# Biology-Inspired Precision Maneuvering of Underwater Vehicles

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## Abstract

This paper summarizes the progress in Japanese side of Japan-U.S. joint project from April 1, 2001. To experimentally and numerically assess the hydrodynamic characteristics of flapping, rowing and feathering fin system in a precise manner, a compact three motor-driven mechanical fin (3MDMPF) device with high speed capability and precise movement was designed and is being manufactured. in the study process of verification and validation of the CFD simulator through extensive baseline tests and comparison with reliable experimental results, we could have the following significant result.A conceptual modeling of a jet-like vortex pattern corresponding to a thrust-generating body has been numerically analyzed by computations of flow around an NACA0012 airfoil pitching in a uniform flow at Reynolds numbers of 12000 and 7200. The propulsive efficiency shows an optimal variation against the Strouhal number, with the maximum between 0.25 and 0.35, that is in excellent agreement with the experimental results.

## 1. Introduction

Many marine animals thrive in near shore, high-energy environments where rapidly changing flow velocities created by surges, currents, and breaking waves present extreme challenges to precision maneuvering and hovering performance. The ability of near-shore animals to achieve extraordinary stability and precision hovering is one key to their survival in wave-swept environments. Many near-shore fishes employ one or more pairs of oscillating fins to increase both stability and maneuverability. It is reasonable to believe that these highly maneuverable fishes serve as excellent biological templates for the design of man-made vehicles with extreme maneuvering and stealth capabilities. This Japan-U.S. joint project describes a multi-year development program to develop an improved understanding of the practical applications of oscillating fins and to demonstrate the utility of replacing cumbersome thrusters with a suite of oscillating fins designed to optimize the hovering and low speed maneuvering performance of an undersea vehicle. Japanese team involves three major components, (1)development and validation of analytic models describing the dynamic forces produced by fin motions, (2)development of a control approach that mimics the hovering fish motion, and (3)implementation of these concepts on an undersea vehicle. This progress summary involves part of (1) and (2).

## 2. Experimental and Numerical Assessment of Mechanical Pectoral Fin Performance

### 2.1 Mechanical Pectoral Fin

Two-motor-driven mechanical pectoral fins (2MDMPFs)(Fig.2-1) generating both rowing (fore-aft) and feathering (pitching) motions (see Fig.2-2) were developed to carry out experiments using a fish robot (Fig.2-3) (Kato, 1999a). A three-motor-driven mechanical pectoral fin (3MDMPF) (Fig.2-4) has been recently developed by Kato (Kato, 1999b). This fin is capable of generating rowing, feathering and flapping motions (see Fig.2-2). It was based on observation and experimental analysis of pectoral fin motion of Black Bass. Furthermore, a pair of 3MDMPFs were installed in a autonomous underwater vehicle (Fig.2-5) to test its maneuverability in both the horizontal plane and the vertical plane.

Based on the available literature, previous demonstrations, and new concepts it is apparent that 1) flapping, rowing and feathering fin systems can be used effectively to control a rigid body vehicle 2) an innovative control system is required to achieve the desired overall vehicle control and 3) predictive models of the unsteady force generated by flapping foils are needed to advance vehicle control concepts.

To experimentally and numerically assess the hydrodynamic characteristics of flapping, rowing and feathering fin system in a precise manner, a compact 3MDMPF device with high speed capability and precise movement will be manufactured. Fig.2-6 shows the plan of the device. The device is equipped with a force sensor measuring normal force acting on the rigid fin and a torque sensor measuring torque around a fin shaft(Fig.2-7). A block gauge measuring 6 components of force is attached to the strut supporting the cylindrical body at its top. Potentiometers for measuring angles of rowing motion, flapping motion and feathering motion are installed inside the device. The range of rowing motion reaches from $-60°$ to $70°$ , flapping motion from $-60°$ to $+60°$, and feathering motion from $-90°$ to $90°$. Speed of movement of fin is designed to reach a maximum of 3Hz.

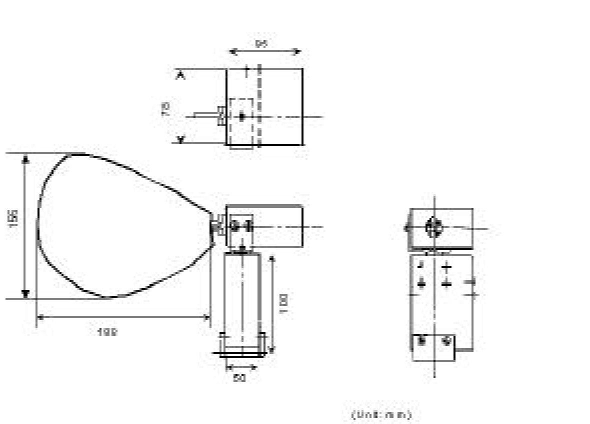



Fig.2-1 Two-motor-driven mechanical pectoral fin

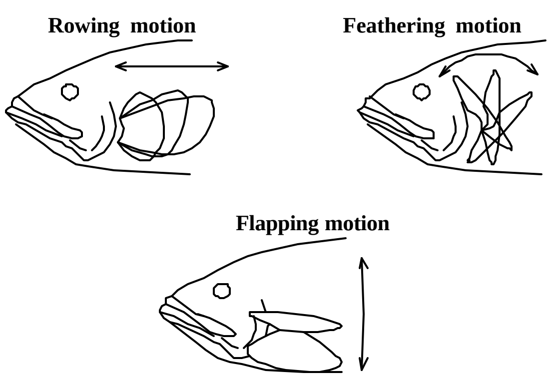



Fig.2-2 Illustrations of rowing motion, feathering motion and flapping motion of a pectoral fin

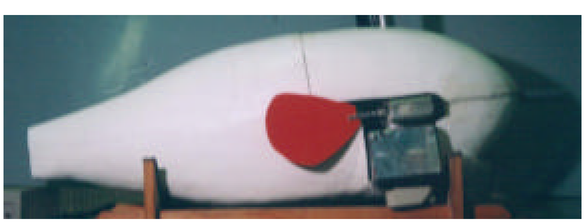
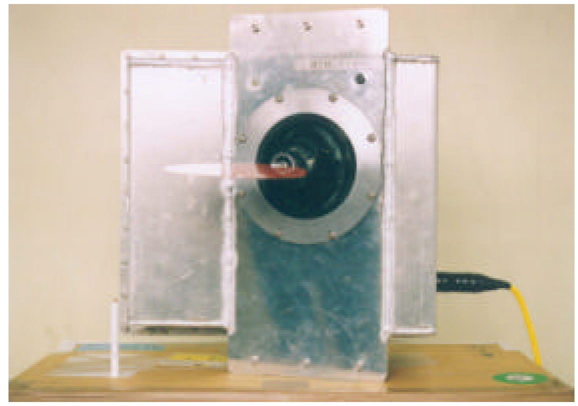


Fig.2-3 Fish robot "BASS-II" equipped with a pair of 2MDMPFs



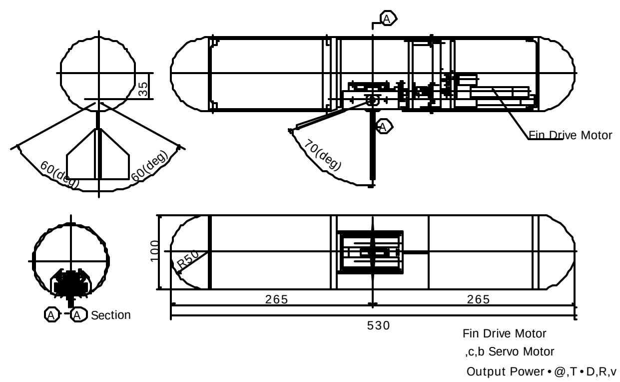




Fig.2-6 A cylindrical body with a 3mdmpf

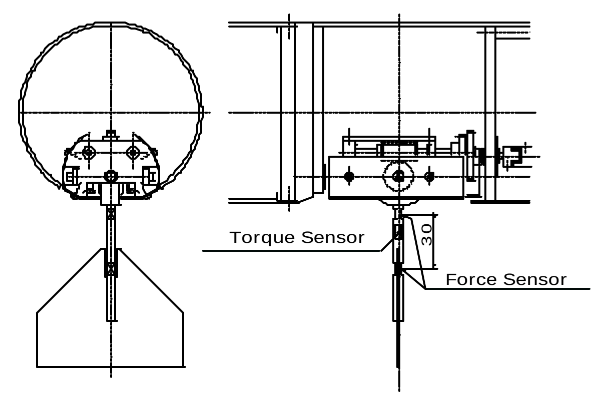



Fig.2-7 Attachment of torque sensor and force sensor

## 2.2 Numerical Analysis of Hydrodynamic Characteristics of Cylindrical Body with a 3MDMPF

A series of stepwise, systemic computational fluid dynamic studies are conducted to evaluate the underwater precision maneuverability of a cylindrical body, in particular the STOP & HOVER motions, by using force and aft pairs of pectoral fins, similar to their usage in a fish. The CFD modeling and simulation will involve the following major tasks:

(1) Establishment of a CFD Simulator (software), which is designed to accurately predict unsteady hydrodynamic forces on flapping pectoral fins

(2) Verification and validation of the CFD simulator through extensive baseline tests and comparison with reliable experimental results, and

(3) Preliminary numerical results on flow field and unsteady hydrodynamic forces on pectoral fins of a model of the underwater vehicles.

### 2.2.1 Baseline studies

*(1)Build-up of a CFD simulator*

A CFD simulator specified for the current problem is based on a solver for unsteady, incompressible Navier-Stokes equations developed by Liu, in which a geometric model and a kinematic model are incorporated. Upon the establishment and modification of the CFD simulator the following issues are taken into account:

Build-up of a CFD simulator with special focus on modeling of unsteady hydrodynamics of a single flapping wing,

Build-up of a CFD simulator with special focus on modeling of unsteady hydrodynamics of a body and a flapping wing.

Two codes for a single wing (pectoral fin) model and a body-wing (fin) model have been set up. Time-accurate solutions to the incompressible Navier-Stokes equations are formulated in the ALE (Arbitrary Lagrangian-Eulerian) manner using the finite volume method (FVM) and are performed in a time-marching manner using the pseudo-compressibility method, with special treatment in the conservation of mass and momentum both in space and in time. A third-order upwind differencing scheme, using the flux-splitting method, is implemented for the convection terms in a MUSCL fashion. The viscous terms are evaluated using a second-order central differencing method based on Gaussian integration in the FVM manner. An implicit approximation-factorization method, based on the Euler implicit scheme, is employed for the time derivatives.

The kinematics of the flapping wing (fin) are defined on a basis of our previous study (Liu et al. 1998) on the kinematic analysis of a hovering hawkmoth wing, in which 3D movements of the wing consist of three basic motions (1) flapping about the x-axis in the stroke plane described by the positional angle; (2) rowing about the z-axis, out of the stroke plane on either side described by the elevation angle; (3) rotation (feathering) of the forewing (leading edge) and hindwing (trailing-edge) with respect to the stroke plane by varying the angle of attack of the forewing and the angle of attack of the hindwing. A single wing (pectoral fin) model is further modified for the present analysis in which no flexing motion is defined between fore-and hindwing. The positional angle, elevation angle and the angles of attack of the wing are defined using the first three Fourier terms based on Kato's data (1999).

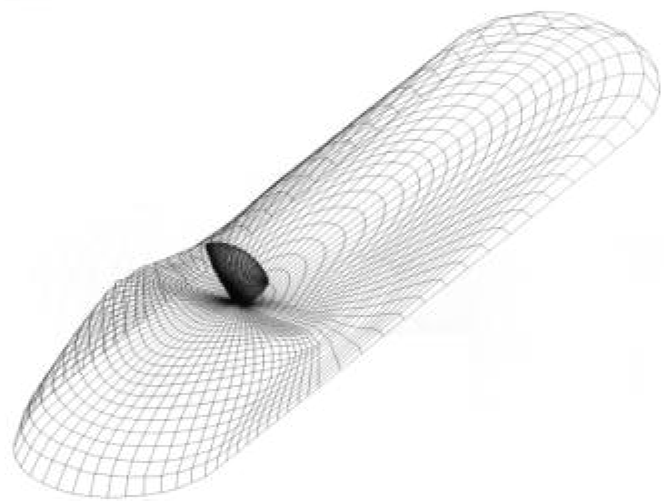


Fig.2-7 Grid systems around a body-fin model

Geometry of the wing is based on a tracing of the outline of a pectoral fin as in Kato's paper (1999). A uniform thickness was taken but with an elliptic smoothing at the leading- and trailing edge as well as at the tip. To facilitate the resolution of viscous flow at leading edge, trailing edge and wing tip, and of requirements for the computer time, an O-O type grid topology is employed. A body-fin geometric model is illustrated in Fig.2-7.

*(2) Verification and validation (V&V) of the CFD simulator*

Upon the V&V of the CFD models and the codes, a series of systemic baseline test studies are carried out, which involve a conceptual model that is a idealized physical model and reliable comparison with available experimental results, such as:

Comparison with experimental results of a well-studied 2D oscillating foil.

Comparison with available experimental results of a *single flapping fin* with special focus on time course of unsteady hydrodynamic forces on the wing at low Reynolds numbers.

Comparison with available experimental results of a *Body with a flapping fin* with special focus on time course of unsteady hydrodynamic forces on the fin at low Reynolds numbers.

A conceptual modeling of a jet-like vortex pattern corresponding to a thrust-generating body has been numerically analyzed by computations of flow around an NACA0012 airfoil pitching in a uniform flow at Reynolds numbers of 12000 and 7200. The foil is placed in a body-centered inertial frame of reference that pitches about the quarter-chord point with a pitching angle of approximately $7.75^0$. The propulsive efficiencies against the Strouhal numbers were plotted in Fig.2-8, compared to the experimental results (Triantafyllou *et al*., 1993). The Strouhal number (*St=fA/U*), defined as a production of oscillating frequency (*f*) multiplied by the width of the

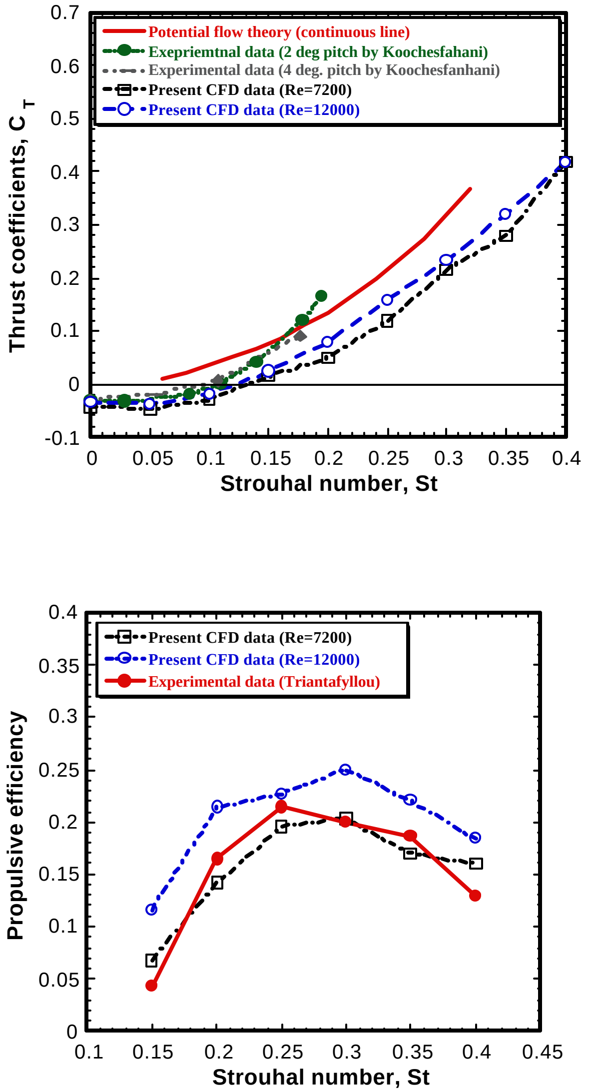



Fig.2-8 Comparison of mean thrust coefficients and propulsive efficiencies against Strouhal numbers of an oscillating two-dimensional foil

wake, i.e., the maximum excursion of the foil's trailing-edge (double amplitude: $2A=0.2L$), divided by the forward speed ($U$), was taken to vary from 0.0 up to 0.4 with an increment of 0.05. The propulsive efficiency shows an optimal variation against the Strouhal number, with the maximum between 0.25 and 0.35, that is in excellent agreement with the experimental results by Triantafyllou *et al*. (1993) though their airfoil was in a different mode of pitching and heaving motion. This optimal phenomenon of thrust generation can be explained by the generation of a jet-like stream in the wake (Fig.2-9). The thrust generation, when the Strouhal number *St* is larger than 0.1, corresponds to a staggered array of the reverse von Karman vortices in the wake and an intense accelerated fluid, the jet-stream in the center, that generates a forward force, i.e., the thrust. Then, an increase of the Strouhal number leads to more vortices shedding from the trailing edge even though the jet-stream strengthens and widens so that more energy is dissipated into the wake through the vortex shedding.

Hence, the thrust is keeping increasing with increasing the Strouhal number (or the reduced frequency) but the propulsive efficiency reaches a peak at some point between 0.25 and 0.35.

*3) Application to assessment of the precision maneuvering of underwater vehicles*

The aim here is to actually apply the developed CFD simulator in assessing the performance of the control force generation of fins. The following items are involved:

- Establishment of a realistic CFD model of the underwater vehicles, which is capable to represent realistic geometry and to mimic realistic movements.
- Numerical analysis of the unsteady hydrodynamic performance of a variety of underwater vehicle models.
- Establishment of a best match between the fin geometry and the motions in terms of optimal control force generation.

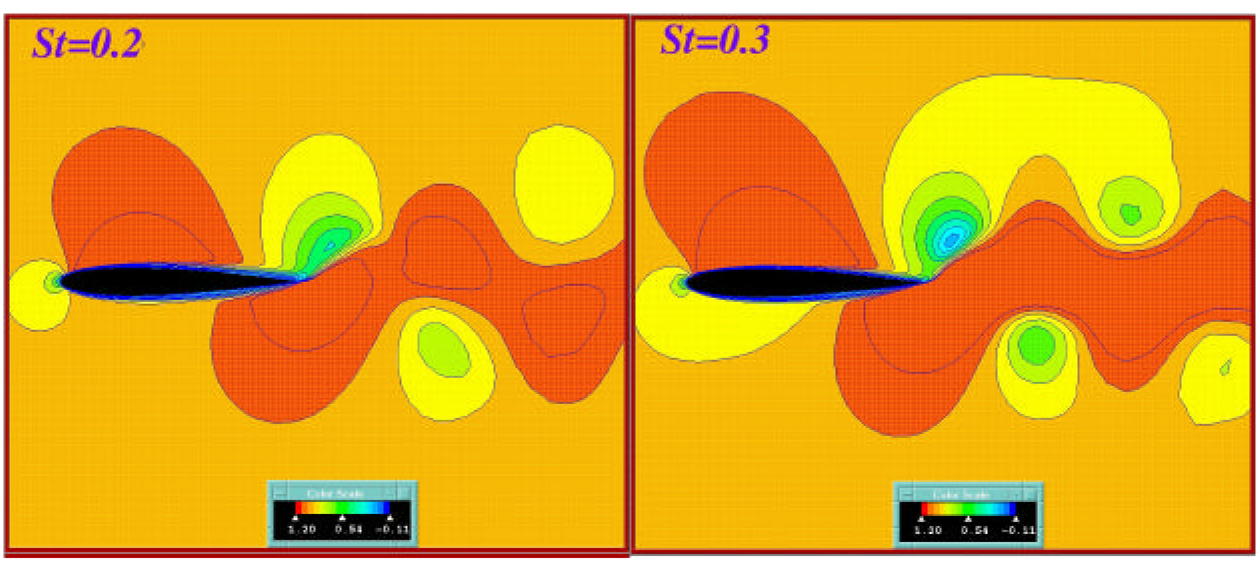



Fig.2-9 Jet-stream pattern behind an oscillating foil

## 2.3 Optimal Control Force Generation

The most important task using the cylindrical body with a 3MDMPF is to establish an optimal match between the fin geometry and the motions in terms of optimal control force generation. The optimal parameters of the fin motions to generate the maximum control force in a particular direction are obtained experimentally and numerically by using several optimization methods such as hill-climbing method, genetic algorithm and evolution strategy. The combination of the experimental device shown in figure 3-6 and an optimization method is suitable for fastness of time it takes to reach the optimal parameters. On the other hand, the combination of the CFD simulator and an optimization method is better from the viewpoint of taking the arbitrary geometry of the fin and the fuselage into account.

For preliminary study the optimal parameters of the fin motions were obtained so as to generate the maximum control force in X, Y, Z directions by using Hooke-Jeeves method, one of non-linear optimization methods, and unsteady vortex lattice method Kato (1999b) developed for the hydrodynamic analysis of 3MDMPF.

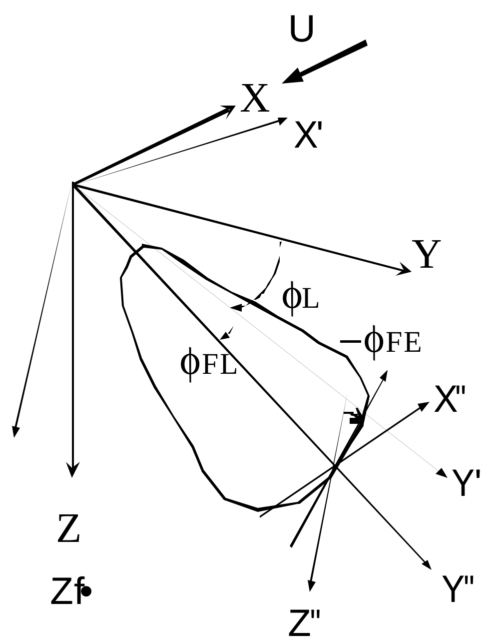



Fig.2-10 Coordinate system

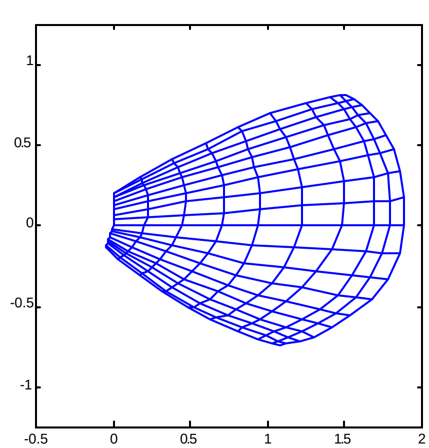



Fig.2-11 Configuration of a pectoral fin for computation and the division of its surface

The lead-lag angle $\phi_L$, the feathering angle $\phi_{FE}$, and the flapping angle $\phi_{FL}$, all of which are defined in Fig.2-10, were varied sinusoidally using the following definitions. The coordinate is transformed in the sequence of $\phi_L$, $\phi_{FL}$ and $\phi_{FE}$.

$$\phi_L = \phi_{L0} - \phi_{LA} \cdot \cos(\omega \cdot t)$$

$$\phi_{FE} = \phi_{FE0} - \phi_{FEA} \cdot \cos(\omega \cdot t + \Delta\phi_{FE})$$

$$\phi_{FL} = -\phi_{FLA} \cdot \cos(\omega \cdot t + \Delta\phi_{FL})$$

Figure 2-11 shows the configuration of the pectoral fin for computation with 130 segmented panels. The uniform flow U flowing in the positive direction of X axis and time step $\Delta t$ were set as 1.0 m/s and 0.026 s, respectively. The computation was done for 1.5 periods for the non-dimensional frequency K of 4.

Here, hydrodynamic force coefficients are defined as follows:

$$C_X = F_X / (1/2 \cdot \rho \cdot U^2 \cdot S),$$
$$C_Y = F_Y / (1/2 \cdot \rho \cdot U^2 \cdot S),$$
$$C_Z = F_Z / (1/2 \cdot \rho \cdot U^2 \cdot S),$$
$$Cm_X = M_X / (1/2 \cdot \rho \cdot U^2 \cdot S \cdot c),$$
$$Cm_Y = M_Y / (1/2 \cdot \rho \cdot U^2 \cdot S \cdot c),$$
$$Cm_Z = M_Y / (1/2 \cdot \rho \cdot U^2 \cdot S \cdot c)$$

(1) $C_X$

In op n in Eq.(1) to obtain the maximum $C_X$, we set the following constraints:

$$\phi_{LA} \le 35°, \phi_{FEA} \le 35°, \phi_{FLA} \le 90°$$
$$-120° \le \Delta\phi_{FE} \le 120°, -120° \le \Delta\phi_{FL} \le 120°$$
$$-0.05 \le C_Z \le 0.05$$

The optimized values of the parameters are as follows:

| $\phi_{L0}$ | $\phi_{LA}$ | $\phi_{FE0}$ | $\phi_{FEA}$ | $\Delta\phi_{FE}$ | $\phi_{FLA}$ | $\Delta\phi_{FL}$ |
|---|---|---|---|---|---|---|
| -55.0 | 0.0 | 10.0 | 5.0 | 90.0 | 15.0 | 20.0 |

In this case, $C_X$=0.133, $C_Y$=-0.206 $C_Z$=0.049. This result indicates that a fish robot equipped with the pair of 3MDMPFs on both sides can swim forward almost with constant depth, if the pair of 3MDMPFs on both sides of the body is actuated symmetrically.

(2) $C_Y$

In optimizing the parameters of the fin motion in Eq.(1) to obtain the minimum $C_Y$, we set the following constraints:

$$f_{LA} \le 35°, f_{FEA} \le 35°, f_{FLA} \le 90°$$
$$-120° \le \Delta f_{FE} \le 120°, -120° \le \Delta f_{FL} \le 120°$$
$$-0.05 \le C_X \le 0.05, -0.05 \le C_Z \le 0.05$$
(4)

The optimized values of the parameters are as follows:

| $f_{L0}$ | $f_{LA}$ | $f_{FE0}$ | $f_{FEA}$ | $\Delta f_{FE}$ | $f_{FLA}$ | $\Delta f_{FL}$ |
|---|---|---|---|---|---|---|
| -40.0 | 0.0 | -25.0 | 25.0 | 55.0 | 20.0 | 5.0 |

In this case, $C_X$=0.050, $C_Y$=-0.276 $C_Z$=0.049. This result indicates that a fish robot equipped with the pair of 3MDMPFs on both sides can swim laterally using one side of 3MDMPF, almost keeping its position both in forward direction and in vertical direction in water current, if the effect of hydrodynamic forces acting on the body is neglected.

(3) $C_Z$

In optimizing the parameters of the fin motion in Eq.(1) to obtain the minimum $C_Z$, we set the following constraints:

$$f_{LA} \le 35°, f_{FEA} \le 35°, f_{FLA} \le 90°$$
$$-120° \le \Delta f_{FE} \le 120°, -120° \le \Delta f_{FL} \le 120°$$
$$-0.05 \le C_X \le 0.05$$
(4)

The optimized values of the parameters are as follows:

| $f_{L0}$ | $f_{LA}$ | $f_{FE0}$ | $f_{FEA}$ | $\Delta f_{FE}$ | $f_{FLA}$ | $\Delta f_{FL}$ |
|---|---|---|---|---|---|---|
| 39.7 | 35.0 | -65.0 | 35.0 | 53.8 | 17.8 | -11.3 |

In this case, $C_X$=0.049, $C_Y$=-0.417 $C_Z$=1.125. This result indicates that a fish robot equipped with the pair of 3MDMPFs on both sides can descend almost keeping its position in forward direction in water current, if the pair of 3MDMPFs on both sides of the body is actuated symmetrically.

## 3. Guidance and Control of Underwater Robot with 3MDMPFs

### 3.1 Underwater Robot with 3MDMPFs

A test body utilizing fore and aft pairs of 3MDMPFs for maneuvering control will be completed in 2002. Specifications of the vehicle are:

| | |
|---|---|
| Diameter | 100mm |
| Length | 1200mm |
| Fin Span | 83mm |
| Fin Chord | 100mm |
| Fin Rotation | 3Hz |

The body will include onboard sensors and will be tethered to a shore-mounted control computer. The complete system will be fully autonomous. The onboard sensors consist of 3 axis rate gyros, 2 axis inclinometer (pitch and roll), an electronic compass, a depth sensor, and 2 CCD cameras. Thin fiber-optic cable will be used for the communication between the vehicle and the control computer on the ground to prevent the motion of the vehicle from being disturbed by the cable. A position measurement system utilizing image processing in a water tank will be developed.

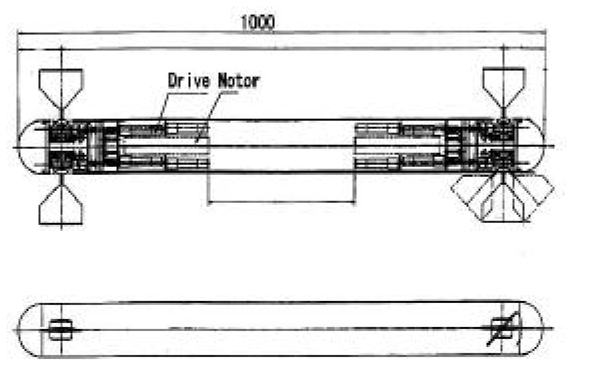



Fig.2-10 Underwater robot with fore and aft pairs of 3MDMPFs

### 3.2 Guidance and Control of Underwater Robot with 3MDMPFs

A fuzzy algorithm was used as the autonomous control algorithm for guidance and control of the fish robot "BASS-II". Kato, et. al. were successful not only on the performance of guidance and control of the fish robot in horizontal plane for rendezvous and docking with an underwater post in water currents and but also on the stabilization of motion of model of an underwater robot equipped with a manipulator with assistance of the pair of 2MDMPFs in horizontal plane (Kato , 2000a). The high maneuverability of the fish robot "BASS-III" was demonstrated such as ascending and descending both in forward and backward directions, turning at almost same point and lateral swimming (Kato, 2000b) .

The following items are involved in this project:

(i) Development of automatic control algorithms for guidance and control of the test body in 3D underwater space. Fuzzy Algorithms will be utilized as necessary to compensate for short-comings in mathematical descriptions of 3MDMPF performance.

(ii) Demonstration of the high maneuverability of the cylindrical underwater vehicle equipped with 3MDMPFs following a prearranged trajectory around undersea obstacles.

## Acknowledgements

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