ICIC Express Letters
Part B: Applications
Volume **11**, Number **3**, March **2020**

ICIC International ©2020 ISSN 2185-2766
pp. **261–266**

COMPARATIVE STUDY ON KEEL EFFECTS OF CATAMARAN-TYPE SAIL DRONE

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Received September 2019; accepted December 2019

Abstract. *Recently, the global needs for the maritime domain awareness are gradually increasing. In order to satisfy these needs effectively, various marine robots are developed and applied globally. Among marine robots, the autonomous marine robot basically has the problem of the energy limitation due to its volume limitation. To solve this problem, a catamaran-type sail drone which is capable of harvesting of marine energies such as wind and solar had been proposed. This catamaran-type sail drone can effectively solve the energy problem in autonomous marine robot and has better performance in terms of stability. However, it has not good straightness because it has not the keel that can reduce the lateral force. To analyze the keel effects, the comparative study is performed. Study results show the keel has an important role in the catamaran-type sail drone and the need for additional studies.*

Keywords: Maritime domain awareness, Autonomous marine robot, Catamaran-type sail drone, Marine energy harvesting, Keel effects analysis

1. **Introduction.** Recently, the global needs for the maritime domain awareness [1-3] such as a monitoring, an exploration and a reconnaissance are gradually increasing in civil and military application area. In order to satisfy these needs effectively, various marine robots are developed and applied globally [4].

Among marine robots, the autonomous marine robot is not affected by the dynamics of a tether cable while it requires a high intelligence level because it is operated by itself without human operator on the mother ship with the cable. However, the autonomous marine robot basically has the problem of the energy limitation due to its volume limitation.

To solve this problem, a catamaran-type sail drone [4] which is capable of harvesting of marine energies such as wind and solar had been proposed. It has abilities of the stability-based locomotion using a catamaran with no keel, an anemometer and a magnetic compass, the wind energy-based propulsion using sails [5-7], a wire and a servomotor, the solar energy-based propulsion using solar cells and thrusters and the rapidity-based maneuvering using rudders. This catamaran-type sail drone can effectively solve the energy problem in autonomous marine robot and has better performance in terms of stability.

However, it has not good straightness in all cases of the downwind, the crosswind and the upwind despite changing the sail and rudder angles because it has not the keel that can reduce the lateral force. To analyze the keel effects, the comparative study is performed.

The fundamentals of a keel design are described in Section 2 and the development of the considered sail drone is described in Section 3. Finally, the conclusions are summarized in Section 4.

DOI: 10.24507/icicelb.11.03.261

2. **Fundamentals of Keel Design.** Related to the fundamentals of a keel design, the example keel design methods according to the boat equipment design methodology [8] are explained as follows.

Generally, the area of the keel that is proportional to those of main and jib sails is expressed by

$$S = \frac{(C_1 + C_2)}{2} T_k = CT_k \tag{1}$$

where S is an area, C_1 and C_2 are upper and lower lengths respectively, T_k is a height and C is an average of upper and lower lengths.

For example, if the ratio of keel to sail is generally chosen 3.5%, the area of the keel is determined to 64.6 in Figure 1.

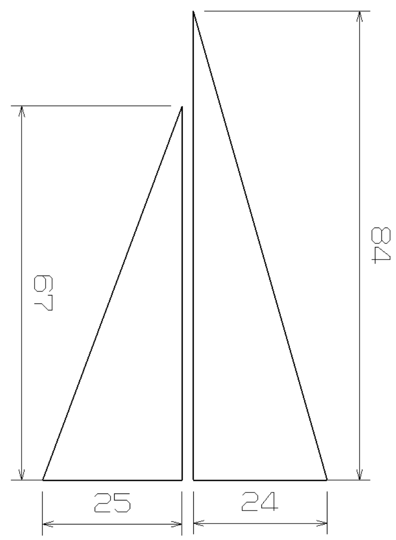

FIGURE 1. Example of area of main and jib sails

In addition, the taper ratio (TR) and the aspect ratio (AR) are expressed by

$$TR = \frac{C_2}{C_1} \tag{2}$$

$$AR = \frac{T_k}{C} \tag{3}$$

If the TR in Equation (2) and the AR in Equation (3) are decided when the area S is given, C_1, C_2 and T_k are calculated from Equation (1).

In order to decide the TR, the curve of the sweep angle and the TR is required and the sweep angle should be chosen by considering the keel performances.

If the sweep angle is increased, the durability becomes high and the drag force becomes large in the keel performances. The example of the keel performance according to the sweep angle is shown in Table 1.

TABLE 1. Example of keel performances according to sweep angle

	Sweep angle = 5	Sweep angle = 10	Sweep angle = 20
Durability	Low	Medium	High
Drag force	Small	Medium	Large

As the one design point in this study is reducing the drag force, for example, the sweep angle is chosen 5 degrees for reducing drag force. According to the curve of the sweep angle and the TR, the TR is determined to 0.4 when the sweep angle is 5 degrees.

In order to decide the AR, the keel performances according to the AR should be considered.

If the AR is increased, the durability becomes low and the roll damping becomes large in the keel performances. The example of the keel performance according to the AR is shown in Table 2.

TABLE 2. Example of keel performances according to AR

	AR = 1	AR = 2	AR = 3
Durability	High	Medium	Low
Roll damping	Small	Medium	Large

As the other design point in this study is increasing the durability and reducing the roll damping, for example, the AR is chosen 1 for increasing the durability. The durability problem in choosing the sweep angle is solved in choosing the AR. In this case, the roll damping problem does not occur because the restoring force of the catamaran is large.

From the above-mentioned procedure, the final keel shapes as the decision results of TR and AR have been designed and are shown in Figure 2.

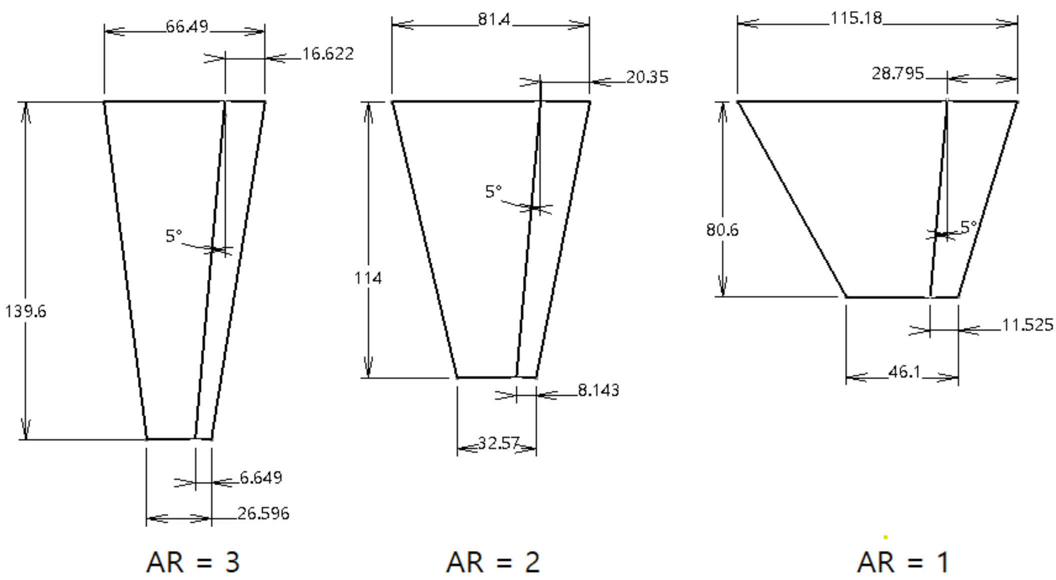

FIGURE 2. Example of final keel shapes

3. **Development of Considered Sail Drone.** Related to the development of the considered sail drone, the system engineering process (SEP) [9,10] as a global standard of the R&D methodology is executed as follows.

Based on the established operation concept, the requirement analysis is executed and consequently the requirements of the mobility, the stability and the maintainability are derived. Based on the requirement analysis, the functional analysis is executed and consequently the functions of the stabilizing-based locomotion function, the wind energy-based propulsion function, the solar energy-based propulsion function and the rapidity-based maneuvering function are derived [4].

Based on the functional analysis, the design is executed and consequently the hardware and software components are derived: The body part and the sensor part are implemented by using one catamaran with two keels that is designed in Section 2 and one magnetic compass related to the stabilizing-based locomotion function. The primary propulsion part is implemented by using two sails, one wire and one servomotor related to the wind energy-based propulsion function. The secondary propulsion part is implemented by using two solar cells and two thrusters related to the solar energy-based propulsion. The steering part is implemented by using two rudders related to the rapidity-based turning. The 3D modeling of these parts is executed by using the computer aided three dimensional interactive application (CATIA) program. This 3D modeling enables to develop the sail drone effectively in terms of time and feasibility. The modeling result of the sail drone is shown in Figure 3.

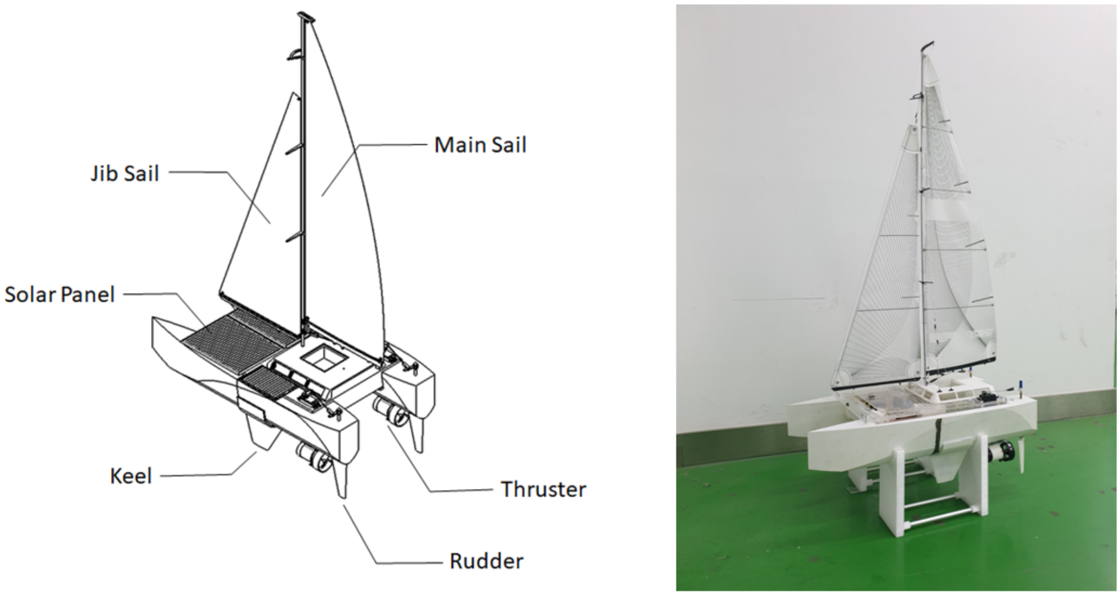

Figure 3. Modeling result and prototype of sail drone

Based on the design, the manufacturing is executed and consequently the hardware and software components are implemented: The 3D printing of these parts is executed by using the rapid prototyping (RP) equipment. This 3D printing also enables to develop the sail drone effectively in terms of time and feasibility. The prototype of the sail drone is also shown in Figure 3.

Based on the analysis, the design and the manufacturing, the test and evaluation are executed and consequently the functions and then requirements are satisfied.

The straightness was verified by testing the downwind sailing of 135 degrees, the crosswind sailing of 90 degrees and the upwind sailing of 45 degrees in three times respectively. This verification of the straightness is shown in Figure 4. The downwind sailing case, the straightness is slightly improved by changing the sail angle and controlling the rudder angle. The crosswind sailing case, the straightness is significantly improved. The upwind sailing case, the straightness is meaningfully improved. These mean that optimal sail and rudder angles can exist and the keel can reduce the lateral force according to the wind direction for heading control.

4. **Conclusions.** In this paper, the keel effects of a catamaran-type sail drone have been well studied. The development of the considered sail drone is summarized as follows: it requires the stabilizing-based locomotion using the catamaran with keel and magnetic compass to effectively implement the body and sensor parts of the sail drone; it requires the wind energy-based propulsion using the sail, wire and servomotor to effectively implement the primary propulsion part of the sail drone; it requires the solar energy-based propulsion using the solar cell and thruster to effectively implement the secondary propulsion part of

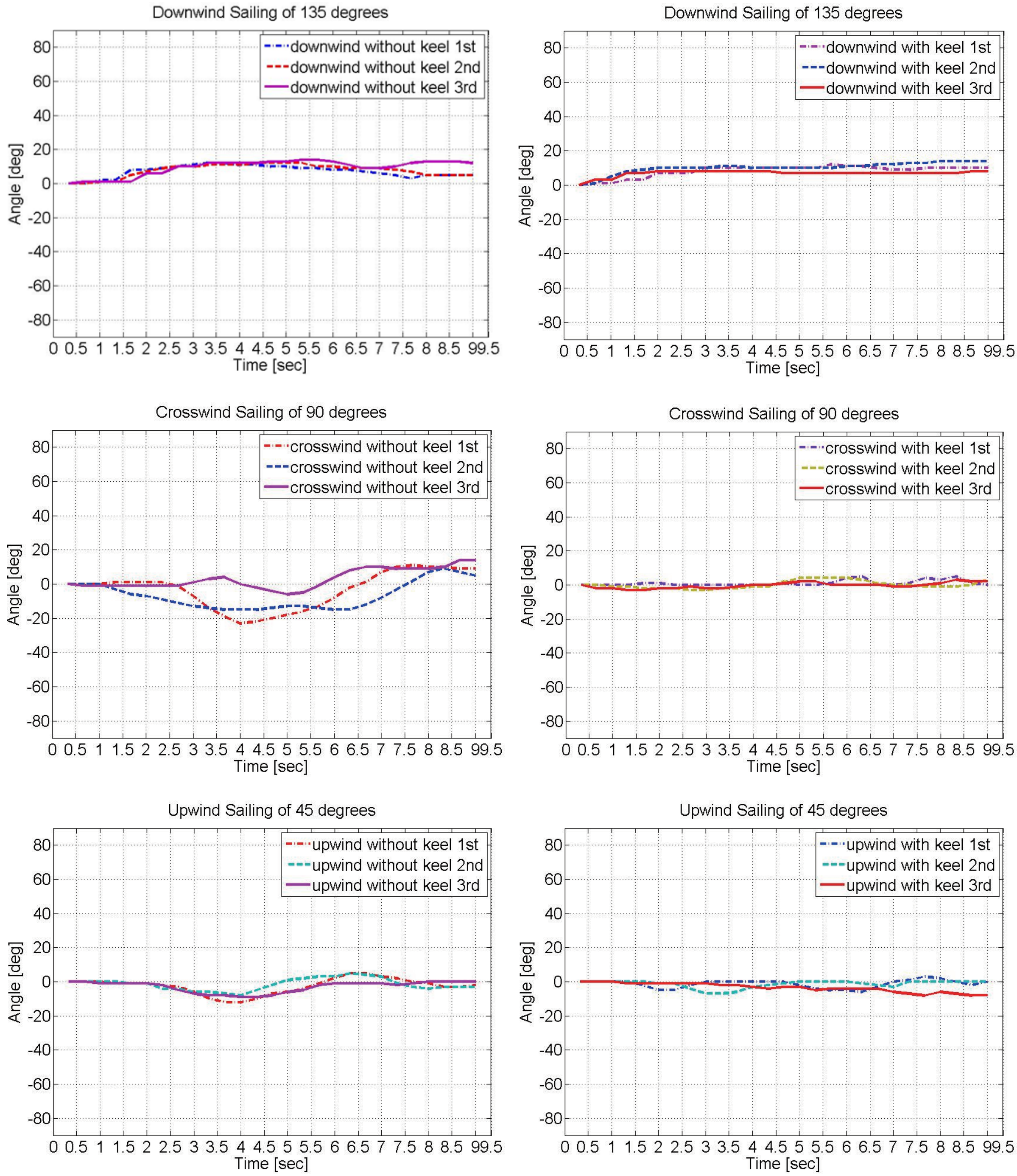

Figure 4. Verification of straightness

the sail drone; it requires the rapidity-based maneuvering using the rudder to effectively implement the steering part of the sail drone. The study results showed that the keel has an important role in the catamaran-type sail drone. In the future, additional studies such as a path control for more concrete mission completion of the sail drone will be conducted.

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