Design, manufacture and flight test of an Electric Ducted Fan (EDF) powered cruise missile

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Abstract. The purpose of this paper is to find the most optimal design for the PASOPATI cruise missile regarding its endurance, maneuverability, and easy manufacture process. Using pre-sizing methods to design and ANSYS Fluent to simulate the cruising condition, it is possible to find the optimal design for this iteration of the PASOPATI cruise missile. The simulations and flight test yielded several data of the design, such as the flight altitude, endurance, and cruising speed for this iteration. The final prototype design of the missile obtain has a specification as follows: 130 km/h average velocity, 13.33 minute endurance, and 280 meter flight altitude.

1. Introduction
A cruise missile is a guided missile with a large warhead that is used against terrestrial target, which remains in the atmosphere and flies the major portion of its flight path at a relatively constant speed. It is required for a cruise missile to fly long distance and also hits with high precision. In recent years, advances in the field of engineering also causes modern cruise missile to be able not only to deliver the warhead, but also to scout the target area and also fly non-ballistic and on a low altitude. The literature study was conducted in the process of researching some pre-existing cruise missiles. ALCM (Air Launched Cruise Missiles) A, ALCM-B, and TOMAHAWK, can be used as a reference because three missiles are the same type of missiles, with similar missions, and have the same guidance systems.

ALCM-A and ALCM-B are the former of TOMAHAWK, both of the missiles are the basic design of TOMAHAWK missile. ALCM-A and ALCM-B was introduced by Boeing. ALCM-A has 4 meters long with a range of about 1200 km and weighing about 900 kg [1]. ALCM-B has 5.97 meters with a range above 2400 km, and weighing about 1270 kg. Both of ALCM missiles has a velocity about 0.75 Mach, with a Tercom (Terrain Correlation and Matching) and inertial as a guidance systems.

The Tomahawk was introduced in the 1970s by General Dynamics, with a speed of up to 890 kilometers per hour. The working altitude is 30 to 50 meters [1], with a Williams International F107-WR-402 Engine using TH-Dimer fuel [2].

Being one of the most advanced and well known cruise missile types, the Tomahawk obviously serves as a design inspiration for PASOPATI. The PASOPATI serves as a blueprint for future mass-produced Indonesian cruise missiles. The first iteration itself is able to travel for 40 kilometers at the speed of up to 130 kilometers per hour. The engine used in this iteration is an Electric Ducted Fan (EDF) Mercury Aluminum Alloy 104 mm 11 Blade EDF Unit CCW (6S 1900KV), which gives a thrust of 3500 g at 115 A.

As one of a newer cruise missile model, PASOPATI has to be able to pass tests regarding its ability, from its maneuverability, its lift and drag, to its thrust before it is able to be mass produced. With the state of computer technology nowadays, data from a simulation instead of having to use experimental was able to be collected, especially using Computational Fluid Dynamics (CFD). By using CFD can help with compressing the overall cost and time needed in collecting data needed for further research.
A CFD simulation tool that is commonly used is ANSYS Fluent, able to simulate both incompressible and highly compressible range of flow. With many meshing options, the PASOPATI uses the unstructured mesh to provide data during its development process. With the aerodynamics simulations results, it will be able to conclude on what factors to improve on the next iteration of the design.

2. Methodology

In this research, several methods were used to design and find the aerodynamic characteristics of the designed missile. The methods used are based on several traditional methods explained by Raymer [3] and Anderson [4], where the writers took into consideration the aspects of an Unmanned Aerial Vehicle and pre-sizing methods, empirically and analytically, and then simulated the model using Computational Fluid Dynamics (CFD).

The next section will explain several steps of the methodology used during the design phase. Starting from a conceptual design, where the first concept is developed from the needs of the mission, and the preliminary design where every component of the missile is analyzed, breaking down the frame to parts, and then the design prototype to test the results of the previous iteration.

2.1. Conceptual design

Conceptual design is essentially a phase where the layout configuration of the missile is developed by first estimating the geometry, weight, aerodynamics aspects, and the performance based on the design requirements [5]. The conceptual design is based on a prior study about the previously available missile designs and adapting several features for the pre-sizing method used. Basic CFD analysis is then used to test and evaluate the preliminary design.

2.1.1. Requirements

The first iteration of the PASOPATI missile is focused on the optimization of the controls and the characteristics of the missile on lower velocity. To simplify the development of the missile, an electric system is chosen since an electric system has the advantage of a more constant flight weight and power compared to other systems. The engine used in this iteration is Mercury 90 mm Electric Ducted Fan (EDF) with the maximal thrust of 3.6 kg. Based on the system used and the engine, the design requirements of the first generation of the missile are as follows:

| Table 1. Design requirement of PASOPATI cruise missile. |
|-------------------------------------------------------|
| Loiter speed                                         | 100 km/h                  |
| Maximum speed                                        | 150 km/h                  |
| Endurance                                            | 40 km                     |
| Payload weight                                       | 1 kg                      |
| Altitude                                             | 200 m                     |
| Material                                             | Composite                 |

2.1.2. Design procedure

The first step is to determine which aspects are to be pre-sized using the methods defined by Raymer [3], and to fit several aspects for an Unmanned Aerial Vehicle.

The first step of pre-sizing is to make a rough estimate of the Gross Take-off Weight (GTOW or \( W_0 \)), which is the total weight of the missile in the beginning of the mission. For the missile system, the loads taken into consideration are the payload weight \( (W_p) \), fuel weight \( (W_f) \), and empty weight \( (W_e) \).

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W_0 = W_p + W_f + W_e
\]
Payload weight refers to the total weight of the electronic systems (e.g. flight controller, radio communications, camera, sensors, etc.) listed on the design requirements and the weight of the attached warhead.

Empty weight is the weight of the vehicle itself, during the design phase. The weight is estimated based on the basic data of the missile with the same configuration and requirements that is still operating now.

Fuel weight is based on the fuel consumption of the missile during the length of the mission segment. In this case, because an electric system is used for the first iteration of the PASOPATI missile, the fuel weight can be considered a constant weight because a Lithium Polymer battery is used as the power source.

2.1.2.1. Preliminary design

Preliminary design is the phase of design where there would be no more major design changes. The configuration arrangement can be expected to be the same with the shown concept design. At some point late in preliminary design, even minor changes are stopped when a decision is made to freeze the configuration [3].

During preliminary design, PASOPATI cruise missile featured a fixed wing and tail layout to maintain the design to be lighter and more rigid. It has “+” type tail configuration, this feature is intended to make the missile has better longitudinal stability [6] at low speed, which can also make the missile more stable at low speed and will be easier to launch without external force. Low aspect ratio wing gave the missile has better maneuverability [7] and more rigid structure can be easier to achieve, it was arranged in the circumferential direction symmetrically to ensure the aerodynamics characteristics in axial symmetry [8].

The design of PASOPATI missile interior layout is based on the needs of the specified weight distribution to maintain the longitudinal stability and the electronic component restriction so it doesn’t interfere others component. To fulfill the endurance purpose during cruising, the engine used for the first model is an Electric Ducted Fan, placed in the back of the missile. The middle section of the missile is used to mount the electrical modules and power pack, such as the flight controller and the battery. The front section of the missile is used to store payload or warhead. The mechanical control for the missile mostly uses the flap and aileron on the wings. The flaps on the rudder and elevator are used to control pitch and yaw, and the ailerons are used on the wings to control the roll of the missile. The “+” type tail configuration is used to make the surface control of rudder and elevator wider and make pitch and yaw control more responsive. All of these features of the design are purposely done to achieve the desired aerodynamics characteristic and to achieve that requirements, it need to simulate the case with computational fluid dynamics to test and evaluate the base design in purpose to improve the design.

The CFD method uses commercial code ANSYS Fluent R18.0 and modelling the fluid with Autodesk Inventor 2017. To achieve the ideal result of aerodynamics characteristics and simplify the calculation, the geometry model is simplified. The simplification included removing some antenna feature and gate connection. The fluid mesh used is unstructured meshing created by ANSYS meshing.

2.1.2.2. CFD methodology

The CFD method was adopted for the research. Steady-state calculations were used to compute the overall performance of PASOPATI missile using ANSYS Fluent R18.0. The Reynold-Averages-Navier-Stokes (RANS) equations were applied here to describe the turbulent flow [9]. Pressure-based type solver with the coupled scheme was used to compute the flow field. The implicit formulation was selected for the solution method. The Least Square Cell Based for gradient. Second Order Upwind scheme for density, momentum, turbulent kinetic energy, specific dissipation rate and energy were selected for spatial discretization [10].
The turbulence model uses k-ε two-equation model that is on the basis of the RANS equation [8][11]. The RANS equation itself is expressed as:

$$\rho \frac{du_i}{dt} = \frac{\partial F}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_t}{\partial x_t} \right) \right] + \frac{\partial}{\partial x_j} \left( -\rho u_i u_j \right)$$

(2)

The k-ε equation is the turbulence model with two equations, which are turbulent kinetic energy equation (k), and dissipation equation (ε). In this paper standard model k-ε is used, because of a constant fluid property. For the standard k-ε equation model is as follows:

Turbulent kinetic energy (k) equation:

$$\frac{\partial k}{\partial t} + u \frac{\partial k}{\partial x} + v \frac{\partial k}{\partial y} = \frac{\partial}{\partial x} \left( \nu_T \frac{\partial k}{\partial x} \right) + \frac{\partial}{\partial y} \left( \nu_T \frac{\partial k}{\partial y} \right) + P - D$$

(3)

Dissipation (ε) equations:

$$\frac{\partial \varepsilon}{\partial t} + u \frac{\partial \varepsilon}{\partial x} + v \frac{\partial \varepsilon}{\partial y} = \frac{\partial}{\partial x} \left( \nu_T \frac{\partial \varepsilon}{\partial x} \right) + \frac{\partial}{\partial y} \left( \nu_T \frac{\partial \varepsilon}{\partial y} \right) + \frac{\varepsilon}{k} \left( C_{\varepsilon 1} P - C_{\varepsilon 2} D \right)$$

(4)

P (production term) is formulated as:

$$P = 2 \nu_T \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right] + \nu_T \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2$$

(5)

Destruction term D is given by ε.

From the calculation above can be concluded for the standard k-ε equation model can be seen below:

Rate of change of k or ε + Transport of k or ε by convection = Transport of k or ε by diffusion + Rate of production of k or ε - Rate of destruction of k or ε

In this research, the longitudinal aerodynamics of PASOPATI missile was investigated. Thus, only half of the fluid region was required to build up, the other half was made by mirroring it with symmetry function. During the meshing process, unstructured mesh are used, using a body sizing in some areas of missile parts, and giving an inflation value corresponding to the value of y* on some parts of the missile body.

Parameters setting:

1.) All condition is no slip condition. For the other scalars are impermeable to wall conditions [8].
2.) Use a second order upwind format as the difference scheme for the Turbulent Viscosity equation, which is more accurate than the first order upwind [8].
3.) Relaxation factor and other values in the solution control are set to the default value.

The solution was deemed converged when the flow residuals of mass, momentum, energy, and turbulent viscosity had stabilized with the value under $10^{-6}$ and the aerodynamic coefficients were changing less than 0.5%. Figure 1 shows the fluid domain used for the simulation and the meshing is concentrated around the missile to achieve more realistic result and easier to calculate during computation. Figure 2 shows the detailed meshing on the missile and the surrounding area during simulation.
2.1.2.3. Prototype testing
After the preliminary design phase, to test the characteristic and endurance capability of the PASOPATI cruise missile in real time a prototype test was done. The prototype manufacture was done at the detailed design phase. During this phase, the design is broken down and analyzed by each component. The designer must also take into account the production design, in which it must considered how each component designed can be manufactured. In production design there are usually changes made to accommodate for an easier manufacturing process.

The data are collected using sensors such as the Global Positioning System (GPS), gyroscope, and an accelerometer in the flight controller. The data are then sent using a radio and then processed using the application Mission Planner. The data on the energy consumption are collected by checking the battery capacity before and after launch using a battery checker. The data are then used as the basis of the PASOPATI cruise missile’s specification.

This test measures some basic data such as the maximum velocity, capability to reach specified altitude and the mean velocity. These data can also be used to analyze and optimize the missile to simulate more accurate aerodynamics characteristics. This test is also done to observe the material endurance during flight at specified condition.

3. Results and analysis
The results from the designs and optimization process through analysis using CFD is how to design a cruise missile with high endurance, good maneuverability, and easy to manufacture. CFD simulations are done to collect the aerodynamic characteristics data during cruising, and to evaluate the characteristics to ensure better cruising characteristics. During the prototype flight test, the data are
obtained using the application Mission Planner and Battery Checker to measure the mileage and energy consumption during the test.

Table 1 shows the final specification data from the optimization test using CFD and the flight test. Figure 3 shows a three-dimensional design representation of the external geometry from several design iteration as seen in table 1. Figure 4 shows the dimension of the fixed layout and configuration of the missile.

**Table 1.** Final specification data of PASOPATI cruise missile.

| Empty Weight       | 1 kg          |
|--------------------|---------------|
| Gross Take Off Weight | 4.5 kg       |
| Flight Altitude    | 280 m        |
| Flight Endurance   | 13.33 minutes|
| Flight Speed       | 36 m/s or 130 km/h |
| Wing Airfoil       | MH – 23      |
| Wing Area          | 150,000 mm²  |
| Wing Span          | 870 mm       |
| Root Chord         | 240 mm       |
| Tip Chord          | 180 mm       |
| Aspect Ratio       | 5.046        |
| Taper Ratio        | 0.75         |

Figure 3. 3D external geometry.

Figure 4. External geometry dimension.

Figure 5 shows the result of CFD calculation of the flow over the missile during cruising at 0° angle of attack. This result is important in optimizing the external geometry of the configuration [12].

Figure 6 shows the pressure distribution over the body during cruising at 0° angle of attack. This distribution pressure information is used to choose the material used for the missile and the structure configuration for some critical place.
Figure 5. Velocity streamline of PASOPATI during cruising at 130 km/h and 0° angle of attack.

The data shown in cfd analysis in figure 5 and figure 6 is the result data during cruising at the ground velocity of 130 km/h and 0° angle of attack condition. Streamline analysis in figure 5 shows a good streamline, no separation and no high velocity drop through the missile, by those result the design have no disadvantage through this streamline analysis. The data from pressure distribution analysis in figure 6 shows the distribution is concentrated mostly on the nose, the highest pressure at the nose reach 7.629 kPa, and on the leading edge of the wing which around 3.751 kPa. The pressure data is used to decide the improved structure model, to make the structure more effective and lighter.

Figure 6. Pressure contour on PASOPATI’s surface.

Figure 7 shows the final design for the prototype testing. The tested prototype is made using polyfoam and is coated using fiberglass to make sure that it is still lightweight but still has a strong structural strength. Design modifications done during the manufacturing of the prototype are making the tail flat because the airfoil used for the tail part is very thin, and thus the CNC wire cutting machine does not accommodate the precision level of the process. For the launching system of the missile an external launcher is used, and in this particular case the writers used a catapult system to launch the missile. The analysis results from the prototype are focused on the cruising condition by collecting several data, such as the range, velocity, and the endurance of the missile itself. Figure 8 shows PASOPATI pitching up to reach the specified altitude during flight test.
Figure 7. Prototype of PASOPATI.

Figure 8. PASOPATI cruise missile during flight.

Figure 9 and figure 10 is the data gained from the sensor in the flight controller and the GPS. These data can be used to measure the mileage and altitude during the prototype testing. This also used to improve the overall performance and the ability to complete the mission.

Figure 9. Altitude Data Record Of PASOPATI During Flight
The data from prototype flight test is presented in figure 9 and figure 10. Figure 10 is the flight lane of the missile and figure 9 is the altitude of the missile, this data is post processed to measure the magnitude range of the missile. The milage achieved by the missile is 5063 meter during 4 minute fly and the missile consumed 30 percent (2.2 volt) from the full capacity of the battery (7.2 volt).

4. Conclusions
From the simulation result of the PASOPATI cruise missile, it is compared with the actual flight test result. From the flight test results, the PASOPATI is able to fly with an EDF motor with a 104 mm diameter, with a 5 kg thrust at 120 A. The missile was launched with a catapult system to achieve the initial velocity, which produced a thrust against the mass of the missile, resulting in an initial lift. The flight test also shows that the missile could fly using the thrust from the EDF motor, since if the power of the motor is decreased, the missile would stall since the glide ability of the missile is low. The missile is able to fly 100 meters above the sea level with the speed of 130 kilometres per hour for 30 minutes with a 5,000 mAh battery. The control surfaces of PASOPATI are the ailerons on both of its wings, and with a “+” wings configuration, with a control channel where the elevons only moves two-ways. From the control system the missile is able to keep the stability.

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