

Bending Properties of Tail Flukes of Dolphin*

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Abstract

The aim of this paper is to study the bending properties of tail flukes of a dolphin. The bending test was carried out to obtain the displacements on different test points of a fluke. The Young's moduli of the ligamentous layer and the dense connective tissue in the flukes were obtained from the tensile test and the compression test. In order to establish an FEM model for bending deformation of the flukes, the thickness of the flukes was measured with two laser displacement sensors, and the thickness of the ligamentous layer was also measured. The displacements obtained by the simulation of the FEM model were compared with those of the bending test of the experiments. It was found that the model could be helpful to investigate the relationship between the hydrodynamic force acted on the tail flukes of a dolphin and the deformation of the tail flukes.

Key words: Dolphin, Tail Fluke, Ligamentous Layer, Dense Connective Tissue, Bending Test, Deformation

1. Introduction

A dolphin is characterized as a high speed swimmer⁽¹⁾. The high speeds of dolphins were reported in many literatures such as *Delphinus delphis* 10.3m/s⁽²⁾, *Stenella attenuata* 11.1 m/s⁽³⁾, *Tursiops gilli* and *Tursiops truncatus* 8.3 m/s⁽⁴⁾, 6.01mm/s⁽⁵⁾. The extraordinary speed had brought a famous paradox so-called "Gray's paradox" that dolphins can swim at the speed higher than the value estimated from both of the muscle power and the frictional drag received by the fluid flow around the animals⁽²⁾. The paradox is not yet solved in spite of numerous investigations into the drag minimization of swimming dolphins from various viewpoints such as the streamlined body shape, viscous dampening⁽⁶⁾, dermal ridges⁽⁷⁾ and boundary layer heating⁽⁸⁾.

The dolphins generate thrust when water is pushed in the direction opposite to swimming by oscillating their tail fins vertically. Thrust is generated as a component of hydrodynamically derived lift force⁽⁹⁾. The thrust is the key to understand the kinetic properties of dolphins, but it is unable to measure the thrust of a swimming dolphin directly.

The tail fin of a dolphin is considered to play an important role in its high speed swimming. Due to the absence of the fin rays in the tail flukes of dolphins, the dolphins can not control the shape of their flukes like some fishes which can control their caudal fin complicatedly by controlling each fin ray. The deformation of the tail flukes of a dolphin was driven by the hydrodynamic force imposed upon the flukes.

We aimed to estimate the thrust of a dolphin by using the relationship between the deformation of the tail fin and the hydrodynamic force on it. This study can be a tentative study to investigate the relationship between the deformation of the tail fin and the force on it.

In this paper, the bending properties of the tail flukes of a dolphin were investigated by a

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bending test apparatus made by ourselves. The thickness of the flukes of a bottlenose dolphin was measured by two laser displacement sensors. Among the tissues that compose the tail flukes of a dolphin, the ligamentous layer and the dense connective tissue account for almost all of the tissue in the flukes. The thickness of the ligamentous layer in the representative points was also measured. It was found that the thickness of the tissues showed a near linear relationship to the thickness of the fluke in the same points. A model for bending deformation of the tail flukes of a dolphin was established. The results of simulation were compared with those of the bending test. The model could be helpful to investigate the relationship between the hydrodynamic force on the tail flukes of a dolphin and the deformation of the flukes.

2. Method and Results of Experiment

Two tail fins of common bottlenose dolphins (*Tursiops truncatus*) were used in this study. They were stored at -20°C until required for testing. The spans of the tail fins were about 520mm and 720mm respectively.

The experiments about the tail fluke did not violate the animal ethics in accordance with Shinshu University animal ethics guidelines.

Morphological Measurements

The morphological data was necessary for building the model of the fin. The fluke was composed of a black rubber-like cutaneous layer, a very thin subcutaneous blubber layer, a ligamentous layer, a series of blood vessels and a core of dense connective tissue⁽¹⁰⁾. We measured the thickness of the fluke and the thickness of the ligamentous layer, and investigated the orientation of the collagen fiber bundles in the ligamentous layer.

In order to investigate the distribution of thickness of tail flukes of dolphin, the flukes were scanned with two laser displacement sensors (KEYENCE LK-G150) along the body axis at an interval of 10mm. The contours lines were made basing on the measurements of the thickness of the fluke (T_F). The scanning paths were shown in Fig.1.

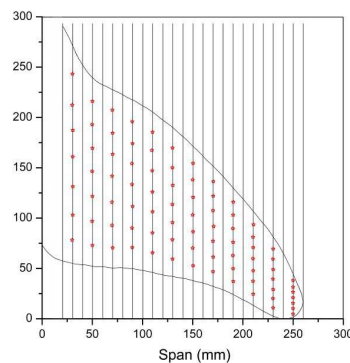


Fig.1. Scheme of sampling on tail fluke.

The flukes were scanned along the solid lines. The data of the thickness of the ligamentous layer were taken in the red points.

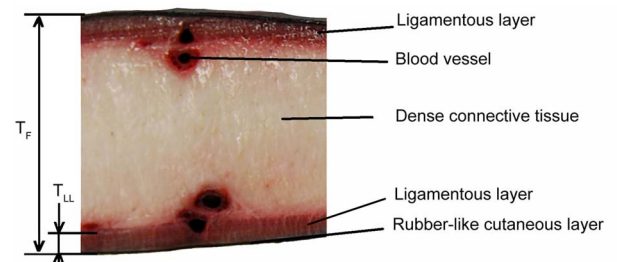


Fig.2. Cross-section of fluke of dolphin.

The thickness of the ligamentous layer (T_{LL}) in the representative points was measured. We took the average value of three repeated measures as the exact thickness value. The sampling points were also shown in Fig.1. The thickness of the fluke (T_F) and the thickness of the ligamentous layer (T_{LL}) were defined in the cross-section of the fluke of a dolphin (Fig.2). The relationship between the thickness of the ligamentous layer (T_{LL}) and the thickness of the fluke (T_F) in the corresponding points were investigated by a correlation analysis.

Figure 3 shows the contour lines of the tail fluke. The cross-section of the tail flukes parallel to the body axis showed a streamlined shape, the thickness of the tail fluke near the leading edge change greatly while the thickness of the tail fluke near the trailing edge decreased slowly.

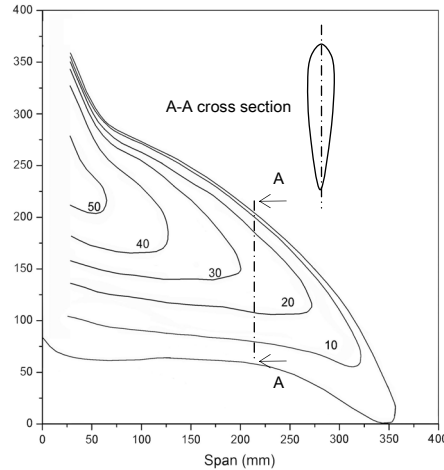


Fig.3 Contour lines of tail fluke.

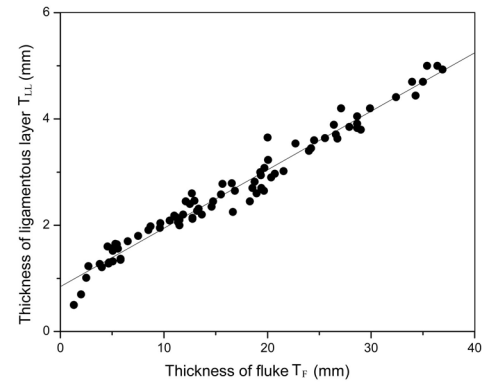


Fig.4. Relationship between thickness of ligamentous layer (T_{LL}) and thickness of the flukes (T_F).

Figure 4 shows the relationship between the thickness of the ligamentous layer (T_{LL}) and the thickness of the fluke (T_F). We found that the ligamentous layer (T_{LL}) increased with the increase of the thickness of the flukes (T_F) linearly. The relationship was described by the linear regression equation as follows.

$$T_{LL} = 0.843 + 0.110T_F \quad (R^2 = 0.97) \quad (1)$$

The coefficient of determination R^2 is 0.97. It means that the regression line approximates the real data points very well.

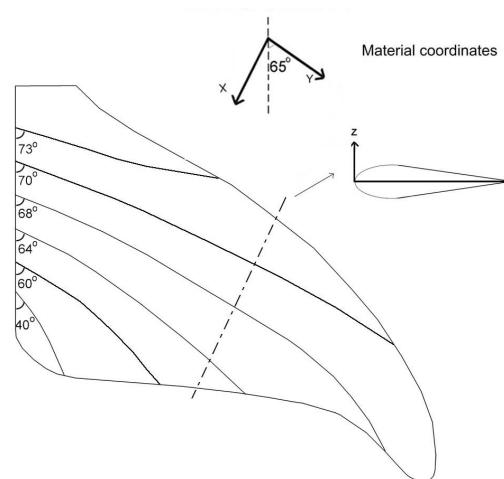


Fig.5. Orientations of collagen fiber bundles and material coordinate system.

The ligamentous layer was composed of collagen fiber bundles, so it was an anisotropic material obviously. We should investigate the orientation of the collagen fiber bundles which may help us to establish the material coordinates. We sliced off the black rubber-like cutaneous layer and the thin subcutaneous blubber layer and observed the orientation of the collagen fiber bundles. The orientation of the collagen fiber bundles were given by the

orientations of a series of characteristic collagen fiber bundles.

The fiber bundles lay at an angle to the body axis. Figure 5 indicated the orientation of characteristic collagen fiber bundles. The angle ranges from 73° near the leading edge to 40° near the central trailing edge. Most of the collagen fiber bundles lay at angles $60^\circ - 70^\circ$. In this study, we took the orientation of the collagen fiber bundles that lay at average angle about 65° to the body axis as the Y axis of material coordinates system. The direction perpendicular to the Y axis in the plane of the fluke was defined as the X axis, and the thickness direction was defined as the Z axis.

Mechanical Measurements

Tensile and compression test

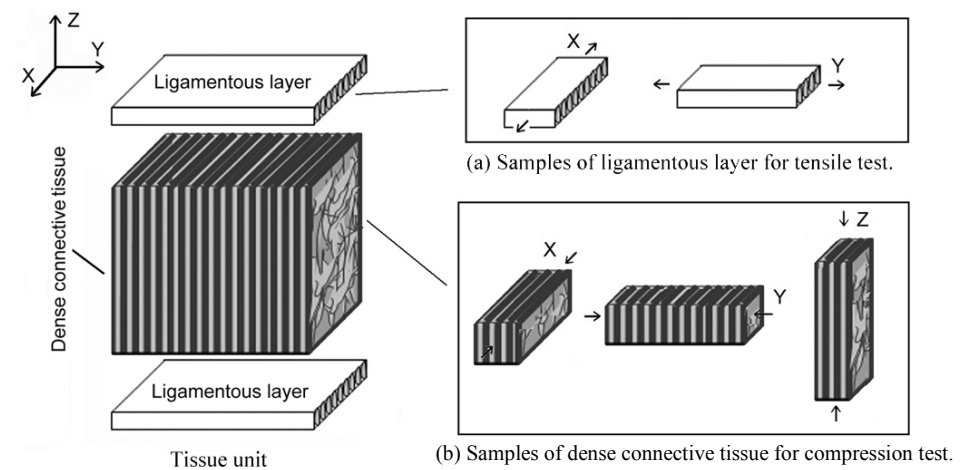


Fig.6. Tissue samples for tensile and compression tests.

The fluke was composed of a black rubber-like cutaneous layer, a very thin subcutaneous blubber layer, a ligamentous layer, blood vessels and a core of dense connective tissue. The cutaneous layer was very thin and had a weak strength. There were only four blood vessels in the cross-section of tail fluke. They accounted for a very small part of the cross-section compared with ligamentous layer and dense connective tissue. We neglected the effect of the cutaneous layer and the blood vessel in this study.

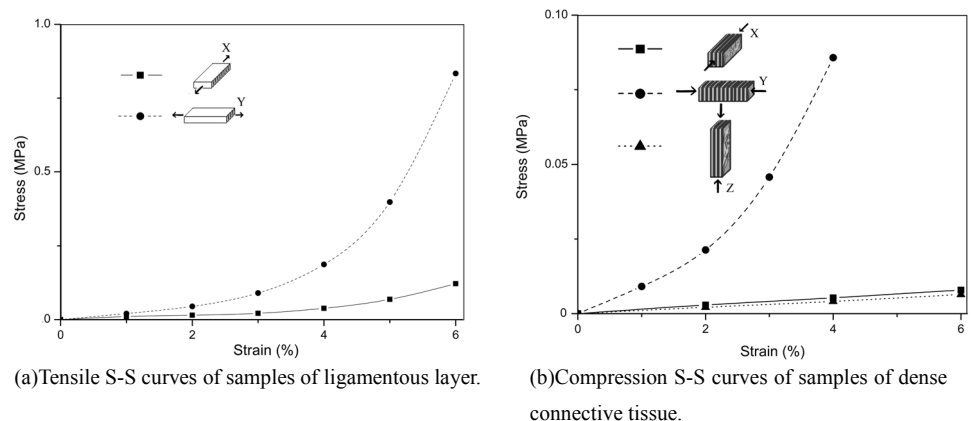


Fig.7. Results of tensile and compression tests.

The mechanical properties of the ligamentous layer and the dense connective tissue were investigated by the tensile test and the compression test. Figure 6 shows the tissue samples for the tensile and compression tests.

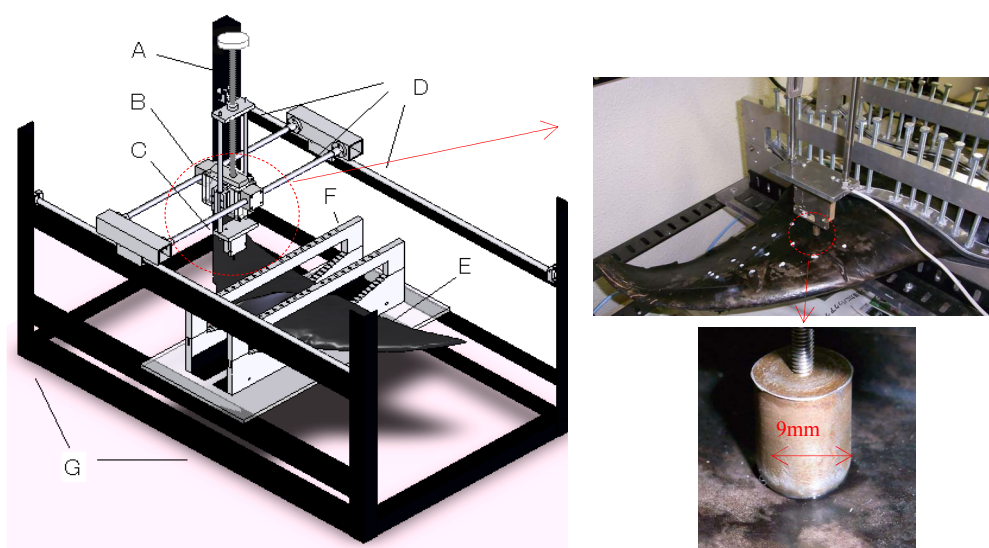
A typical strain-stress curve for a soft tissue had a nonlinear beginning which was called as the “toe” region. The “toe” region was usually the physiological range in which the tissue normally functions⁽¹¹⁾. In many models of soft tissues, the moduli used were calculated from the stress-strain relationship in the linear region. They paid little attention on the toe region, nevertheless, this region was thought as the physiological range in which the tissue normally functioned^(11, 12).

The tensile S-S curves of the samples of the ligamentous layer and the compression S-S curves of the samples of the dense connective tissue were given in Fig.7. The moduli of the main two tissues in the “toe” region, especially at the beginning of the stress-strain curves, were obtained from the both tests (Table 1).

Table 1. Young’s moduli of tissues.

		<i>X</i>	<i>Y</i>	<i>Z</i>
Ligamentous layer	E_l	0.96	4.67	
Dense connective tissue	E_2	0.25	2.14	0.21

Bending test



(a) Schematic drawing

(b) Head of load cell

Fig.8. Bending test apparatus.

A: Screw, B: Laser displacement sensor, C: Load cell (the head of the load cell is a round end cylinder with a diameter of 9mm shown in Fig.8 (b).), D: Linear motion guide, E: Tail fluke, F: Clamp, G: Frame

The bending test for whole tail fluke was carried out by using an apparatus made by ourselves shown in Fig.8. The apparatus contained four units as follows; a frame, a clamp unit, a loading and measuring unit, and a movement unit. The clamp unit contained two same parts which held the tail flukes by two sets of screws. The loading and measuring unit consisted of a screw to give the fluke a deflection, a laser displacement sensor to measure the deflection and a load cell to measure the load acting on the fluke. And the movement unit contained three groups of linear motion guide which enabled the loading and measuring unit to move to different measuring points.

The tail flukes were held by the clamp. The measuring unit was moved to a test point (Fig.9), and then the tail fluke was pressed by driving the screw. When the reaction force measured by the load cell reached to the value of 10N, we measured the displacement by the laser displacement sensor.

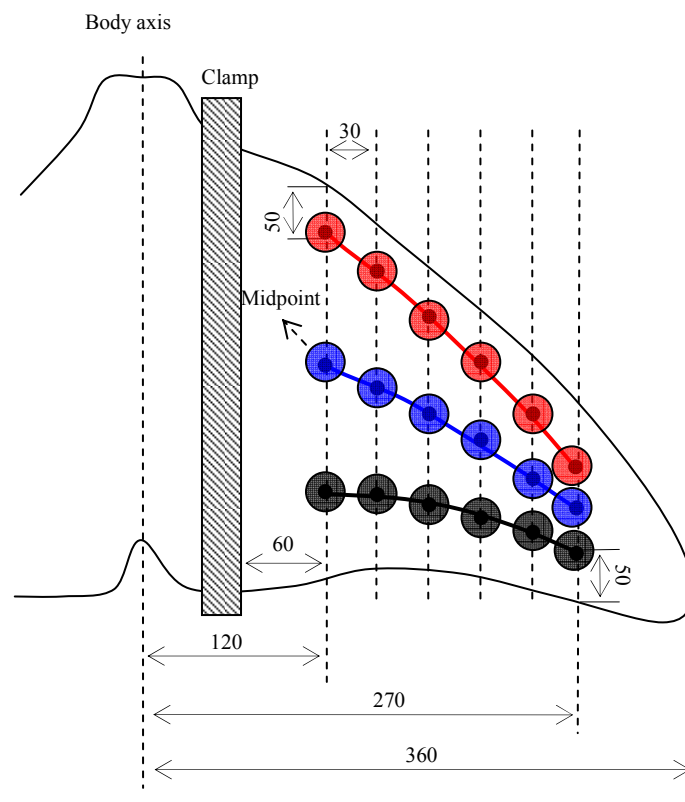


Fig.9. Test points

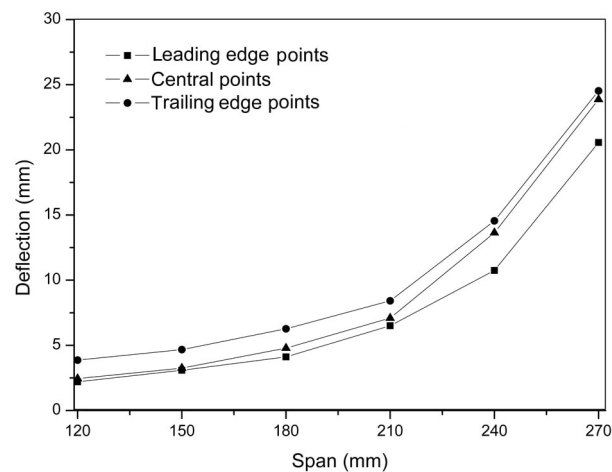


Fig.10. Displacements in different test points when press was 10N.

In Fig.9, we took 18 test points in the area between the positions with spanwise distance of 120mm and 270mm. Red points lie with a distance of 50mm from the leading edge. Blue points lie at the center of the chords. Black points lie with a distance of 50mm from the trailing edge. Hereafter the test points are called leading edge point, central point and trailing edge point for short respectively.

Figure 10 shows the displacements of different test points in the case a point force of 10N

were given. With the increase of the distance between the test points and the body axis, the deflections increased. The deformations for the leading edge points were lower than those for the trailing edge points and the central points.

Fin Model

Figure 11 showed a model of layers composite material. The moduli of the tissue which had a sandwich structure (Fig.11 (a)) were calculated from the moduli and the thicknesses of the tissues. In this study, we considered that the top ligamentous layer was affected by the tensile stress in X and Y directions, the top ligamentous layer was affected by the compressive stress in Z directions, and the central dense connective tissue received the compressive stress in the X and Y directions. So we took the tensile modulus as the modulus of the top ligamentous layer in the X and Y directions and the compressive modulus as the modulus of the dense connective tissue in the X, Y and Z directions. It is difficult to measure the compressive modulus of the ligamentous layer because of its small thickness. We took the compressive modulus of the dense connective tissue as the modulus of the bottom ligamentous layer, and then the sandwich structure became two layers structure (Fig.11 (b)). Equations 2 and 3 showed the methods to calculate the equivalent moduli of the two layers composite material.

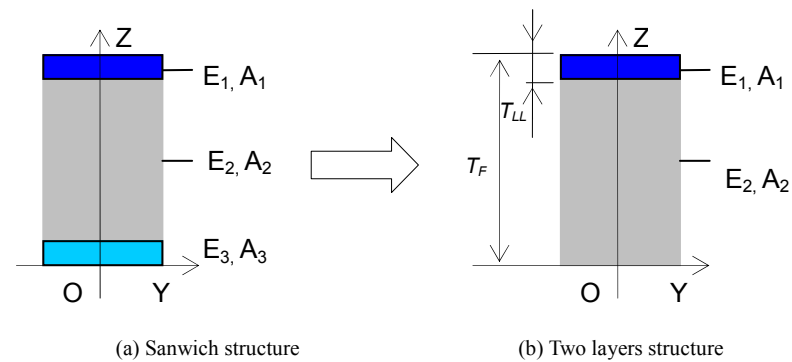


Fig.11. Model of layers composite material.

$$\sum_{k=1}^2 (E_k \iint Z_k dA_k) = 0 \quad (2)$$

$$EI = \sum_{k=1}^2 E_k I_k \quad (3)$$

Where E_k is the modulus of the layer k , Z_k is the displacement between the center of the cross-section of the layer k and the neutral axis, A_k is the area of the cross-section of the layer k , I_k is the second moment of area of the layer k .

By Eqs.2 and 3, we could express the equivalent modulus E as follows.

$$E = f(E_1, E_2, \frac{T_{LL}}{T_F - T_{LL}}) \quad (4)$$

By Eq.1, we could calculate the values of $T_{LL} / (T_F - T_{LL})$. The values in the position with different fluke thicknesses T_F were given in Fig.12. We found that the values of $T_{LL} / (T_F - T_{LL})$ decreased slowly when the fluke thickness was over 10mm. Because the thicknesses of most part of the tail fluke were over 10mm, we considered the value of $T_{LL} / (T_F - T_{LL})$ as a constant approximately. In this paper, $T_{LL} / (T_F - T_{LL}) = 0.168$ when $T_F = 25\text{mm}$. E_1 was the Young's moduli of the ligamentous layer, and E_2 was the Young's moduli of the dense connective tissue. E_1 and E_2 in Table 1 were also constants. Then the independent

variables of Eq.4 were all constants, so we could think that the moduli of tissue in the tail flukes were constants, that is, the tissue in the tail flukes could be considered as a uniform material.

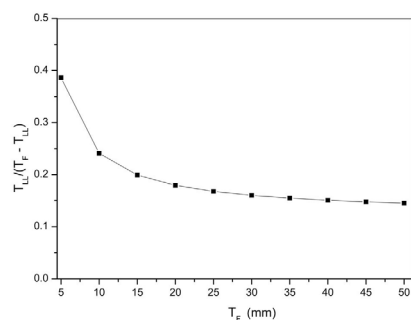


Fig.12 Relationship between $T_{LL} / (T_F - T_{LL})$ and fluke thicknesses T_F

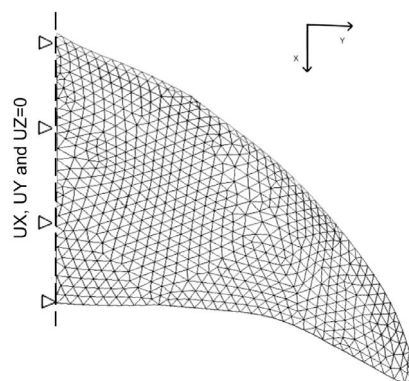
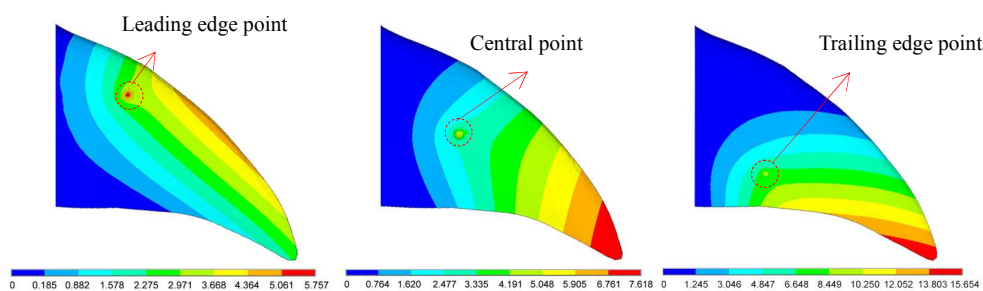
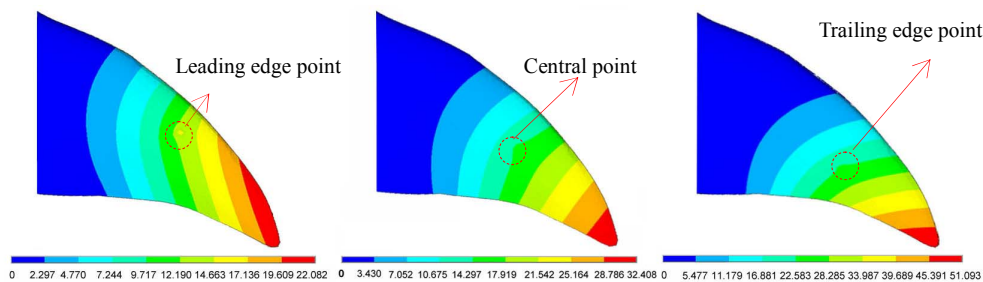


Fig.13. Sketch of tail fluke model.



(a) Leading edge point, central point and trailing edge point in the position spanwise 150mm.



(b) Leading edge point, central point and trailing edge point in the position spanwise 240mm.

Fig.14. Contour graph of displacement from the original position in the Z-direction (mm).

We made the model the tail fluke of dolphins using the software ANSYS 9.0. The coordinates of the model, the meshes and the constraints condition of the FEM model were also shown in the sketch of the tail fluke model (Fig.13). The chordwise, spanwise and thickness directions were defined as the X, Y and Z directions of the model respectively. We used the Solid 64 element to express the anisotropic material property of the tissues. We meshed the central part and the flukes all by tetrahedron elements. The model totally contained 2569 nodes and 11258 elements. The displacements in the X, Y and Z directions were defined as the UX, UY and UZ respectively. The tail fluke was constrained in three directions as UX=0, UY=0 and UZ=0 at the position Y=60mm as the bending test.

The displacement of the tail fluke of a dolphin was investigated by the model. A point force P=10N was applied on the corresponding test points of the bending test for an example. The results of bending tests on finite element model of the tail fluke of a dolphin were obtained. Figure 14 showed that the contour graph of the displacement from the original position in the Z direction in this case that a point force of 10N was applied on test points in the positions spanwise 150mm and 240mm from body axis.

When the point force was applied on the leading edge points and trailing edge points, it brought torsional bending deformations clearly, but the press applied on central point didn't bring so much torsional deformation (Fig.14).

The results of simulations were compared with the corresponding bending test (Figs. 15(a), 15(b) and 15(c)).

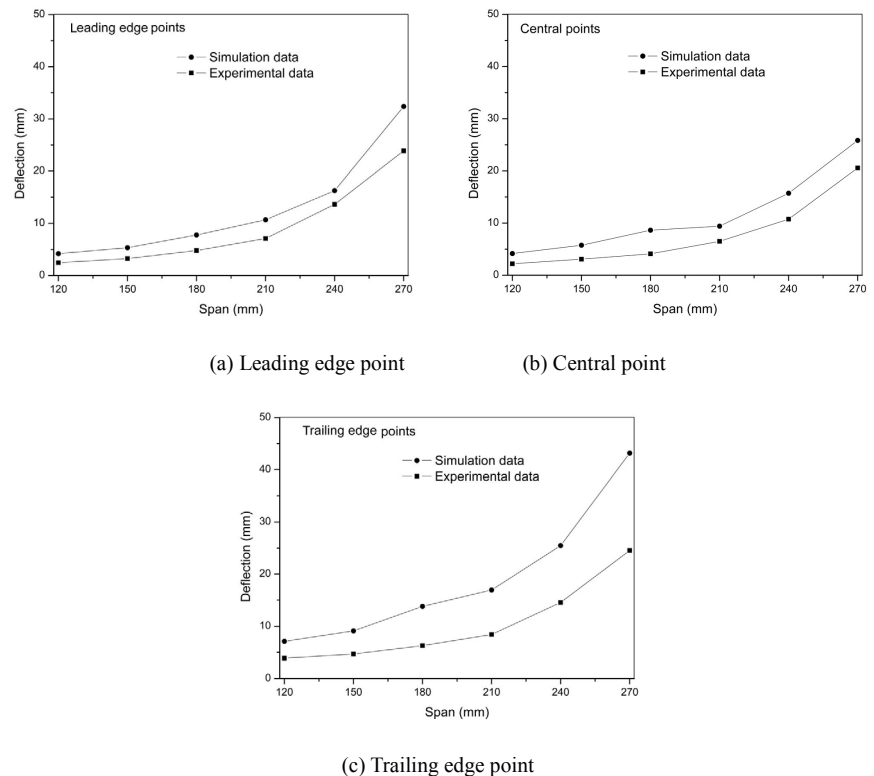


Fig.15. Comparison between experimental results and simulation results.

In Fig.15, we found that the simulation results on the leading edge points and central points were close to the experimental results compared with that in trailing edge. Although the curves of the simulation data and the experimental data had similar shape, there was a discrepancy between them obviously. The fluke thicknesses in the trailing edge point were lower usually. As shown in Fig.12, when the fluke thickness was low, the value of $T_{LL} / (T_F - T_{LL})$ changed dramatically. So the mechanical parameters of the tissue in these positions

were different from those in other positions probably. The discrepancy may be brought by this reason.

We also found that the simulation results were higher than the deformations measured in bending test for all the simulations. In the simulation the press was a real point force, but in bending test the point force was not. To avoid impalement and damage to the fluke, the press was applied by a round end cylinder with a diameter of 9mm which would reduce the deformation. This may contribute to the lower deformation.

3. Conclusions

In this paper the morphological data and the mechanical properties of the tissues in the tail flukes were investigated. The FEM model of the tail fin was established to research the bending properties of the tail flukes of a dolphin. The results of simulation were compared with that of the bending test.

The morphological data of the tail fin showed that the cross-section of the tail flukes parallel to the body axis showed a streamlined shape, the thickness of the tail flukes near the leading edge change greatly while the thickness of the tail flukes near the trailing edge decreased slowly; The thickness of the ligamentous layer (T_{LL}) had a linear relationship with the fluke thickness (T_F); The fiber bundles in the tail flukes laid at an angle to the body axis. The angle ranged from 73° near the leading edge to 40° near the central trailing edge.

By the tensile test and the compression test, we obtained the Young's moduli of the tissues in the tail flukes. The ligamentous layer had a high Young's modulus and the dense connective tissue had a high compression modulus in the Y direction of the material coordinates we set.

By the bending test, the displacements on different test points in the case a point force of 10N was applied were obtained. The point force applied on the leading edge points and trailing edge points brought torsional bending deformations, but the force applied on central point didn't bring so much torsional deformation.

A model of the tail fluke was made to investigate the bending properties. The simulation results on the leading edge points and central points were close to the experimental results compared with that in trailing edge.

By this study, we knew the relationship between the deformation and a point force applied on the tail flukes. The experimental results also validated the established model. The model can be helpful to understand the relationship between the deformation of the tail flukes and the force on them.

The FEM model established in this paper just a tentative example of a simple bending test by point forces. In the model, the tissues in the tail fluke were considered as a uniform material roughly; the different orientations of the collagen fiber bundles were neglected; the press on the tail fluke of a swimming dolphin was not a point force as applied in the bending test, although it is still unknown. In the future we will improve the model and investigate the deformation of the tail fin of a swimming dolphin. And then we will use the model and the observed deformation of the flukes to estimate the thrust of a dolphin.

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References

- (1) Rohr, J.J., Fish, F.E. and Gilpatrick, J.W., Maximum swim speeds of captive and free ranging delphinids: Critical analysis of extraordinary performance, *Marine Mammal Science*, Vol. 18, No.1 (2002), pp.1-19.

- (2) Gray, J., Studies in animal locomotion VI. The propulsive powers of the dolphin, *Journal of Experimental Biology*, Vol.13, No.2 (1936), pp.192-199.
- (3) Lang, T.G., and Pryor, K., "Hydrodynamic performance of porpoises (*Stenella attenuata*)," *Science. Magazine*. Vol. 152, No.3721 (1966), pp.531-533.
- (4) Lang, T.G., and Norris KS., Swimming speed of a pacific bottlenose porpoise, *Science. Magazine*, Vol. 151, No.3710 (1966), pp.588-590.
- (5) Fish, F.E., Power output and propulsive efficiency of swimming bottlenose dolphins *tursiops truncatus*, *Journal of Experimental Biology*, Vol.185, No.1 (1993), pp179-193.
- (6) Kramer, M.O. "Boundary Layer Stabilization by Distributed Damping," *Naval Engineers Journal*, Vol.72, No.2 (1960), pp.25-33.
- (7) Yurchenko, N. F., and Babenko, V.V., Stabilization of the longitudinal vortices by skin integuments of dolphins, *Biophysics*, Vol. 25, No.2 (1980), pp.309-315.
- (8) Vogel, S. "Life in Moving Fluids." Princeton University Press, Princeton, NJ, 1996.
- (9) Fish, F., Comparative kinematics and hydrodynamics of odontocete cetaceans: Morphological and ecological correlates with swimming performance. *Journal of Experimental Biology*, Vol.201, No.20 (1998), pp.2867-2877.
- (10) Felts, W., Some functional and structural characteristics of cetacean flippers and flukes, *Whales, Dolphins, and Porpoises (edited by Norris, K.S.)*, University of California Press, Berkeley, pp.255-276, 1966.
- (11) Fung, Y.C., "Biomechanics: Mechanical properties of living tissues", Springer-Verlag, New York, pp.242-320, 1993.
- (12) Loren G. J., and Lieber, R. L., Tendon Biomechanical Properties Enhance Human Wrist Muscle Specialization, *Journal of Biomechanics*, Vol. 28, No. 7(1995), pp. 191-199.