

Establishment of a Development Method of a Water Jet Pump for 4-Stroke Personal Watercrafts

Masahiko TSUCHIYA*

Tomohiro FUSE*

Takashi WATANABE*

ABSTRACT

Honda's first Water Jet Pump for a Personal Watercraft with a 4-stroke engine has been developed. In the development, correlation of the calculation results with the actual test results was verified, and design tools such as an examination method of intake shape optimization, a characteristic calculation method for various aerofoil shapes, and a prediction method of Water Jet Pump performance were established. Using these tools, two Water Jet Pumps that matched each of the 4-stroke engines with different output power have been developed.

1. Introduction

At present, most personal watercraft (PWC) on the market utilize two-stroke engines. However, increasing awareness of environmental issues is causing restrictions on the operation of two-stroke PWC, and emissions regulations are also becoming increasingly stringent. Honda has therefore developed two cleaner, quieter and more comfortable four-stroke PWC, the AquaTrax F-12 and F-12X. Fig. 1 shows an external view of the AquaTrax F-12X.



Fig. 1 External view of AquaTrax F-12X

The AquaTrax F-12 engine is normally aspirated, and has a displacement of 1,235 cm³. The F-12X engine has the same displacement, but the addition of a turbo-charger gives it the most powerful powerplant on the market. When developing the optimum water jet pumps for this PWC, in addition to matching pump performance, it was necessary to significantly control cavitation to achieve a match with the output characteristics of a turbo-charged four-stroke engine. Original 'design tools' were therefore developed in order to design new, high-efficiency pumps by analyzing the factors contributing to the characteristics of each section according to pump design theory.

2. Outline of Water Jet Pumps

PWC normally use axial flow or mixed flow water jet pump to provide propulsion. Because there is no necessity for any components to project from the bottom of the craft, these pumps are ideally suited to PWC. Another reason for the choice of these pumps is the fact that they function efficiently at high engine speeds, making them suited to the comparatively high-speed engines utilized in PWC. Fig. 2 shows the layout of the newly developed axial flow water jet pump, and the function of each section.

* Asaka R&D Center

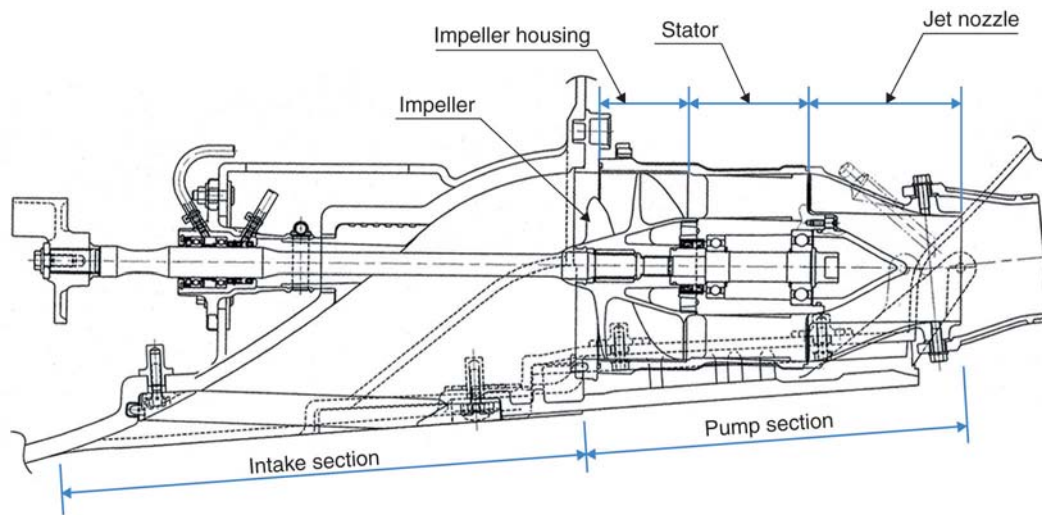


Fig. 2 Structure of developed water jet pump

2.1. Intake Section

The intake section, provided with curvilinear pipes to guide water from the flat bottom of the craft to the impeller, is one of the elements composing the water jet pump. The shape of the intake section has a tremendous influence on the performance of the craft. The shape of the comb-like intake grate positioned on the inlet, the shape of the inlet, the form of the pipes (in particular height), the cross-sectional area, and the rate of change of cross-sectional area, all affect intake efficiency.

2.2. Pump Section

The pump section of the axial flow water jet pump is composed of three parts: a cylindrical duct surrounding the impeller (impeller housing), a stator and a jet nozzle. For the sake of convenience, this paper will define the jet nozzle as part of the pump. The impeller is the most important component in the water jet pump, and transmits power by pressurization with water from the intake section. The stator efficiently converts the kinetic energy of the swirl from the impeller into propulsion, and is made of supporting materials to support the impeller shaft. The jet nozzle converts the amount of motion transmitted to the head by the water pressurized in the pump section into thrust. The diameter of the jet nozzle outlet affects the characteristics of the craft. Because dynamic pressure is high, a suction type bilge pump is also located in this section.

3. Aims of the Development

3.1. Intake Section

In deciding on the shape of the intake duct, it is necessary to give consideration to the minimization of cavitation and pressure loss within the intake section. The parameter which defines how much energy from ship velocity will be recovered as dynamic pressure in the intake duct is ε , the recovery ratio of dynamic pressure, and is found using equation (1):

$$\varepsilon = \frac{Pa + Po}{Pa + \frac{1}{2g} V_{ship}^2} \quad (1)$$

Po : Total pressure directly in front of the impeller

Pa : Atmospheric pressure

V_{ship} : Ship velocity

g : Acceleration of gravity

The magnitude of this value is known to affect propulsive efficiency, particularly at high speeds, but conducting tests with a completed craft to improve the shape of the intake is a complex and inefficient procedure.

Tests were therefore conducted on the performance of the intake section in isolation, using a scale model. By correlating the results of these tests with the results of computational fluid dynamics (CFD) calculations, a method of examining the shape of the intake duct was developed.

3.2. Shape of Impeller/Stator Aerofoils

The aerofoil shape is determined by the chord length, the camber and aerofoil thickness. The aerofoil shape is an important element which affects the aerofoil's lift coefficient (C_L) and drag coefficient (C_D). Furthermore, if the pressure distribution on the surface of the aerofoil causes negative pressure to exceed a certain limit and generates saturated vapor pressure, the phenomenon known as cavitation occurs. Excessive cavitation changes the characteristics of the aerofoils, which causes their efficiency to drop; in addition, the shock waves which occur when cavities collapse may cause erosion of the aerofoil surface, leading to serious damage to the aerofoils.

In the development of the pump section, the first necessary factor was understanding the characteristics generated by the shape of the aerofoils. A calculation program was optimized using the results of actual measurements of two-dimensional aerofoil characteristics, and a method was developed to allow calculation of these characteristics.

3.3. Pump Section

A calculation program for pump section performance was created using existing theory. This program was improved by correlation of calculation results with measurement results obtained from tests of the performance of the pump section in isolation, enabling the development of a method for calculating the performance of the pump section.

4. Development of the Intake Section

4.1. Performance Tests of Intake Section in Isolation

The loss coefficient ξ_s is defined using equation (2), where $\bar{p}_s$ is the mean value of static pressure in the intake duct.

$$\xi_s = \frac{\frac{V_s^2}{2g} - \left(\frac{\bar{p}_s}{\rho} + \frac{V_i^2}{2g} \right)}{\frac{V_i^2}{2g}} \quad (2)$$

V_i : Mean velocity directly in front of the impeller

V_s : Principal velocity in front of intake

g : Acceleration of gravity

A half-scale model of the intake section, as shown in Fig. 3, was used to conduct measurements of the pressure loss coefficient, to make flow visualization possible and to verify the velocity distribution in an isolated intake. The scale model was placed in the upper observation section of a cavitation tunnel. A new channel was created for the rear of the scale model, and flow velocity was varied using another pump. Pressure and flow velocity were measured at each section of the scale model, and the loss coefficient was measured for different intake and intake grate shapes. Pitot tubes distributed like a comb were set up at the position where leading edge of the impeller should be placed; by rotating the set of Pitot tubes, the distribution of flow velocity directly in front of the impeller could be measured. Fig. 4 shows details of the observed section, and Fig. 5 shows an example of velocity distribution directly in front of the impeller. The intake grate can be seen in the lower left of Fig. 4, and the Pitot tubes can be seen on both sides of the cone-shaped section just to the right of the center. This test verified the fact that variations in intake shape produced large differences in flow velocity directly in front of the impeller. By making the flow within the intake duct visible, the sections which made the greatest contribution to performance could be directly observed.



Fig. 3 1/2 scale model of intake

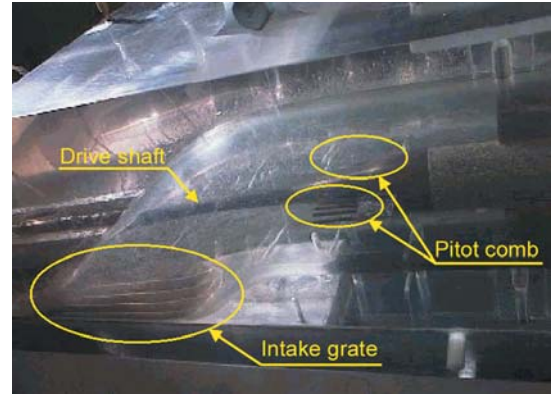


Fig. 4 Detail of intake 1/2 scale model

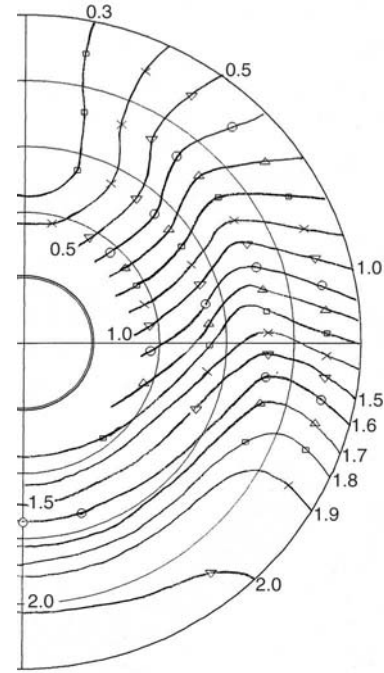


Fig. 5 Measurement result of velocity distribution inside intake duct

4.2. Intake Design Tools

A commercially available CFD solver was utilized to verify loss coefficient and internal flow conditions using the same intake shape as used in the tests of isolated intake performance. Calculation conditions were reset on the basis of correlation of intake performance test measurements and CFD calculation results.

Fig. 6 shows the flow in an axial cross-section, and Fig. 7 shows the velocity distribution in a duct section directly in front of the impeller. Figs. 6 and 7 show that the areas of highest flow velocity occur below the center. Intake velocity ratio, r , is defined using equation (3):

$$r = V_s / V_i \quad (3)$$

Examples of examination of various intake shapes using CFD are shown by plan in Fig. 8. Restricting the size of the inlet, as Fig. 9 shows, reduces the loss coefficient at high speed ($r = 2.5$), but increases it at standstill ($r = 0$). In other words, in this example, there is a tradeoff between the performance at high speed and low speed.

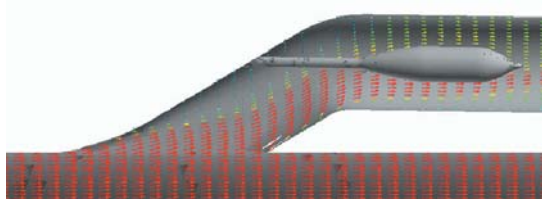


Fig. 6 Flow pattern inside intake duct by CFD
(Side view)

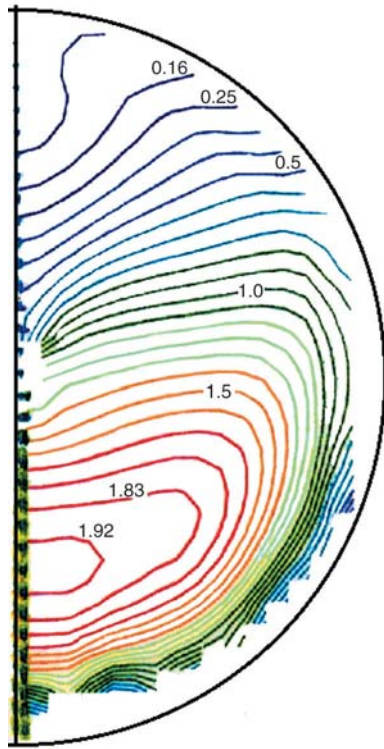


Fig. 7 Velocity distribution inside intake duct by CFD
(Front view)

4.3. Correlation of Isolated Unit Test Results and Calculation Results

The velocity distribution directly in front of the impeller in Figs. 5 and 7 show the same qualitative tendencies. Fig. 10 shows a graph comparing intake loss coefficients found by CFD and measured in tests, and it is clear that there is a good correlation between the two sets of results. This method was used to establish target loss coefficient values to achieve a balance of flow velocities, and the intake shape was improved on this basis.

5. Aerofoil Development

5.1. Aerofoil Design Tools

Using existing theoretical formulas as a base, a program was formulated to calculate the characteristics of two-dimensional aerofoils.⁽¹⁾⁻⁽³⁾ Cavitation may be predicted to occur easily because of the harsh conditions under which PWC water jet pumps are operated. Both cavitation and non-cavitation states were therefore examined. To verify the accuracy of calculations, an NC1 foil⁽⁴⁾ was used to correlate the calculated and the measured values. This aerofoil shape

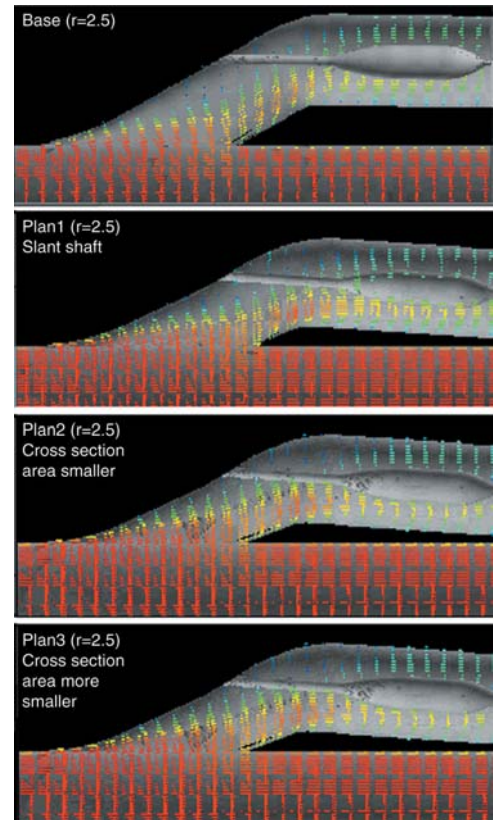


Fig. 8 Flow patterns obtained from CFD for intakes of different inlet shapes

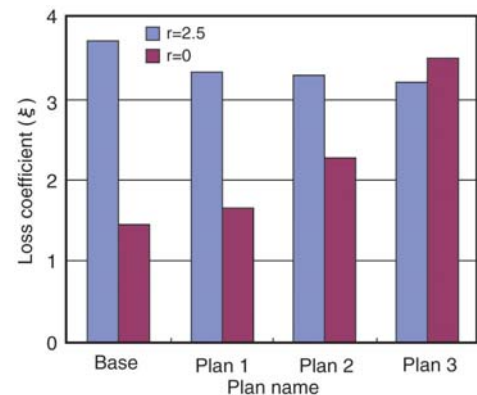


Fig. 9 Comparison of intake loss coefficient of various plans

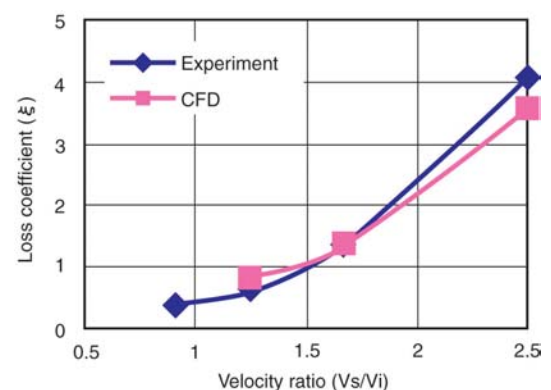


Fig. 10 Comparison of loss coefficients between experiment value and CFD value

was chosen because it is the model with the lowest thickness ratio (thickness ÷ chord length × 100) (ratio: 3.86) from which reliable test measurements can be obtained. Results showed an excellent correlation between the lift coefficients obtained from calculations and test measurements. A quantitative difference in drag coefficient was observed, but it was possible to verify that calculation results displayed the same general trend as test results. However, the thickness ratio which formed the target of this development was less than 3.0. Attempts were made to improve the accuracy of calculations, but given the necessity for data on thinner aerofoils, it was decided to obtain test data on the characteristics of super thin aerofoils.

5.2. Test for Two-dimensional Aerofoil Characteristics

Fig. 11 shows the test piece used to reproduce the characteristics of actual aerofoils with the same thickness ratio in cavitation tunnel tests. Two different aerofoil shapes were utilized in these tests to measure cavitation characteristics and the relationship between drag and lift and cavitation and non-cavitation states, and to provide data on the characteristics of super-thin aerofoils. The cavitation number, σ , is found using equation (4). These figures are used as a scale to express the ease of occurrence of cavitation. Fig. 12 shows representative cavitation states occurring during testing. These are model cavitation states obtained by measuring lift and drag and adjusting the cavitation number by varying the pressure within the cavitation tunnel (depressurization), the angle of attack and the flow velocity. From the left, these forms of cavitation are known as bubble cavitation, sheet cavitation and cloud cavitation.

$$\sigma = \frac{P - P_v}{\frac{1}{2} \rho V^2} \quad (4)$$

P : Static pressure of flow medium
 P_v : Saturated vapor pressure of flow medium
 ρ : Density of flow medium
 V : Velocity of flow medium

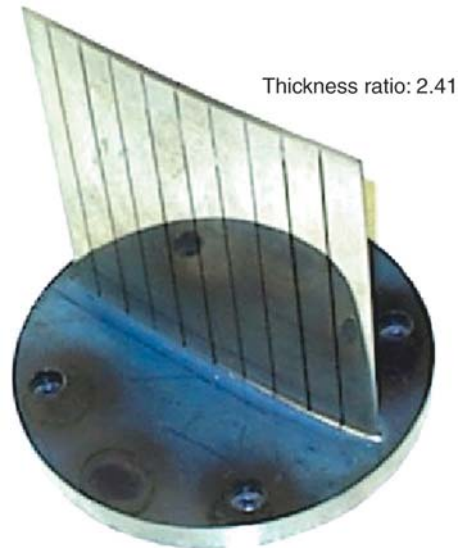


Fig. 11 Test piece of 2-dimentional aerofoil

5.3. Correlation of Calculation Results and Results of Tests of Characteristics

The calculation program for aerofoil characteristics described in 5.1 was optimized using the results of the tests described in 5.2, enabling the formulation of a “calculation program for the prediction of aerofoil characteristics”. This program makes it possible to predict the characteristics of unknown super-thin aerofoils. Figs. 13 and 14 show examples of comparisons between calculated values and measured values. Fig. 13 shows lift and drag coefficients and lift-drag ratio when angle of attack is varied. Fig. 14 shows lift and drag coefficients when cavitation number is varied for a particular angle of attack. These results verify an acceptable level of accuracy in the program’s predictions.

6. Development of Pump Section

6.1. Non-cavitation state

6.1.1. Pump section design tools

The calculation program for the prediction of two-

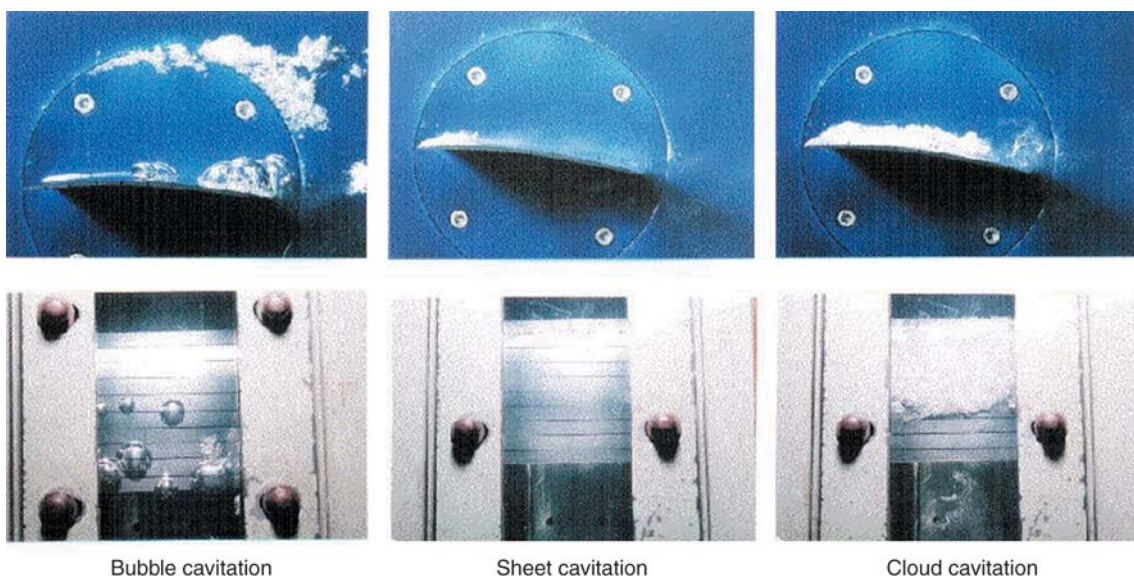


Fig. 12 Cavitations on 2-dimensional aerofoil

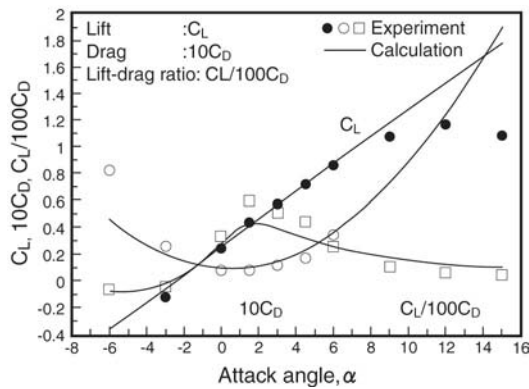


Fig. 13 Comparison of measurement results and calculation results in difference of attack angle

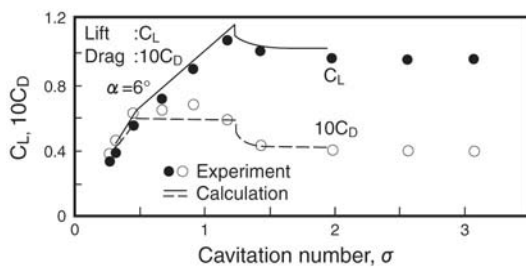


Fig. 14 Comparison of measurement results and calculation results in difference of cavitation number

dimensional aerofoil characteristics described in 5.3 was developed into a calculation program for the prediction of three-dimensional pump performance. This program uses three-dimensional lifting surface theory to calculate the performance of a pump section given the geometric shape of an impeller and stator when operating in a non-cavitation state with uniform flow.

6.1.2. Tests of pump performance in isolation

Tests were conducted on the performance of an actual pump section in isolation in a non-cavitation state. Figs. 15 and 16 show test equipment. These tests enabled the following improvements:

- By making stream lines observable using the oil film method, it was possible to verify differences between the actual stream lines on the surface of the impeller aerofoil and the hypothetical stream lines obtained by calculation. These results were used to optimize the calculation algorithm.
- Bilge pump efficiency (the bilge pump removes water from inside the craft using negative pressure generated by the dynamic pressure of the jet nozzle) and improvements were made to performance.
- The intense swirl flow arriving at the nozzle from inside the stator was studied, and a method for its efficient recovery was developed.

Fig. 15 shows the pump section installed in the test equipment. Inlet flow volume and velocity, pump section pressure and impeller torque and speed were measured, and pump performance data (head coefficient, load coefficient, pump efficiency) were obtained. Fig. 16 shows the test equipment in operation.

6.1.3. Correlation of calculation results and isolated unit test results

Coefficients for the calculation program for pump



Fig. 15 Test equipment for water jet pump



Fig. 16 Test equipment for water jet pump in operating

performance described in 6.1.1 were adjusted on the basis of the results of the tests described in 6.1.2, to create a program capable of predicting the performance of the newly designed pump. Fig. 17 shows an example of a comparison between calculation and test results. This plot charts pump performance results obtained from running tests in addition to isolation test results and calculation program results, with a high degree of correlation demonstrated between the three sets of results.

6.2. Cavitation States

6.2.1. Performance tests of the pump section in isolation

Water jet pumps used in normal watercraft require optimization of performance and efficiency for a certain fixed range of operating conditions. However, an extremely broad range of operating conditions must be taken into consideration in the case of PWC: it is necessary to achieve performance not only at maximum speed, but across the range from standstill to fully open throttle and at sudden

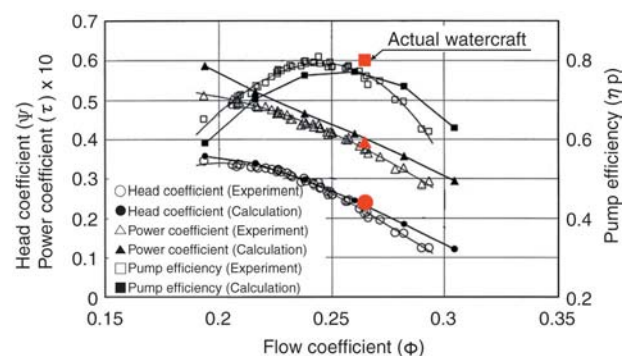


Fig. 17 Comparison of pump performance between measurement results and calculation results

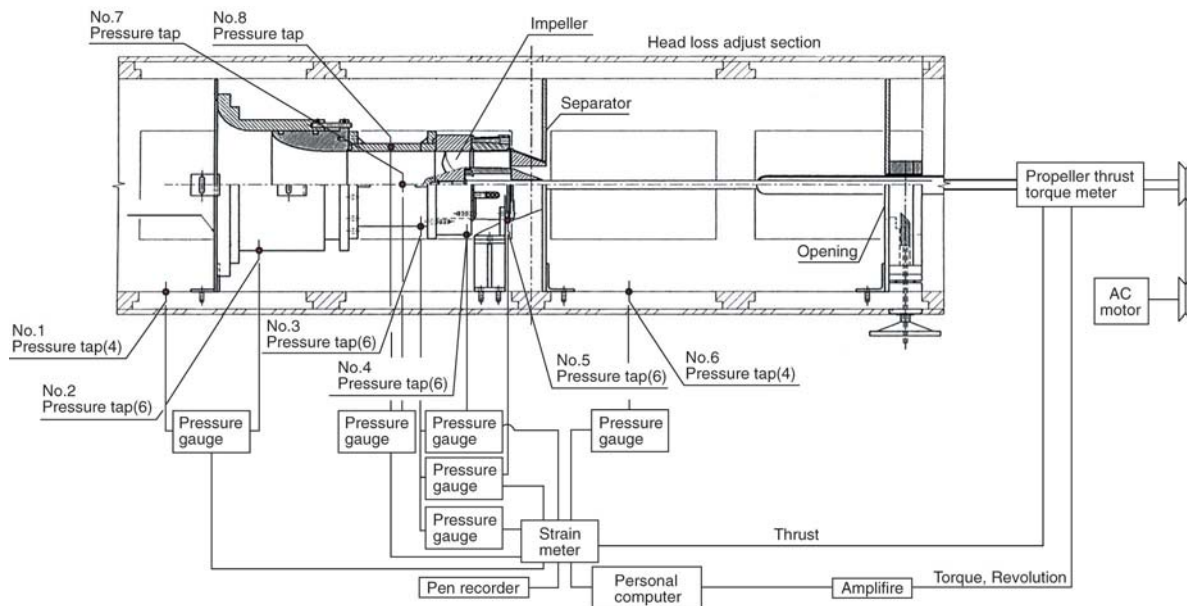


Fig. 18 Design of cavitation test equipment

acceleration and deceleration. The impellers in these craft turn at high speeds, making the possibility of cavitation extremely high, but for the reasons discussed above, the pumps cannot only be optimized for high speeds, but must achieve a balanced cavitation performance.

In addition, in the newly developed PWC, rapid pickup from the four-stroke engine's characteristic idling to high engine speeds and sudden changes in power characteristics due to increased supercharging from the turbo-charger cause cavitation to occur easily, leading to engine revolution overshoot and a feeling of insufficient acceleration when sudden acceleration is applied. To prevent this, it was necessary to develop a water jet pump in which cavitation was reduced as much as possible.

The cavitation test equipment shown in Figs. 18 and 19 was designed to enable quantification of this phenomenon, to render it observable, and allow improvement of cavitation performance under a wide range of operating conditions. Tests were conducted on a pump placed in the flow channel of this cavitation tunnel.

This equipment was designed to make impeller torque and thrust measurable by positioning the pump in the observation window of the cavitation tunnel. The volume of flow was regulated by a throttle valve downstream from the pump to adjust the loss head. This equipment not only rendered cavitation observable through depressurization, but enabled values to be obtained for thrust, which was impossible using the test equipment for the water jet pump in isolation shown in Fig. 15.

By making cavitation states in an actual pump observable, it was possible to verify that the shape of the impeller aerofoil tips contributes significantly to the occurrence of cavitation. The results made it possible to understand the general outline of optimum shapes.

Fig. 20 is a bucket chart for initial generation of cavitation for different impeller shapes. The results demonstrate that the impeller type termed C12 is the shape which suppresses cavitation to the greatest extent. Figs. 21 and 22 show the results of actual observations of cavitation. Fig. 21 shows the base impeller, and Fig. 22 shows the C12

type. Both types were tested simulating the same high-speed conditions, and the results make it clear that the improved type has significantly reduced cavitation.

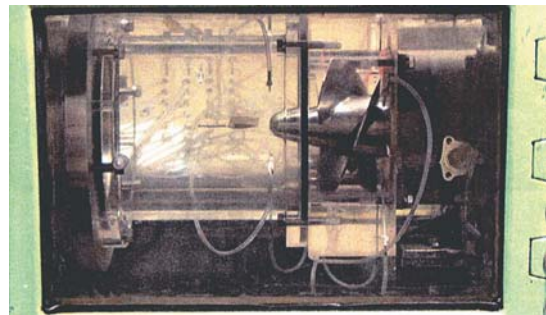


Fig. 19 Observation window of cavitation test equipment

7. Tests on the Completed Craft

7.1 Water Jet Pump Performance Required in PWC

In the normal development flow of water jet pumps, the first prerequisite is estimating the drag of the completed craft. The flow continues with the establishment of the power consumption of a pump matched to the engine's maximum power, the choice of housing diameter and the design of the impeller and stator, examination of the intake shape, the selection of nozzle diameter, etc. In tests of the completed craft, performance in the following points used to evaluate PWC water jet pumps must match target performance:

- Sufficient propulsion at running start and re-acceleration, and efficient use of that propulsion for acceleration.
- Accurate response of propulsion in line with rider's intention (throttle control).
- Thrust reengages smoothly at a dead start when over-revving after a spin, etc.
- Sufficient level of hook-up performance.

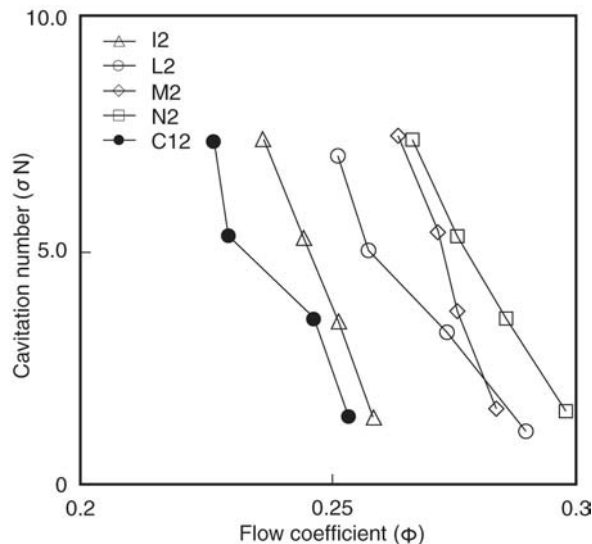


Fig. 20 Initial generation of cavitation by flow coefficient

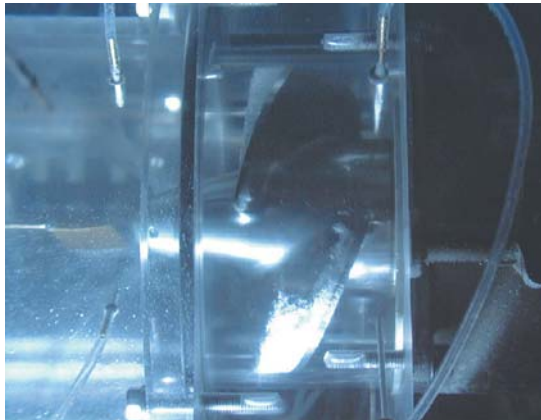


Fig. 21 Cavitation test result before improvement

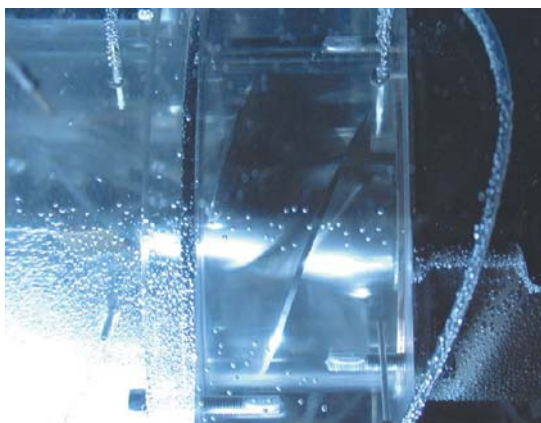


Fig. 22 Cavitation test result after improvement

7.2. Results of Tests on Completed Craft

The water jet pump which was designed on the basis of the results of the studies previously described was tested in the completed craft to evaluate matching and feeling. No difficulties in basic performance were observed. Improvements were made using data obtained in isolated unit

tests and cavitation tests, and the pump was tuned to increase power consumption of a pump in the transients. Adjustment of engine power characteristics improved the sense of continuity of acceleration and the feeling of initial acceleration.

8. Conclusion

Honda has developed water jet pumps matched to two different four-stroke engines with different power outputs. An original method of development of water jet pumps was created, using the following design methods:

- (1) Results from isolated unit tests utilizing a scale model were correlated with CFD calculation results. The calculation guidelines established in this way enabled the creation of a method for prediction of intake loss coefficient.
- (2) Data obtained from measurements of the characteristics of super thin aerofoils were correlated with the results of calculations of aerofoil characteristics, enabling the creation of a method for predicting the characteristics of unknown aerofoil shapes.
- (3) Results of tests on pump performance in isolation and results of the newly formulated calculations for prediction of pump performance were correlated, enabling the creation of a method for the prediction of water jet pump performance.

Reference

- (1) Kato, Y.: Cavitation, Maki Shoten, p. 96 (1979)
- (2) Kinnas, S.A., Fine, N.E.: "A Numerical Nonlinear Analysis of the Flow around Two- and Three-Dimensional Partially Cavitating Hydrofoils," Journal of Fluid Mechanics, Vol. 254, pp. 151-181 (1993)
- (3) Nakatake, K., Ando, J., Kataoka, K., Yoshitake, A.: "A Simple Method for Planar Aerofoils," Journal of the West-Japan Society of Naval Architects, Vol. 88, pp. 151-181 (1993)
- (4) Yamaguchi, H., Kato, Y., Tanimura, S., Toyota, M.: "Research on Aerofoil Shapes for Trans-Cavitation Propellers," Journal of the Society of Naval Architects of Japan, Vol. 182, pp. 49-57 (1997)

■ Authors ■



Masahiko TSUCHIYA



Tomohiro FUSE



Takashi WATANABE