

Development of an Off-Throttle-Steer System for Personal Watercraft

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ABSTRACT

Personal Watercrafts (PWC) are vehicles propelled by a water jet and steered by changing the direction of the water jet. Because of the decreasing of the thrust when the throttle is fully closed during running, the steering force also decreases. This phenomenon is different from that of land vehicles. To minimize this, the Off-Throttle-Steer (OTS) System has been developed. Basically, the system controls engine speeds using the signal of full steering, and also uses a throttle opening, a running speed of PWC predicted by engine speed, and a timer for determining the control timing as other control signals. Thus, a natural steering characteristic was obtained by balancing a turning characteristic at high speed and controllability at low speed.

1. Introduction

Personal watercraft (PWC below) have become popular with large numbers of users as a means of enjoying leisure time on the water, with the US being the major market. PWC are propelled by a water jet and steered by changing the direction of the water jet. This system causes thrust to decrease when the throttle is fully closed (off throttle) during normal running, and in some cases the rider may be unable to turn in the intended direction. This paper introduces the Off-Throttle-Steer system (OTS), developed to resolve this issue. The Honda AquaTrax F-12 and F-12X have been provided with this system.

2. Outline of the OTS System

There are two types of OTS systems: rudder type OTS and OTS which increases engine speed. The present system enables turning by increasing engine speed. Fig. 1 shows a structural diagram of the throttle body used in this system.

In this system, full steering of the steering handle with the throttle off activates a switch positioned on the steering shaft. This engages a solenoid valve, which causes a diaphragm to release the negative pressure built up in the surge tank, opening the throttle valve. This increases engine speed, ensuring turnability. Because paddle speed sensors are unstable and easily affected by waves, in this system calculation of the craft speed, a necessary element of control information, is calculated in the ECU on the basis of engine speed and the level of openness of the throttle.

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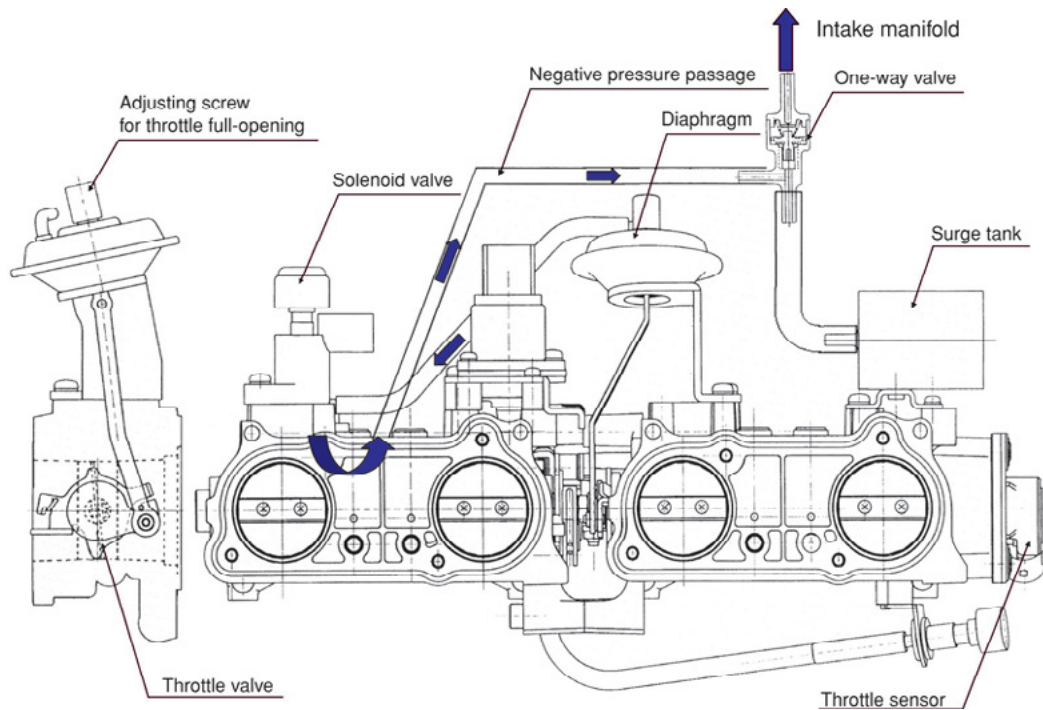


Fig. 1 Construction of OTS system

3. Evaluation of OTS System Performance

3.1 Running Test Method

The PWC's performance was evaluated by measuring running locus and yaw rate when turning with the throttle off and with full steering from low speed to high speed, with and without operation of the OTS system. As running conditions, engine speed was maintained between 1,400 and 2,000 r/min, and the craft was run at 50, 70, and 90 km/h. Evaluation of unnatural feelings in turning response and acceleration were conducted with multiple riders. Fig. 2 shows the scale used for this subjective evaluation.

3.2 Measurement System

Evaluation of running locus is important in evaluating turnability. However, it is difficult to accurately measure running locus in the case of watercraft. When a craft is run over a course marked out by buoys, etc., the effect of waves and wind do not allow the achievement of sufficient accuracy, and it is difficult to obtain measurement results enabling appropriate evaluations. In these tests, a running locus measurement system (Dual RTK system) using GPS was employed to resolve these difficulties. Two high-accuracy GPS antennas and an A/D converter were fitted to the craft. Running locus data at an accuracy of ± 5 cm for every 200 ms were obtained by measuring the position, direction and speed of the test craft and calculating its relative position with a land-based GPS ground station. By positioning GPS antennas at the front and rear of the PWC, it was possible to measure the craft's drift angle, etc. Craft behavior was measured using a gyroscope, and these data were later used in analysis. Fig. 3 shows the test craft.

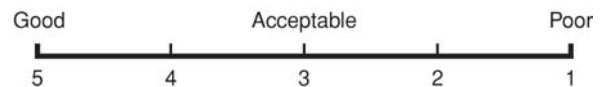


Fig. 2 Subjective evaluation rating scale

3.3 Performance Targets

To establish performance targets for the OTS system, PWC steering characteristics with the throttle disengaged were first measured without the OTS system. Fig. 4 shows a time history data for yaw rate at full steering with the throttle fully closed. The time history data for the yaw rate of a motorcycle (MC below) performing a J-turn from the same starting speed as the PWC is shown for comparison with land vehicle characteristics. MC resemble PWC in their on-saddle riding position, and exhibit similar banking



Fig. 3 Prototype PWC

behavior during turning. It can be seen that the MC yaw rate tends to maintain a constant value. By contrast, the PWC demonstrates a positive yaw rate at the beginning of its turn, but this then decreases, to reach a negative value inverse turning direction. Fig. 5 shows the PWC running locus at this time. The PWC demonstrates turning behavior at the beginning of the steering operation, but as the area of Fig. 5 circled in red shows, in the second half of the time period represented, it tends to move in a straight line, despite the continuation of the steering operation. Running locus data obtained from the front and rear GPS equipment on the test craft also indicate that the PWC is not turning. It was conjectured that this phenomenon was the origin of the unnatural feeling in turning response experienced by PWC riders. These results established the performance target for the OTS system as the maintenance of yaw rate above a negative level while steering continues.

In addition, to realize a natural feeling of control in line with the intentions of the rider, the following targets were established:

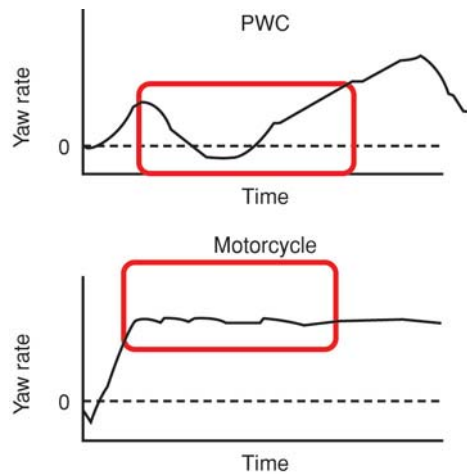


Fig. 4 Comparison of yaw rate characteristic between PWC and motorcycle

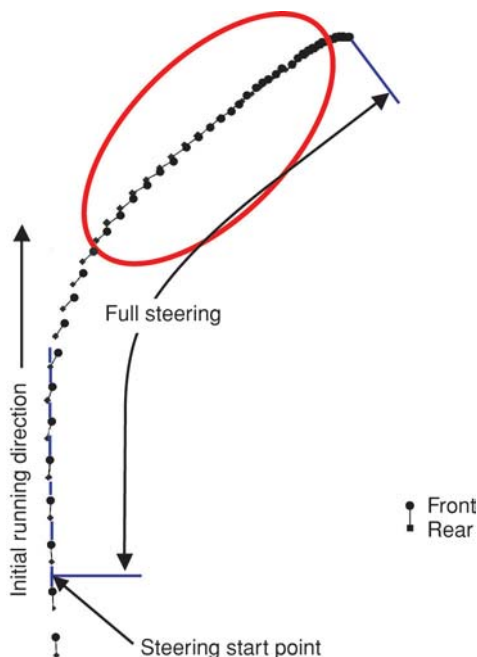


Fig. 5 Running locus without OTS system

- (1) Reduction of the unnatural feeling of increase in engine speed when the throttle is closed.
- (2) Operation of the OTS system at low speed only when the necessary conditions are met.
- (3) Stable turning behavior when the OTS system operates at high speed.

3.3.1 OTS operating conditions

Fig. 6 shows the results of subjective evaluations of turning feeling at various speeds without the OTS system. Because the engine and pump are directly linked, the pump provides thrust at low speeds, including when idling, and turning response was therefore rated acceptable at these speeds even without the OTS system. On the basis of these results, the speed for operation of the OTS system was established at 40 km/h and above, at which the turning feeling had been rated at 3 and below (acceptable range).

It is difficult to estimate craft speed from engine speed when the craft is decelerating with the throttle off. Taking into account the deceleration characteristics shown in Fig. 7, time to deceleration to 40 km/h was taken as standby time, and used to estimate craft speed directly before the point at which the throttle was turned off. Fig. 8 shows the relationship between craft speed and standby time. If the time from turning off the throttle to operation of the steering switch is within standby time, craft speed is judged to be 40 km/h or over, and the OTS system operates.

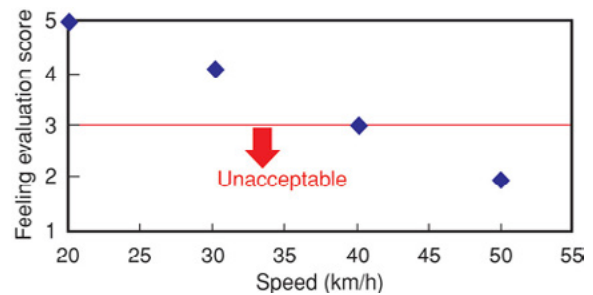


Fig. 6 Subjective evaluation result of turning feel without OTS

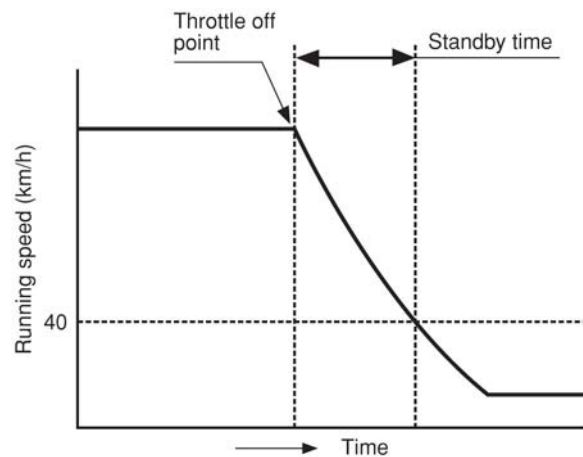


Fig. 7 Prediction of deceleration characteristic

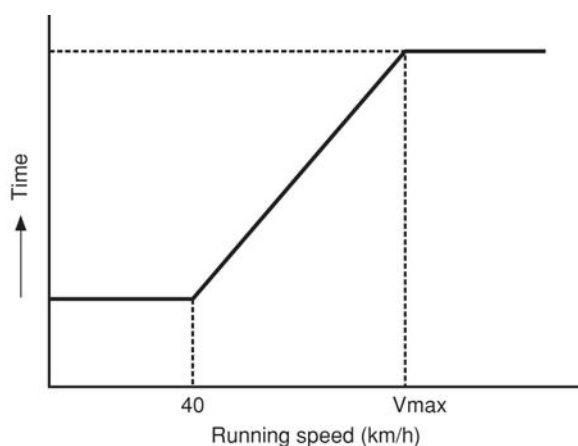


Fig. 8 Relation between PWC running speed and standby time

The following were established as conditions for stopping operation of the OTS system when the rider is turning the craft in the direction he or she desires:

- When the steering switch turns off at full steering
- When the rider opens the throttle
- When 7 seconds have elapsed since the system commenced operation

3.3.2 Engine speed for OTS operation

Fig. 9 shows the results of subjective evaluation of turning and acceleration feeling with the OTS system operating at various engine speeds. The broken line indicates that as the set engine speed gets higher, evaluation of turning response tends to increase, but when it gets too high, the craft's behavior becomes unstable and the evaluation drops. The evaluation of acceleration feeling is also observed to decline as engine speed increases. To minimize an unnatural feeling of acceleration, engine speeds of 2,000 r/min and below were established. Table 1 shows the tendency of minimum yaw rate values. Yaw rates are considered positive when they occur in the same direction as the direction of steering. The yaw rates tend to reach negative values at high craft speed. However, at 1,800 r/min and above, yaw rate remains positive even at 90 km/h. From subjective feeling and yaw rate results, target engine speed was established as 1,800–2,000 r/min.

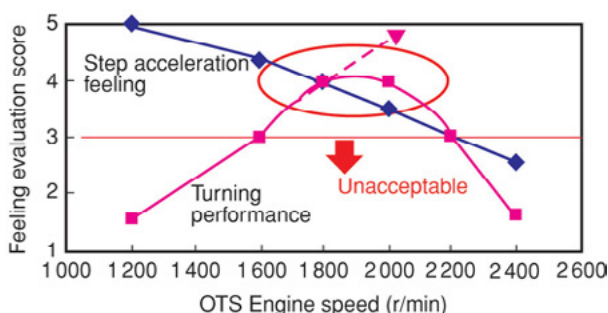


Fig. 9 Subjective evaluation results of acceleration and turning feeling by different engine speeds

3.3.3 Control at high speed

Fig. 10 shows the relation between craft speed and yaw rate with OTS in operation for a variety of initial craft speeds. With only simple control of increase of engine speed, yaw rate tends to increase rather than decrease during high-speed turns, giving rise to an excess yaw rate. This is because at high speed, directly after the throttle is fully closed, engine speed does not fall to idle level, and turning is executed at a higher engine speed than that established for OTS. Delay times for operation of the OTS system after the throttle is closed were therefore established. Fig. 11 shows test results for various delay times. If a delay time of 0.9 sec or above is set, it is possible to control the excess yaw rate.

Table 1 Observed direction of minimum yaw rate

	OTS Engine speed (r/min)		
Speed (km/h)	1 200	1 600	1 800
40	Positive	Positive	Positive
50	Negative	Positive	Positive
70	Negative	Positive	Positive
90	Negative	Negative	Positive

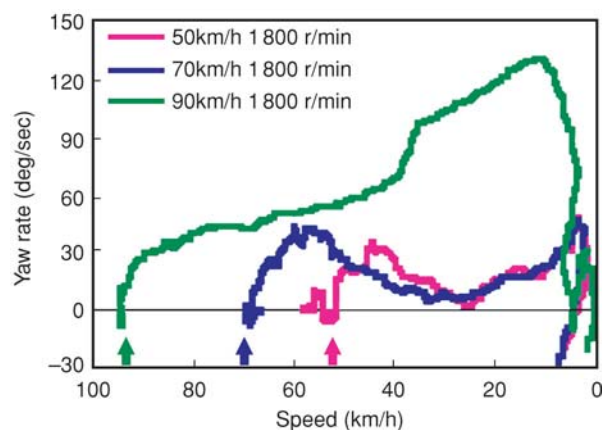


Fig. 10 Yaw rate during decelerating by different initial running speeds

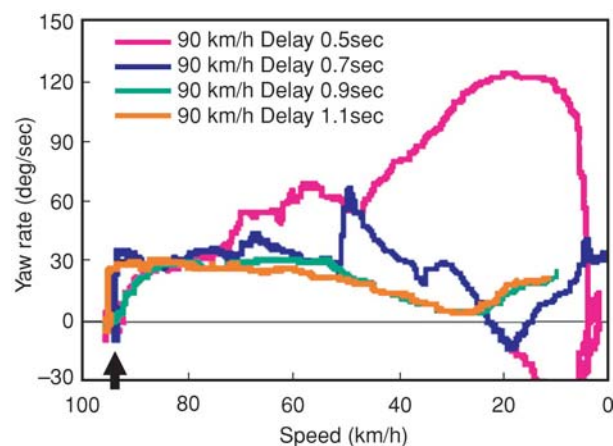


Fig. 11 Yaw rate during decelerating by different delay times

3.3.4 Overall evaluation of OTS system control

Fig. 12 shows a chart of OTS system operation for the various points at which the system operates. Fig. 13 shows the running locus of a PWC with the throttle off using this configuration of the OTS system, compared with the running locus without the OTS system. It is clear that with the OTS system the craft continues to turn while steering is maintained. This system has been utilized in the AquaTrax F12 and F12X, which feature different engine characteristics, and has achieved the same evaluation with changes only to set engine speed and delay time required to respond to craft characteristics.

4. Conclusion

An OTS system for PWC which exerts control which the rider experiences as natural has been constructed. The following findings were obtained:

- (1) Subjective evaluation of turning feeling established that the craft speed for which OTS was required was 40 km/h and over.
- (2) Appropriate engine speed for operation of the OTS system was 1,800–2,000 r/min.
- (3) Delaying the timing of operation of the OTS system was effective in preventing excess yaw rate at high speed.

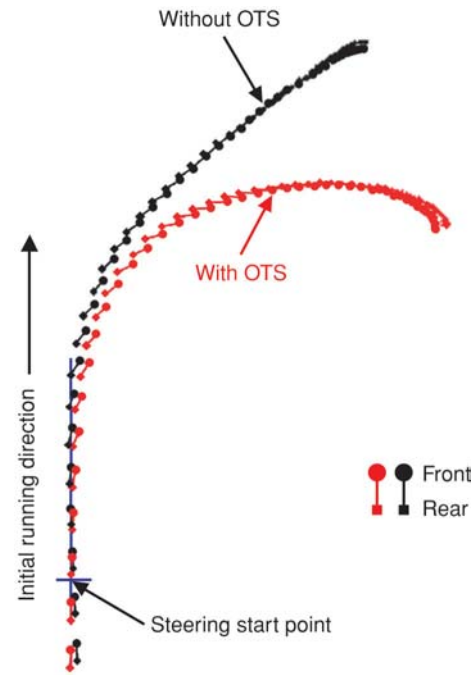


Fig. 13 Comparison of running locus between without and with OTS

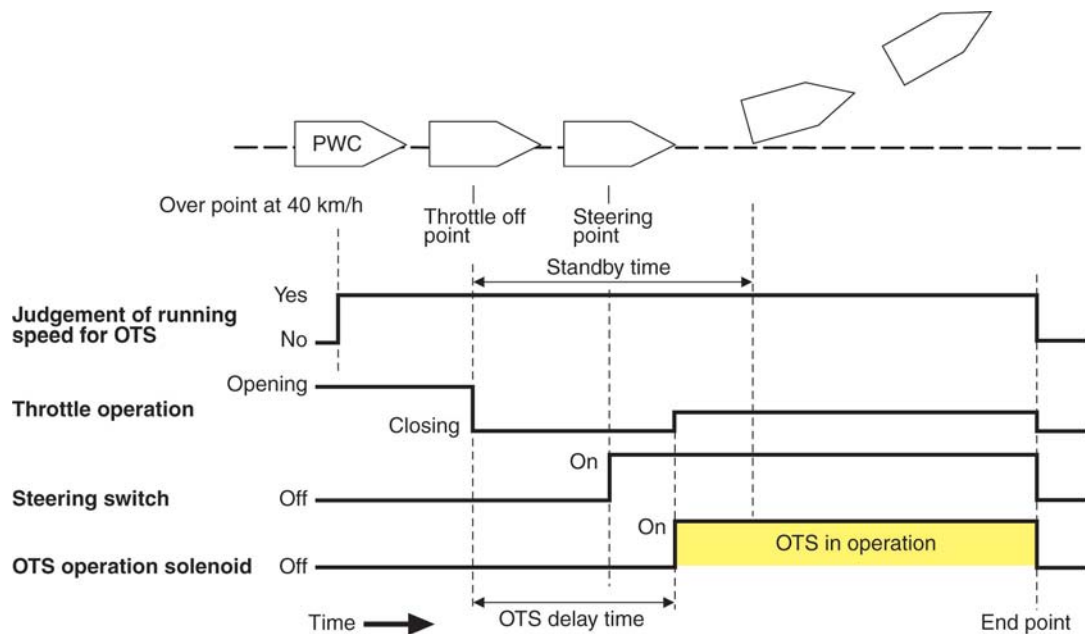


Fig. 12 OTS system operation

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