A FIXED-MOVABLE COMBINATION CONTROL SYSTEM FOR A HUMAN-POWERED SUBMARINE

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Abstract-The mission of the human-powered submarine team is to design and build a high-speed, controllable underwater vehicle. The team determined that the control system must meet the following criteria: create as little drag as possible, function efficiently, and have a quick response to the pilot's signals. Three different fin configurations are considered: a thrust vectoring system, a separate stability and control fin configuration, and fixed fins with movable trailing edge flaps. The three systems were simulated using a two-dimensional computer code, XFOIL. Results of turning moment and drag from each system are present, along with discussion. The fixed fins with control flaps were found to be the most efficient system, producing nearly 1/3rd the drag of the other two systems for the same control moment. A detailed description of the final design is presented as it was developed for Phantom IV.

I. INTRODUCTION

The Virginia Tech Human-Powered Submarine Team has been designing submarines for the last fourteen years. This team continues to try and improve the controllability of the submarine while designing a high-speed underwater vehicle. The control system for the human-powered submarine is important so the pilot can make it down the course as fast as possible. For this to happen the control system needs to create as a little drag as possible, function efficiently and have a quick response to the pilot's signals. There have been various types of control systems developed for Virginia Tech's three previous submarines. The goal of this paper is to analyze the past control systems and develop an efficient control system for the team's next submarine. This paper discusses three basic control systems based on two that the team previously used, and one new concept. The three systems are analyzed numerically and based on past experience. Results are present on the drag and turning authority of each system.

II. PAST CONTROL SYSTEMS

The Virginia Tech team has used several types of fin based control systems. The first was a set of movable fins placed behind the propeller, controlled by a set of wheels in the front of the submarine. This system was effective on Phantom II, the team's second submarine. The control fins not only produced hydrodynamic lift for turning the submarine, but also effectively vectored the thrust to produce large turning forces. However, this technique reduced the amount of thrust available to accelerate the boat down the course.

Another technique the team has used in the past was to mount a set of moveable control fins at the stern of the submarine and a set of fixed stability fins just aft of the center of gravity. This system, used on Phantom III, performed well. It provided the pilot with sufficient control without wasting thrust on control; however it required the use of eight fins, which each added to the total drag of the submarine.

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III. PRELIMINARY FIN DESIGN

Three basic fin configurations were investigated for the Phantom IV control system. From experience and research, the systems considered were: a fin-based thrust vectoring system, a system with moveable control fins and a set of static stability fins, and a system with a set of fins placed at the aft end of the boat with only a small movable flap on the trailing edge.

The thrust vectoring system, concept 1, consists of a pair of control fins located behind the propeller of the submarine which could be deflected to change the direction of the thrust, and turn the submarine. One fin is mounted vertically to control horizontal motion and the other is mounted horizontally to control depth. A set of streamlined supports had to be added to the aft end of the sub that went around the propeller and provided an attachment point for the control fins. This concept is shown in fig 1.

Figure 1. Example of fin based thrust vectoring system used on Phantom II.[5]

The second concept, shown in figure 2, consists of 4 movable fins located at the aft end of the submarine ahead of the propeller, and 4 static fins mounted just aft of the center of gravity. The static fins increase the area behind the submarine's center of gravity, which makes it naturally more stable. The movable fins are used to control the direction of the submarine. The fins are internally linked in horizontal and vertical pairs to control depth and horizontal motion respectively. As the angle of attack of the control fins is changed the lift produced by the fins creates a moment on the submarine which causes it to turn.

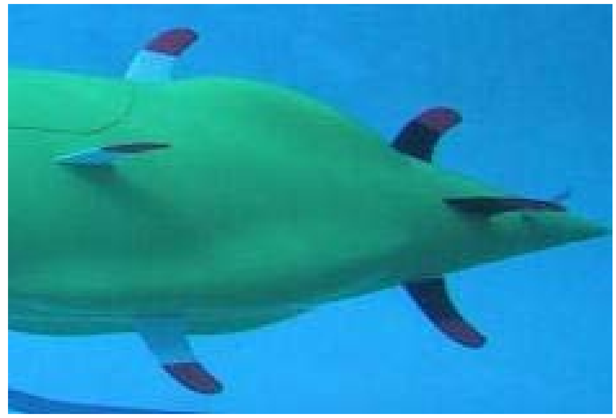

Figure 2. Example of fixed and movable fin system used on *Inviscid*.[4]

The third concept consisted of four fixed fins with moveable trailing edge flaps mounted at the aft end of the submarine. Fins served for stability and control purposes, but by combining the two elements of a fixed and moveable fin the system is more efficient. When the flap is moved the entire system produces lift which turns the submarine, not just the flap itself. This allows the total control area need to be reduced.

Figure 3. Example of third control concept used on Phantom IV.[5]

XFOIL, a numerical airfoil design code, is used to analysis the theoretical control moments and drag produced by each system. Results are presented for a range of control inputs for each concept with the submarine at no angle of attack and no side slip.[1] This program proves to be a good tool to analyze the drag over the three different proposed fin configurations.

IV. ANAYLSIS OF FIN DESIGNS

The three fin designs discussed above where researched and analyzed by using the program XFOIL and other boundary layer methods. The first two systems were tested with control deflections from 0 to 5°, the flapped system was tested for deflections of 0 to 3°. This is about the maximum angle a control fin would need to be deflected to correct the direction of the boat for a straight course.

The first system that was analyzed was the thrust vectoring system. It was modeled in XFOIL by the NACA 0012 airfoil because it is an easy airfoil to construct and has high angles of attack for stall. This design had two control fins located behind the propeller. Results from XFOIL and a WALZ boundary layer code show the drag on this setup was the largest of the three fin designs considered. Fig 4 shows that most of the drag from this system is caused by the fixed structure needed to hold the control fins in place. This structure was modeled using an NACA 0006 airfoil with a surface area of .155 m^2.

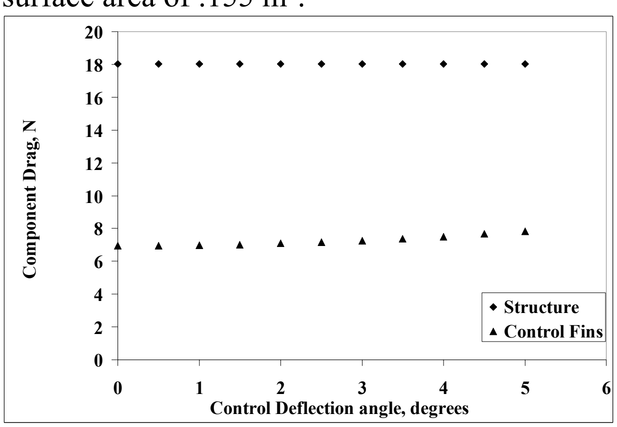

Figure 4. Drag breakdown between structure and control fin for thrust vectoring concept.

The high amount of drag the thrust vectoring system creates reduces the available propulsion. This system provides additional control power by the vectored thrust that is unnecessary since only minor control corrections need to be made.

A set of moving control fins with a set of stability fins was the second concept analyzed. The XFOIL model consisted of a fixed NACA 0006 airfoil 0.254 m aft of the center of gravity and a NACA 0008 airfoil 0.762 m from the cg used as the control fin. The NACA 0008 was used for the all moving control fins because it is a thin airfoil so it has low drag, but is large enough to avoid stall at moderate angles of attack. The NACA 0006 was used for the fixed stability fins because it also has low drag and the stall angle doesn't have a large effect on this airfoil since these fins are in line with the flow. The analysis of this system showed that the drag on this design is a little less than that of concept 1. The drawbacks to this system were the eight required fins and at high deflection angles, the fins were at a risk to stall. The drag breakdown for this system is shown in fig 5.

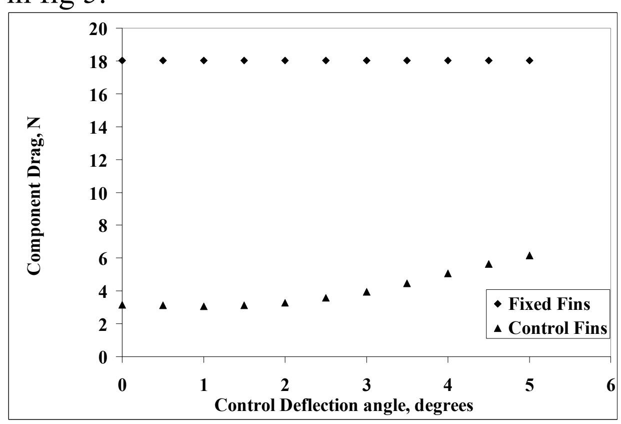

Figure 5. Drag breakdown for the second control system concept.

Finally the system of four fixed fins with moveable trailing edge flaps was evaluated. This system was also modeled in XFOIL with a NACA airfoil of 0012, however a trailing edge flap was used when looking at the drag and lift values at zero angle of attack. This airfoil was used for this design because the fin had to be thick enough for foam to fit inside of it to add buoyancy to the back of the boat. By bringing the fixed and movable parts of the fin together the overall system area was reduced, while maintaining equal effectiveness as the pervious systems. This results in a significant decrease in the drag of this system as shown in fig 6.

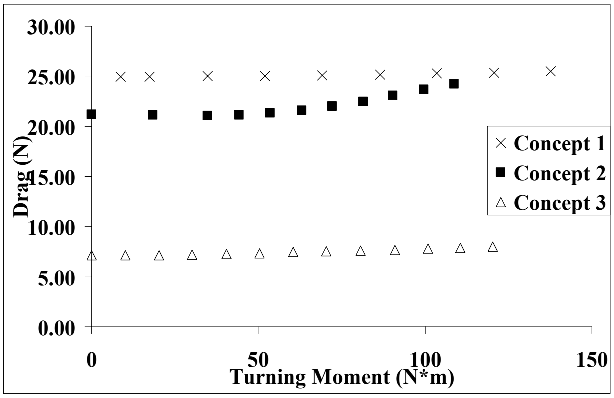

Figure 6: Turning Moment versus Drag for the three different concepts.

The third concept was selected because the overall drag was reduced, while still providing increased static stability and control authority similar to previous successful systems.

V. DETAILED DESIGN OF FINAL CONCEPT

Concept three was then designed for the Phantom 4 submarine since it had the least amount of drag. This design was developed based on previous experience and information provided by Dr Thomas Huang. The information showed that the control surface area needed to be between 25% and 30% of the side area of the submarine hull for the vertical fins, and similarly for the horizontal fin. Using this method the control surfaces would be sized to 0.098 m^2 for the vertical control surfaces and 0.065 m^2 for the horizontal control surfaces. The total surface area was split so that the fixed portion of the fin was 55% of the area and the remainder was the movable portion. All fins were made to 0.091 m^2, which is in between the two suggested sizes. This was done for several reasons. First, the shape of the submarine was inherently stable in the lateral direction. The large flat sides helped to naturally stabilize the submarine. The pilot also had a better sense of direction in the lateral plane than the horizontal plane. Therefore the pilot's ability to control the sub in the lateral direction was naturally better so the vertical fin size was reduced.

To aid in construction of the fins, a simple trapezoidal planform was used for the fixed portion of the fins. The height of the fins was chosen based on several criteria, first the fins should have as large an aspect ratio as possible to improve efficiency, but this was limited by structural constraints. The fin span should not be much greater than the maximum diameter of the submarine, so that they would not break. This proved to be the limiting constraint and the fin height was set at 0.365 m. With a width of 0.94 m the total span allowed the submarine to fit out the door of the lab.

With the span fixed at 0.94 m, the shape of the fins was designed to provide the required area. The moveable fin chord was 0.106 m and the fixed portion of the fin had a tip chord of 0.091 m and a root chord of 0.302 m. This resulted in an effective aspect ratio of less than three. To increase the effective aspect ratio an endplate was added to each fin. The endplate reduced the bleed flow around the fin tip, and made the flow along the fin more two-dimensional. The endplate also served the purpose of connecting the fixed and movable portion of the fin, and provided something for the movable fin to mount to.

The airfoil section varied along the span of the fin from a NACA 0018 at the tip to a 0006 at the root, so that the maximum thickness was always 1.9 cm, this was done for several reasons. One reason was the more rounded the airfoil the less likely the flow would separate from the fin surface. A symmetric airfoil was used for its low drag and because the fins were needed to produce lift in both directions. The thickness was held constant along the fin because a piece of foam was built into each fin to help provide buoyancy in the back of the submarine. The thickness of the fin also remained high at the tip so that the endplate was able to secure to the fin and carry the loads created by the movable fin.

The fins were mounted in a staggered configuration with the elevators mounted 5.1 cm behind the rudders for two reasons. First, because it gave the pilot more control of pitch and depth by placing the elevators farther from the center of gravity. Second, because the fins were linked together inside the boat, they had to be staggered so that the control arms did not interfere with one another during operation. The maximum deflection allowed in the flaps was 15°, which translates to a control movement of 1.9 cm in either direction; therefore, the 5.1 cm step was required to prevent interference.

VI. CONCLUSION

Of the three systems analyzed in this study the fixed fin with moving flaps system performed the best. By combining the effects of the fixed and movable fins into one unit the system becomes more efficient and reduces total system size requirements. Results showed that fixed supports and stability fins produce over half the drag in systems using them, while that part of the system produces not control forces. The most efficient systems consist of as few parts as possible and reduce system size to minimize drag.

VII. REFRENCES

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