Naval Architectural Aspects in The Design of a Hybrid Hydrofoil-Submarine Craft.

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Abstract. Indonesia is the largest archipelago country in the world. Territorial disputes and illegal fishing are some main threat of maritime defense. One of the solutions is to provide a multi-mission vehicle. Submarine craft has the advantage of undetectable to ambush the threats. Hydrofoil craft has the advantage of higher speed than the conventional high-speed craft. The purpose of this research is to combine two distinctive and one conventional concept into one craft. This craft has to has a light structure to support hydrofoil mode and able to submerge. The material of the hull uses aluminum and for wing and propulsion system structure use carbon steel. This craft uses hydraulic propulsion that the main engine moves the hydraulic pump. The hydraulic pump flows oil to the hydraulic motor where located in the nacelle. The hydraulic motor rotates the shaft and propeller. This propulsion system requires the propeller to submerge in the water, therefore the strut which supports the wing and propulsion system has to design retractable. All important parameters are included in this paper. (Keywords: hydrofoil, submarine, conventional, hydraulic propulsion, Aluminium)

1. Introduction

The hybrid-submarine hydrofoil craft, the crocodile craft, built to operate in three modes such as conventional mode, hydrofoil mode, and submarine mode. This craft is a result of Ristek-Dikti research program designed to secure Indonesia’s seawater region, especially the western part, which relatively shallow. As we know that pirating, smuggling, and territorial violating in Indonesia’s seawater are endanger national sovereignty that has to tackle. This craft has a length 12 meter and a width 3 meter designed in high-speed in hydrofoil mode and undetected in submarine mode, as a result, it increases shock effects because those illegal fishing vessels do not recognize it. It is propelled by 2x350 Hp diesel engine with 40 knots in hydrofoil mode, 15 knots in submarine mode, and approximately 25 knots in the conventional craft. This craft uses Aluminium as the main hull construction material and carbon steel in the strut and wing system. The design is the result of optimized space and craft’s maximum speed. The struts are designed to be able to lift the craft in hydrofoil mode and able to rotate in certain degrees and the craft uses a hydraulic propulsion system because it should be able to deliver thrust in every mode as the picture is shown below[1][2][3][4][5][6].

![Figure 1. The Croc Design Concept.](image-url)
Philosophically, hydrofoil or submarine craft is illustrated as two circles below. In the design process, moving those circles close to each other makes a feasible area of this craft that relatively has a narrow area. Hydrofoil is a light structure as this craft has to move upward above free surface and wave whereas submarine is a heavy structure as it has to submerge below free surface. Hence, hydrofoil can move faster but still detected by radar because it is still above free surface. Submarine, on the other hand, can move slowly but it is undetected because it is under water, This is the factor try to maintain so that this type of craft has two importance factor in defense, it is fast and at the same time undetected[1][2][3][7].

2. Methods
The design thinking method illustrated in the following flowchart below. At the design step, the craft’s form and weight obtained at the hydrofoil design, and the size of the ballast tank in submarine mode also should be considered in this step. This condition is also applied to estimate engine power, strut and wing specification, hydraulic pump, and hydraulic motor. The size and location of the ballast tank obtained from the craft’s static stability. After this step, submarine and conventional mode craft can be considered. The towing tank test is taken as a reference for resistance calculation and craft performance for hydrofoil mode, submarine mode, and conventional mode. The method can then be describe in the following figure[1][2].

\[ \sum F = 0, \sum M = 0 \] (1)

Figure 2. Design Thinking Flowchart.

This flow chart shows that the design should start from design in hydrofoil mode in which the equilibrium of
should be satisfied during this mode[1][2]. The first consists of the resistance of all components such as
the resistance of wing, nacelle, propeller etc and must be equal to the propulsion of the craft. The
dimension of the wing, including chord and type of the wing section, is set up so that its resistance is
found. The dimension is designed such that if the Lift and Drag force is not enough, it is then re-designed
until it is able to support the craft to get its equilibrium. It is found that the chord size of the aft wing is
65cm and the fore chord is 40cm. The propeller is chose to be B series 3 blades with diameter 50 cm. It
is also found that the engine power is 2 x 350 HP and is designed using hydraulic propulsion system.
As the craft has to be designed submerge then it is need to design the hull to have the equality of
weight and volume displacement which result in the specific form. The main ballast tank is placed in
the middle and in the fore and after part of the hull. The fore and after part is used as trim and
compensating tank to arrange the trim of the hull.

3. Hull Configuration

Hydrofoil craft is designed to be light structure. However, the submarine structure requires heavy
structure. To achieve these conditions and space requirements, therefore the hull is designed to
accommodate two main engines and ballast tank space requirements. Two fixed wings at a half-length
to the fore of the hull have to build to increase lift force when take-off in hydrofoil mode. At the top of
the craft, there is a sail as an envelope of the piping system that connects installation in the engine room
and accommodation room. Therefore, the craft able to control in accommodation room located in the
fore of the craft. This craft designed for four crews consists of a pilot, a co-pilot, and two researchers.
The main ballast tank is located in mid-ship to not affect the trim of the craft, fore and stern ballast tank
use when necessary to control the trim. The engine room is located in the stern, but the fuel tank is
located in mid-ship, in which the same room as the main ballast tank.

The propulsion system of this craft uses hydraulic propulsion which the main engine propels a
hydraulic pump. The hydraulic pump flows oil to the hydraulic motor in the nacelle uses two hose or
flexible pipe. The hydraulic motor connects with the shaft system to propel the propeller. The result of
the hydrofoil calculation obtains the length of the stern wing chord is 65 cm and the fore wing system
is 40 cm. The essential characteristics of hydrofoil craft is that the craft be supported by buoyancy force
when floating on the water and by dynamic lift of the foil while flying above the water. The lift of the
foil is the function of foil area, lift coefficient, and dynamic pressure ($\frac{1}{2}\rho v^2$). The basis formula of foil
area to support its weight is therefore [11],

$$S = \frac{W}{0.5 \rho v^2 c_L} = \frac{790\Delta}{c_Lv_k^2}$$  \hspace{1cm} (2)

Where,
\begin{align*}
S & = \text{Total area of foil} \text{ ft}^2 \\
W & = \text{Weight} \text{ lb} \\
\rho & = \text{density of water} \left( \text{lb/ft}^2\text{sec}^2 \right) \\
v & = \text{speed} \text{ ft/sec} \\
v_k & = \text{speed} \text{ knots} \\
c_L & = \text{lift coefficient} \\
\Delta & = \text{weight} \text{ tons}
\end{align*}
The configuration of the craft is as shown below[5][6].

![Diagram of the craft configuration]

**Figure 3. General Arrangement of The Crocodile.**

4. **Static Calculation of Hydrofoil Craft**

Hydrofoil craft calculation obtains by configuring various chord geometry of wing. The best configuration obtains at a trim angle of 4 degrees [2]. The dihedral angle of the fore and stern wing are the same approximately 40 degrees. The hydrostatics can be seen as follows,

![Graph of static characteristics]

**Figure 4. Hydrostatic Curve of The Crocodile.**

This graph is calculated for draft until 1 meter which is the draft for surface mode. This draft is about half of the depth of the craft. This graph shows the static characteristics of the craft. This graph is produced using Maxsurf software [10].

5. **Polygon Diagram**

Some of critical conditions are obtained by running the craft model in Maxsurf software describes below:
Table 1. Various Static Stability Position of Crocodile Ship with Reference Point at Keel Plate

| No. | Position                                                                 | Draft FP [m] | Draft AP [m] |
|-----|---------------------------------------------------------------------------|--------------|--------------|
| (1) | Hydrofoilcraft condition with the fore and the stern strut both in perpendicular position | 1.028        | 1.052        |
| (2) | Hydrofoil craft condition with the fore and the stern strut both in perpendicular position with fully ballast water | 1.725        | 1.325        |
| (3) | Submarine craft condition with the fore strut rotates in maximum position and the stern strut rotates 90 degrees without ballast water | 0.693        | 1.346        |
| (4) | Submarine condition with the fore strut rotates in maximum position and the stern strut rotates 90 degrees with ballast water | 1.572        | 1.517        |
| (5) | Conventional craft condition with the strut is in maximum-rotated position and the stern strut rotates 45 degrees. | 0.761        | 1.250        |

Figure 5. Polygon Diagram shown as respect to position number at Table 1.

Figure 6. The Crocodile Static Stability Condition Respect to Position Number at Table 1.
5. Resistance Calculation of Hydrofoil Craft

The resistance calculation of hydrofoil craft that affected by force and moment and has 3 factors:

1. Hydrodynamics forces consist of [8][9][10]:
   a. Wave making resistance
   b. Flows around the foil and its interaction
   c. Current

2. Aerodynamics forces that caused by upper surface craft’s body interact with airflows

3. Propulsion forces that caused by the propeller and its propulsion system

Equilibrium condition could be achieved if:

\[
\sum F_H \left( DH, \tau, \frac{\delta}{\alpha}, T \right) = 0, \text{Horizontal forces equilibrium} \tag{3}
\]

\[
\sum F_V \left( DH, \tau, \frac{\delta}{\alpha}, T \right) = 0, \text{Vertical forces equilibrium} \tag{4}
\]

\[
\sum M \left( DH, \tau, \frac{\delta}{\alpha}, T \right) = 0, \text{Equilibrium Moment} \tag{5}
\]

The design of the Crocodile has the biggest weight distribution at the stern of the craft. Hence the most suitable foil configuration is canard, as shown in the figure above. The canard configuration has a bigger stern wing dimension than the fore wing.

The hull form of the Crocodile is not simply adopted conventional high-speed as illustrated above but it has to has knuckle in the mid-section which a combination of conventional high-speed planing craft and hydrofoil craft.
The resistance of the hydrofoil ship is formulated below:\cite{8}\cite{9}\cite{10}:

\[
RT = RH + DFL + DST + RAP + RAA + DW
\]

(6)

Which,

\[
RH = \text{Resistance of Hull Form}
\]

\[
DFL = \text{Resistance of the Foil}
\]

\[
DST = \text{Resistance of the Struts}
\]

\[
RAP = \text{Appendages Resistance}
\]

\[
RAA = \text{Air Resistance}
\]

\[
DW = \text{Wave Resistance}
\]

6. Dynamics Ship’s Motion

The equation of hydrofoil craft is expressed below \cite{8}\cite{9}\cite{10}:

\[
m(\dot{u} + qw - rv) = X + mg \sin \theta
\]

(7)

\[
m(\dot{v} + ru - pw) = Y - mg \cos \theta \sin \phi
\]

(8)

\[
m(\dot{v} + ru - pw) = Z - mg \cos \theta \sin \phi
\]

(9)

\[
\dot{p}l_{xx} + qr(l_{zz} - l_{yy}) = K
\]

(10)

\[
\dot{q}l_{yy} + rp(l_{xx} - l_{zz}) = M
\]

(11)

\[
\dot{r}l_{zz} + pq(l_{yy} - l_{xx}) = N
\]

(12)

These equations are used to check whether the craft is stable in hydrofoil mode under a specific wave type. The equations are run in 200 seconds, and the motion of the craft is recorded.

7. The Software

Using all equations above, the resistance calculation of hydrofoil craft requires input and output as shown below \cite{8}\cite{9}\cite{10}:

| General Input Data | CANARD |
|-------------------|--------|
| Foil area distribution type | CANARD |
| Total craft weight | 15000.00 [kg] |
| X-coordinate C.O.G. | 3.40 [m] |
| Z-coordinate C.O.G. | 0.95 [m] |
| Projected chine length of hull | 10.00 [m] |
| Average chine beam | 2.50 [m] |
| Mid-ship deadrise angle | 20.00 [deg] |
| Zero speed trim angle | 2.30 [deg] |
| Design speed trim angle | 0.00 [deg] |
| Hull clearance at design speed | 1.00 [m] |
| Density of water | 1025.00 [kg/m3] |
| Temperature of water | 15.00 [deg-C] |
| Foil roughness allowance | 0.00040 |
| Hull correlation allowance | 0.00040 |
| Ambient pressure | 99600.00 [N/m2] |

| Propulsion Properties | 3 |
|------------------------|---|
| Propulsion type/ IPROP | 3 |
| Thrust vector angle | 0.00 [deg] |
| X-coord. thrust vector | 0.90 [m] |
| Y-coord. thrust vector | 2.09 [m] |
| Z-coord. thrust vector | -1.68 [m] |
| Number of Propulsion units | 2 |
Table 4. Foil System Properties Input Data.

| Panel No. | X- Coord. 1 [m] | X- Coord. 2 [m] | Y- Coord. 1 [m] | Y- Coord. 2 [m] | Z- Coord. 1 [m] | Z- Coord. 2 [m] |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1         | 9.67            | 9.67            | -2.14           | -0.38           | 0.00            | -1.48           |
| 2         | 9.67            | 9.67            | -0.38           | 0.38            | -1.48           | -1.48           |
| 3         | 9.67            | 9.67            | 0.00            | 2.14            | -1.48           | 0.00            |
| 4         | 9.67            | 9.67            | -0.38           | -0.388          | 0.00            | -1.48           |
| 5         | 9.67            | 9.67            | 0.38            | 0.38            | -1.48           | 0.31            |
| 6         | 9.67            | 9.67            | -0.38           | 0.00            | -1.48           | -1.48           |
| 7         | 9.67            | 9.67            | 0.38            | 0.00            | -1.48           | 0.31            |
| 8         | 1.61            | 1.61            | -0.63           | 0.38            | 0.00            | 0.31            |
| 9         | 1.61            | 1.61            | -0.63           | 0.00            | -1.68           | -1.68           |
| 10        | 1.61            | 1.61            | 0.00            | 0.63            | -1.68           | -1.68           |
| 11        | 1.61            | 1.61            | 0.63            | 2.93            | -1.68           | 0.00            |
| 12        | 1.61            | 1.61            | -1.25           | -2.93           | 0.41            | 0.00            |
| 13        | 1.61            | 1.61            | -0.63           | -0.63           | 0.20            | -1.68           |
| 14        | 1.61            | 1.61            | 0.63            | 0.63            | -1.68           | 0.20            |
| 15        | 1.61            | 1.61            | 2.93            | 1.25            | 0.00            | 0.41            |

Using that input for a certain configuration, the hydrofoil mode can be ensured to be stable. Hence, at the end of the iteration, results are as follows

Table 5. Propeller design output data.

| Propeller Design Data          |
|--------------------------------|
| Pitch-diameter ratio           | 1.4  |
| Blade area ratio               | 1.000|
| Open Water Efficiency          | 0.691|
| Number of revolutions          | 2720.3 [1/min] |
| Delivered thrust               | 9.2 [kN] |
| Absorbed torque                | 0.9 [kNm] |
| Delivered power                | 253.5 [kW] |

8. Towing Tank Experiment

Three experiments have been carried out in the towing tank under the conventional mode, hydrofoil mode, and submarine mode as shown in the following figure, with the following results [9][10]

Table 6. Hydrofoil Mode in Towing Tank Test.

| No | V Ship (Knot) | V Ship (m/s) | V model (Knot) | Strip Chart (Kotak) | Resistance Model (Kg) |
|----|---------------|-------------|---------------|--------------------|-----------------------|
| 1  | 4             | 2.0576      | 0.6507        | 0.0000             |                       |
| 2  | 6             | 3.0866      | 0.9760        | 0.0000             |                       |
| 3  | 8             | 4.1152      | 1.3013        | 0.0000             |                       |
| 4  | 10            | 5.1440      | 1.6267        | 5.00               | 0.1124                |
| 5  | 12            | 6.1728      | 1.9520        | 10.00              | 0.2247                |
| 6  | 14            | 7.2016      | 2.2773        | 17.00              | 0.3820                |
| 7  | 16            | 8.2304      | 2.6027        | 31.50              | 0.7079                |
| 8  | 18            | 9.2592      | 2.9280        | 70.00              | 1.5730                |
| 9  | 20            | 10.2880     | 3.2534        | 84.00              | 1.8876                |
| 10 | 22            | 11.3168     | 3.5787        |                    | 0.0000                |
Table 7. Convention Ship Mode in Towing Tank Test.

| No | V Ship (Knot) | V Ship (m/s) | V model (m/s) | Strip Chart (Kotak) | Resistance Model (Kg) |
|----|---------------|--------------|---------------|---------------------|----------------------|
| 1  | 4             | 2.0576       | 0.6507        | 0.0000              | 0.0000               |
| 2  | 6             | 3.0864       | 0.9760        | 5.50                | 0.3667               |
| 3  | 8             | 4.1152       | 1.3013        | 14.50               | 0.9667               |
| 4  | 10            | 5.1440       | 1.6267        | 28.00               | 1.8667               |
| 5  | 12            | 6.1728       | 1.9520        | 48.00               | 3.2000               |
| 6  | 14            | 7.2016       | 2.2773        | 6.50                | 3.2500               |
| 7  | 16            | 8.2304       | 2.6027        | 5.50                | 3.7500               |
| 8  | 18            | 9.2592       | 2.9280        | 8.00                | 4.0000               |
| 9  | 0             | 0.0000       | 0.0000        | 0.0000              | 0.0000               |
| 10 | 0             | 0.0000       | 0.0000        | 0.0000              | 0.0000               |

Table 8. Submarine Mode in Towing Tank Test.

| No | V Ship (Knot) | V Ship (m/s) | V model (m/s) | Strip Chart (Kotak) | Resistance Model (Kg) |
|----|---------------|--------------|---------------|---------------------|----------------------|
| 1  | 4             | 2.0576       | 0.6507        | 0.0000              | 0.0000               |
| 2  | 6             | 3.0864       | 0.9760        | 1.50                | 0.4054               |
| 3  | 8             | 4.1152       | 1.3013        | 5.50                | 1.4865               |
| 4  | 10            | 5.1440       | 1.6267        | 9.00                | 2.4324               |
| 5  | 12            | 6.1728       | 1.9520        | 17.00               | 4.5946               |
| 6  | 14            | 7.2016       | 2.2773        | 0.0000              | 0.0000               |
| 7  | 16            | 8.2304       | 2.6027        | 0.0000              | 0.0000               |
| 8  | 18            | 9.2592       | 2.9280        | 0.0000              | 0.0000               |
| 9  | 0             | 0.0000       | 0.0000        | 0.0000              | 0.0000               |
| 10 | 0             | 0.0000       | 0.0000        | 0.0000              | 0.0000               |

Figure 9. Experiment conducted in towing tank.

A wooden model experiment with length 1.1 meter, the experimental result is then extrapolated to find the resistance of full-scaled using ITTC extrapolation skin [2].

9. Manufacturing Process

The making of the Croc prototype is underway and now is about 90%. Hull is almost finished, and only the propulsion system and the control engine is not yet finished. The strut and wing are already installed but left only the piston and its equipment.
10. Conclusion

Naval architectural aspects of Crocodile-Hydrofoil craft is presented. The craft is designed using Aluminium material with the wing is made of carbon steel. The craft uses NACA 16 type Canard with surface piercing wing system. The struts are designed retractable to make certain angle needed for every mode. The principle dimension of the craft is $L = 12 \text{ m}$, $B = 3 \text{ m}$, $H = 3 \text{m}$, with engine power $2 \times 350$ HP with design speed 35 knots for hydrofoil mode, 25 knots for surface speed and around 15 knots for submerge mode. This craft is designed for 4 crews, 1 pilot, 1 co-pilot and 2 researchers.

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