 \quad (4)$$

This selected range for Eq. (4) is equal to the actual swimming race velocity range (1.4 m/s to 1.9 m/s).

3.2 Residual thrust results

During the measurement of residual thrust Tr , the subjects were required to maintain the pre-determined stroke frequencies. To confirm the pre-determined stroke frequency, we surveyed it for each subject using the VTR image. The results of stroke frequency are shown in Table 2. Every subject's stroke frequency seemed to have very small variance and achieved the required target frequency.

Table 2 Average and standard deviation of the stroke frequency

Subjects	F_{max} (Hz)	$F_{3/4}$ (Hz)	$F_{1/2}$ (Hz)	$F_{1/3}$ (Hz)
A	0.86 ± 0.04	0.61 ± 0.02	0.44 ± 0.02	0.33 ± 0.03
B	0.99 ± 0.03	0.79 ± 0.01	0.52 ± 0.02	0.34 ± 0.01
C	0.98 ± 0.04	0.61 ± 0.02	0.44 ± 0.02	0.32 ± 0.04
D	1.04 ± 0.02	0.71 ± 0.03	0.48 ± 0.02	0.35 ± 0.03
Average	0.97	0.71	0.50	0.35
Standard Deviation	0.07	0.07	0.05	0.03

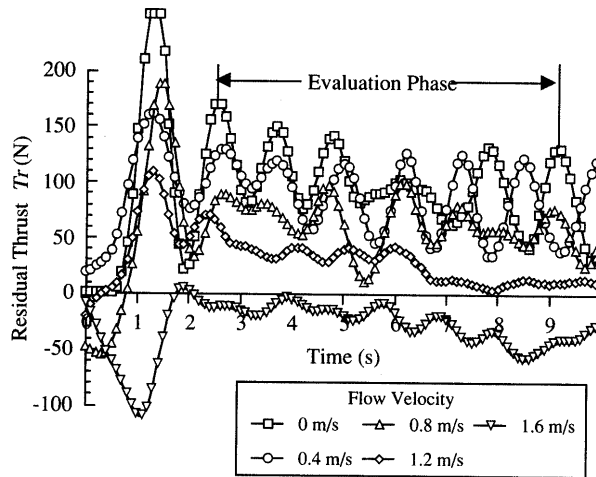


Fig. 8 Typical example of the Tr data on each flow velocity at maximal stroke frequency in the front crawl. (Sub. C)

Moreover, we measured the attack angle of the body with respect to the horizontal line analyzing the VTR image. The mean attack angle during the Tr measurement was $20.5^\circ \pm 3.1^\circ$ and was smaller than during the Dp measurement ($25.4^\circ \pm 3.9^\circ$), however it was steady regardless of the change in flow velocity.

A sample output of Tr for Sub. C at the maximum stroke frequency F_{max} is shown in Fig. 8. In this figure, a positive value means that the force acts upstream and a negative value means that the force acts downstream. The output changed periodically due to the alternate arm stroking of the swimmer. As the swimmer swam at the maximal effort, the output trended to decrease due to fatigue. To obtain the mean Tr , violently changing data at the beginning were discarded, while the relatively stable data for the "evaluation phase" (from 2.5 to 9 seconds later) were adopted to calculate an average of the Tr at each flow velocity stage. With regard to other stroke frequencies, the mean Tr was obtained as described above. A typical example of the relation between the Tr and U for Sub. C at four various stroke frequencies is shown in Fig. 9. The Tr and U data were least-squares fitted to Komune's⁽¹⁾ regression formula Eq. (5) and the regression curves are drawn in Fig. 9.

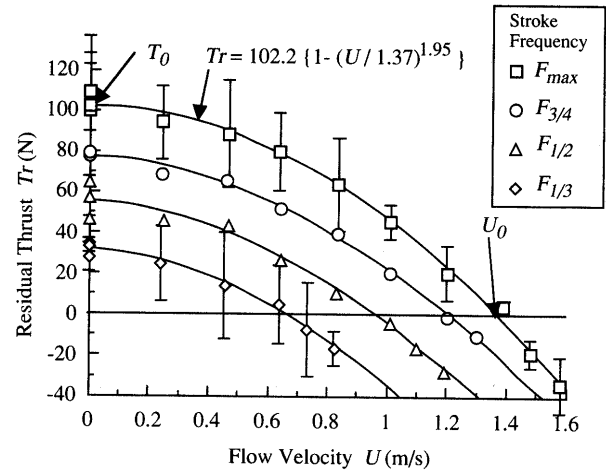


Fig. 9 Typical example of a Tr - U relationship on each kind of stroke frequency (Sub. C)

$$Tr = T_0 \left\{ 1 - \left(\frac{U}{U_0} \right)^\mu \right\} \quad (5)$$

where T_0 means the thrust at a certain stroke frequency when velocity equals zero, U_0 is the theoretically achievable swimming velocity when the residual thrust equals zero and μ is an experimental constant.

The maximum Tr values at all stroke frequencies were observed at $U=0$ m/s and the values of Tr decreased exponentially with the increase in velocity. The reason why Tr decreased with an increase of U could be explained the following assumption: If the production of propelling force keeps steady, the overcome drag increases proportional to the square of U so that Tr must be getting smaller. When U gets higher propulsion and drag balance. On further increase in velocity, drag exceeds the propulsion so that Tr value indicated negative value.

Similar results were observed for the other three subjects.

3.3 Estimation of active drag

The active drag Da is assumed to consist of the following two major elements. One is the passive drag Dp , which originated from the body shape. The Dp consists of frictional drag, pressure drag (included eddy making drag), and wave making drag. Another major element is kinetic drag Dk , which originated from stroking movements of the arms and legs. The Dk consists mainly of wave making drag. Thus the Da is equal to the sum of the Dp and Dk :

$$Da = Dp + Dk. \quad (6)$$

As the subject always swam at an even stroke frequency, we assumed that the swimmer could produce a constant thrust, which is equal to the thrust at zero velocity T_0 . The Tr is the residual thrust, which is T_0 minus the active drag Da , thus

$$Tr = T_0 - Da = T_0 - (Dp + Dk). \quad (7)$$

The Dp value was obtained by Eq. (4) so that the Da

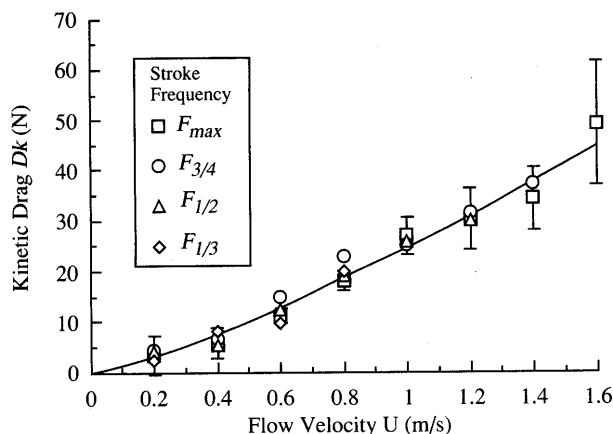


Fig. 10 The relation between kinetic drag Dk and flow velocity U

value can be estimated if the Dk value is known. According to Eq. (7) the following expression for Dk can be obtained:

$$Dk = T_0 - Tr - Dp \quad (8)$$

The Dk values of all the subjects were calculated by Eq. (8) and the results are shown in Fig. 10. The Dk values were increased with an increase of U . The increasing pattern is not proportional to the square of the U , such as that observed in the Dp , but it is linear.

The coefficient of the kinetic drag C_{Dk} is calculated as shown in Eq. (9). In comparison to Eq. (2), the representative area was different. We adopted two-thirds power of the body volume $V^{2/3}$. That adaptation is commonly used for calculating the coefficient of wave making drag in shipbuilding engineering. Because Dk consists mainly the wave making drag component, it seemed better that we did not use the body surface area, but $V^{2/3}$ for the representative area. Based on the same reason, the non-dimensional flow velocity was changed into the Froude number Fr not the Reynolds number using the Eq. (10).

$$C_{Dk} = \frac{Dk}{0.5\rho V^{2/3} U^2} \quad (9)$$

$$Fr = \frac{U}{\sqrt{gH}} \quad (10)$$

The relation between the average C_{Dk} at each stroke frequency and the Fr is shown in Fig. 11. The Re that corresponds to the Fr is also drawn in the figure to compare with the C_{Dp} . Even though the C_{Dp} was steady independent of the Re , the C_{Dk} decreased with an increase of Fr . The reason why the C_{Dk} decreased with the Fr is not clarified yet. It was, however, possible to express the relation between the C_{Dk} and Fr by a simple equation. The following equation for the two parameters was obtained:

$$C_{Dk} = 0.86 \exp(-3.9Fr) \quad (11)$$

Since C_{Dk} was determined by Eq. (11) the expression

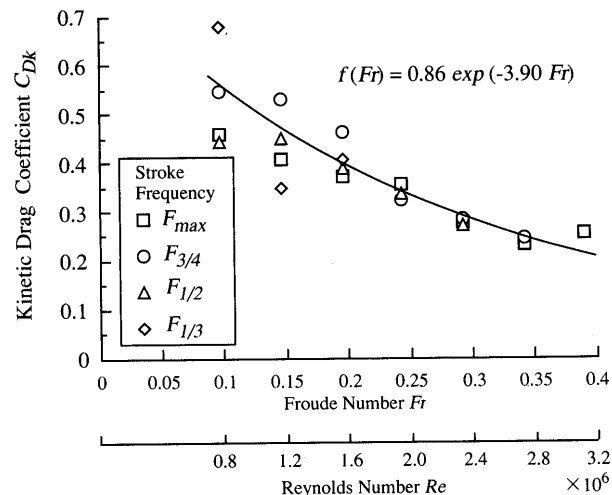


Fig. 11 The relation between C_{Dk} , Fr and Re

for Dk yields:

$$Dk = \frac{1}{2} \rho V^{2/3} U^2 \{0.86 \exp(-3.9Fr)\} \quad (12)$$

Since Dp was determined by Eq. (4) and Dk is determined by Eq. (12). Hence the Da can be estimated according to Eq. (6) and substituted into Eq. (13)

$$Da = 0.015 \rho A_s U^2 + \frac{1}{2} \rho V^{2/3} U^2 \{0.86 \exp(-3.9Fr)\} \quad (13)$$

However, Eq. (13) was valid only in a certain range ($2.6 \times 10^6 < Re < 3.4 \times 10^6$), since it was only possible to estimate Da in above mentioned Re range. Finally, the Da values were transformed to C_{Da} by Eq. (14).

$$C_{Da} = \frac{Da}{0.5 \rho A_s U^2} \quad (14)$$

3.4 Comparison to previous studies

To examine the validity of Eq. (13), we compared the results with those of previous studies⁽²⁾⁻⁽⁶⁾. When Da was computed, the average value of A_s , V , and Fr for all subjects were put into Eq. (13) and C_{Da} was given by Eq. (14). In previous studies, the drag force and velocity were directly recorded in physical unit so the data in the previous study had to be transformed into dimensionless indices such as C_{Da} and Re . The velocity data were transformed into Re by Eq. (3). The body surface area A_s was computed by substituting the height and weight data for Eq. (1) and the drag forces were transformed into C_{Da} by Eq. (14).

Figure 12 shows the comparison of the estimated C_{Da} values. In Fig. 12, the present values are drawn by a thin line for the range that covered all Re range examined in the previous studies. Especially for the available range ($2.6 \times 10^6 < Re < 3.4 \times 10^6$) the present results are shown by a thick line. As shown in Fig. 12, the C_{Da} in the previous studies tend to decrease with an increase of Re and the results in the present study show the same tendency. Particularly, in the range of

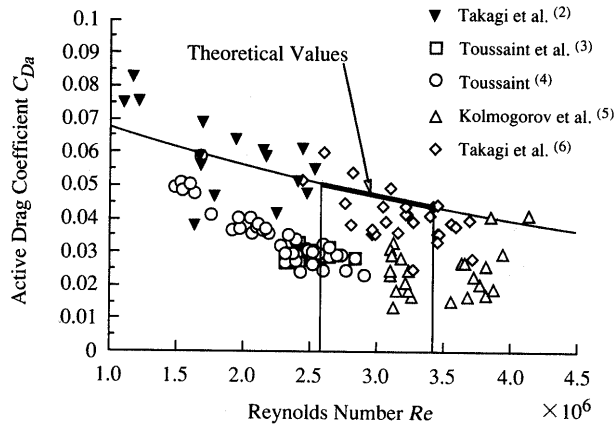


Fig. 12 Comparison with the theoretical values of C_{Da} and the previous study

$2.6 \times 10^6 < Re < 3.4 \times 10^6$ (indicated by the thick line), the present values fit well to Takagi's⁽⁶⁾ results. Moreover in the range of $Re < 2.5 \times 10^6$, the validity of Eq.(14) was also confirmed. Toussaint's^{(3),(4)} results indicated a lower value than the present values. The reason might be depend on the measuring device, because the device did not allow the legs to be used during swimming, so that forces during only arm stroking were measured. Kolmogorov's⁽⁵⁾ results indicate a different tendency in comparison to the present study. Kolmogorov calculated active drag value based on the assumption that active drag is proportional to the square of the velocity. This assumption might make a difference between the present results and Kolmogorov's results.

4. Conclusion

We tried to develop a new device and a new methodology for measuring the active drag Da . The following conclusions can be presented:

- (1) The new device is capable of measuring active drag Da without disturbing the natural swimming movement, so it was possible to measure the active drag more precisely than before.
- (2) Assuming that the active drag consisted of the passive drag Dp and the kinetic drag Dk , the estimated equation for each element was obtained. This equation fitted well with the previous results in the range of the Reynolds number, which equal the actual swimming velocity, so that the validity of this equation was confirmed.

Acknowledgment

The authors wish to thank Mr. Hiroshi Onogi and Mr. Yoshitane Kusagawa of Japan Technomate Corporation, and Mr. Ryou Saitou of Mie University for

their kind assistance.

References

- (1) Komune, T. and Ogura, M., An Analysis and an Evaluation of Swimming Using CWC, In Korea-Japan Joint Workshop on CWC. Korea, (1994), p. 85-92.
- (2) Takagi, H., Shimizu, Y., Kodan, N., Onogi, H. and Kusagawa, Y., Development of Methodology of the Active Drag Measurement in Swimming, Proc. of Jpn. Soc. Mech. Eng., (in Japanese), No. 96-15 (1996), p. 201-202.
- (3) Toussaint, H. M., Beelen, A., Rodenburg, A., Sargeant, A. J., de Groot, G., Hollander, A. P. and van Ingen Schenau, G. J., Propelling Efficiency of Front-Crawl Swimming, J. Applied Physiology, Vol. 65 (1988), p. 2506-2512.
- (4) Toussaint, H. M., Differences in Propelling Efficiency between Competitive and Triathlon Swimmers, Med. Sci. Sports Exerc., Vol. 22 (1990), p. 409-415.
- (5) Kolmogorov, S. V. and Duplishcheva, O. A., Active Drag, Useful Mechanical Power Output and Hydrodynamic Force Coefficient in Different Swimming Strokes at Maximal Velocity, J. Biomechanics, Vol. 25 (1992), p. 311-318.
- (6) Takagi, H., Shimizu, Y., Maeda T., Nomura, T. and Wakayoshi, K., The Development of a Methodology to Evaluate Training Effects Using the Active Drag Index, Desant Sports Science, (in Japanese), Vol. 16 (1995), p. 149-159.
- (7) Taneda, S., Drag of a Self-Propulsive Object, Nagare, (in Japanese), Vol. 9 (1977), p. 10-16.
- (8) Nagamine, S. and Suzuki, S., Anthropometry and Body Composition of Japanese Young Men and Women, Human Biology, Vol. 36 (1964), p. 8-15.
- (9) Ishii, T., Izumida, Y., Takano, T., Fukuda, M., Shirota, K. and Okuyama, A., Newly Developed Control and Measuring System of Vertical Circulating Water Channel, Technical Report in Nihon Koukan, (in Japanese), Vol. 116 (1987), p. 83-91.
- (10) Clarys, J. P., Hydrodynamics and Electromyography: Ergonomics Aspects in Aquatics, Appl. Ergonomics, Vol. 16 (1985), p. 11-24.
- (11) Shimizu, Y., Suzuki, T., Suzuki, K. and Kiyokawa H., Studies on Fluid Drag Measurement and Fluid Drag Reduction of Woman Athlete Swimming Suit, Trans. Jpn. Soc. Mech. Eng. B, (in Japanese), Vol. 63, No. 616 (1996), p. 107-113.
- (12) Azuma, A., Hydrodynamics, (in Japanese), (1993), p. 74-77, Asakura Syoten, Tokyo.
- (13) Tagori, T., Arakawa, C., Masunaga, K. and Okamoto, H., Experimental Research on Water Flow around Human Body and Effects of Swimming Suits at Swimming, Desant Sports Science, (in Japanese), Vol. 5 (1984), p. 173-184.