FINITE ELEMENT ANALYSIS, PROTOTYPING AND FIELD TESTING OF AMPHIBIOUS UAV

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Unmanned Aerial Vehicles are extensively exploited for diverse applications importantly surveillance, reconnaissance, defense and military. Development of unmanned amphibious vehicle with integrating features of multirotor and hovercraft principles to navigate along and above water body, land surface and also flying in air is challenging task. This article presents conceptual design of amphibious vehicle for the payload capacity of 7 kg with an endurance of 20 minutes and provision for mounting water sampler to collect water samples in remote water bodies. Finite element analysis (FEA) is performed to evaluate the structural strength characteristics of each part of amphibious vehicle and integrity of structure is analyzed. FEA results indicated that the designed amphibious vehicle structure is well within the stress limit and minimal displacement is obtained. Based on structural analysis materials for various parts of amphibious vehicle are determined and integrated structure is analyzed with a due consideration of lift carrying capacity, payload, battery and other electronic module weights. Modal analysis predicted the natural frequencies of the structure which are very near to vortex shedding frequency and safe operation speed of propelling the motors is determined. A scaled down model is prototyped and tested for its functionality in land, water and flying in air.

Keywords: amphibious UAV, quadcopter, hovercraft, finite element analysis, water quality.

1. Introduction

Unmanned Aerial Vehicles (UAVs) are classified with reference to body shape and size are fixed, flapping and rotary wings [1]. These UAVs made vivid impact in multifaceted applications including environmental monitoring, search and rescue, bridge inspection, traffic monitoring, mapping of mines, wild life surveying and precision agriculture etc [2]. Design and development of aerial vehicles with diverse pay load capacity and an ability to perform necessary missions pertaining to specific applications are in the rise. There have been few

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researchers developed amphibian vehicle [3]. A robotic amphibious vehicle is developed to navigate in the underwater and rough terrains [4]. Yayla et al. [5] investigated the amphibious UAV characteristics such as rate of climb, turn radius and maximum velocity. A small sea plane [6] model to carry a payload of 4 kg is constructed. The designed vehicle is tested for its autonomous capability for air and water missions. Hasnan and Wahab [7] designed a helicopter with pontoon to achieve gliding along the land and water surface. Frejek and Nokleby [8] developed a amphibious UAV which has four paddle wheels incorporated with ultrasonic sensors. The effect of Buoyancy is experimented with a suspension system having 2 degrees of freedom. There are few research findings in design of hover craft systems [9-14]. However, usage of UAVs in water quality monitoring and collection of water samples in remote water bodies are scarce. Especially, design of amphibian characteristics UAVs which can fly, land and glide along the water surface imposing lot of challenges in terms of control in flight transition, selection of materials, propulsion, energy consumption and payload capacity. In addition, other factors such as durability, reliability, safety and minimal cost are utmost important for industrial demand and customer requirement. There are few floating UAVs which have been developed and commercialized in the market. However, integrating the characteristics of multi rotor and hover craft systems are not being explored in the literature. These vehicles are aimed to cover large areas of water bodies in short span of time. Unlike other floating vehicles, due to the principle of hovercraft, the friction between the vehicle and water surface is avoided [15-16] and there by a considerable amount of energy can be saved. The vertical take-off and landing ability of vehicle can position the vehicle in precise water locations across rivers, ponds and other water bodies to collect water samples. Design of amphibious vehicle with sufficient strength characteristics to withstand lift conditions and carrying necessary payload are considered to be challenging.

In this work, an amphibious conceptual model is developed to carry a pay load of 7kg. Finite element analysis is performed for UAV frame, hull, skirt and amphibious structure through varying the materials to examine the structural strength and integrity of the structure. Modal analysis is carried out to determine the natural frequency of the amphibious structure. A scaled down model is constructed through integrating the sub systems of quad rotor and hovercraft.

2. Conceptual Model of Amphibious Vehicle

Amphibious model is conceptualized through integrating the principles of Quadcopter and Hovercraft as shown in Fig.1. The concept is a hybrid prototype of two different vehicles. The basic H configuration - UAV frame is used as the prototype design. For the vehicle to be airborne, four brushless electric motors and propellers are assembled to generate sufficient thrust force to lift the entire vehicle. A water sampler mechanism is assembled at the center of the vehicle. For surface missions and tasks, the prototype can be transformed into a hovercraft. It has two electronic duct fans (EDFs) mounted on the hull that inflate the skirt and another EDF is positioned at the rear to achieve directional control while in hovercraft mode which acts as a rudder. The batteries, electronic accessories, flight controllers and other electrical elements are appropriately distributed to balance the center of gravity of the vehicle.

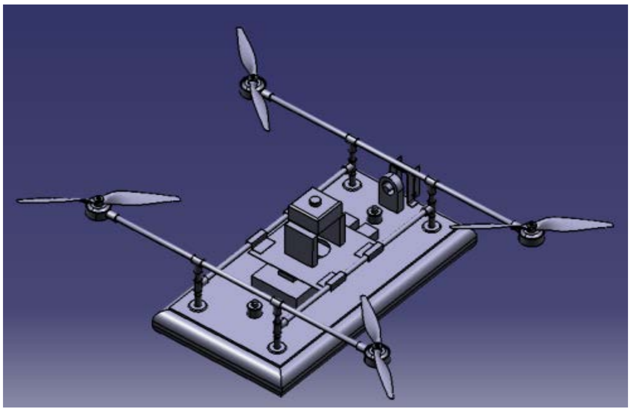


Fig. 1. Conceptualized Model of Amphibious Vehicle

3. Structural Analysis of Amphibious UAV

In order to identify suitable material for each amphibious part to withstand thrust forces, payload and other load carrying members, structural analysis is performed through considering various materials. They are selected with respect to several criteria including strength to weight ratio, manufacturability, cost and also availability of materials.

3.1. Quad rotor frame

The quad rotor frame is meshed (Fig.2) using 3D tetrahedron element. Finite element (FE) model consists of 72087 nodes and 229988 elements. The mesh quality is evaluated mainly with 3 major criteria: skewness (best value=0; worst value=1), aspect ratio (best value=1; worst value=100) and shape factor (best value=1; worst value=0). FE model obtained good mesh quality with an average skewness of 0.527, an average aspect ratio of 2.298 and an average shape factor of 0.601. As for the boundary conditions, the generation of thrust force from each propeller of about 100 N is applied at each corner of motor frame [17-18], central load of 7kg as a payload is concentrated, batteries and other loads are distributed appropriately in the frame structure. For various materials, structural analysis is performed to determine the minimal displacement and stress and their results are given in Table 1. Carbon fibre attained minimal displacement and stress than other materials. However, based on ease of availability, aluminum is chosen for the present study which is carbon fibre. FEA results of aluminium having maximum stress of 15 MPa (Fig. 3) and displacement of 2.22 mm (Fig. 4) suggested that, aluminium can withstand the thrust force and other distributed loads. It is less weight, better corrosion resistance and high strength to weight ratio.

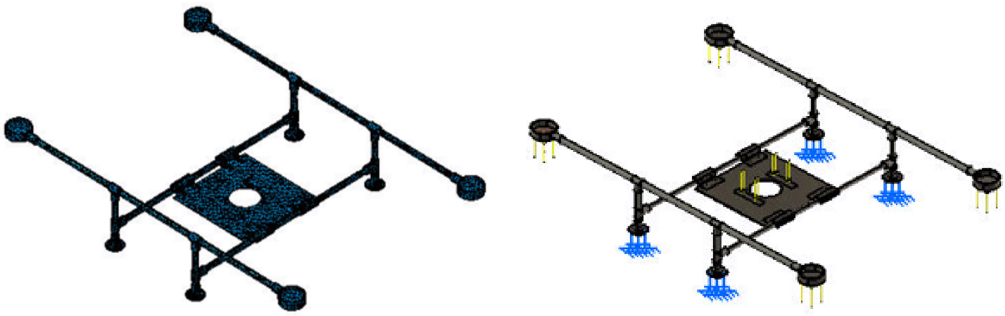


Fig. 2. Finite element frame model with boundary conditions

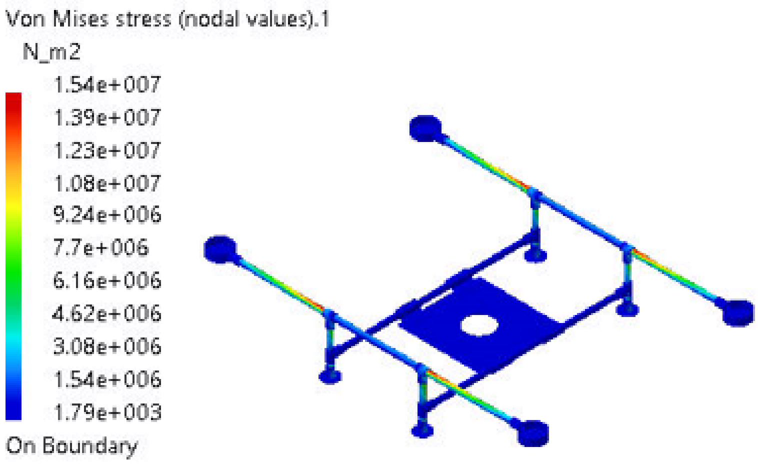


Fig. 3. Stress contour of UAV frame – Aluminum

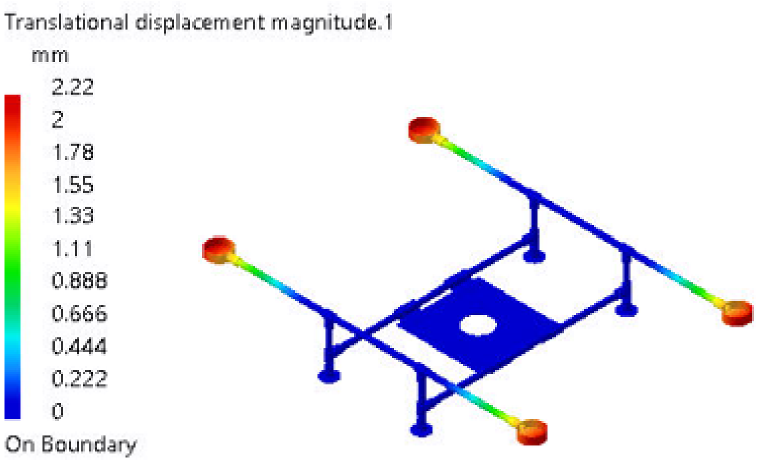


Fig. 4. Deformation of UAV frame – Aluminum

Table I
Structural analysis results of various materials for UAV frame

Materials	**Max stress (MPa)**	**Max displacement (mm)**	**Structure mass (kg)**
Aluminum	15.4	2.2	6.6
Carbon fiber	12.4	1.7	3.9
ABS	12.2	45.8	2.6
PEEK	12.0	30.5	3.2
ULTEM	11.9	39.4	3.1

Polymers such as ABS, PEEK and ULTEM are light weight but may not be the best choice as they do not provide sufficient stiffness. Thus, with respect to cost and availability criteria, aluminum is preferred over carbon fiber.

3.2. Hull

The hull serves as a platform [19] to fasten the frame of the quadrotor together and hold the electronics hub. It also incorporates all hardware units, propulsion, wireless communications, soldered circuitry, and battery. The structure is quite particular as it is made up of anisotropic materials. The panel made of wooden sheet and foam core and are sandwiched together in order to achieve minimal weight without compromising structure strength. The FEA is performed for a differential pressure of 731 Pa acting on the internal plenum chamber. The pressure load is due to the air intake by the two EDFs mounted on the hull which inflate the skirt when the vehicle is performing maneuvers in hovercraft mode. The FE model consists of 45970 nodes and 140792 elements (Fig.5). It has a fairly good mesh quality with an average skewness of 0.557, an average aspect ratio of 17.217 and an average shape factor of 0.566. The boundary conditions including 10 kg battery weight and other loads of 1.5 kg acting on the hull is also considered for the analysis. Simulation results indicated that, maximum stress (Fig. 6) of 20 MPa and deformation of 0.21 mm (Fig.7) is experienced at the hull structure.

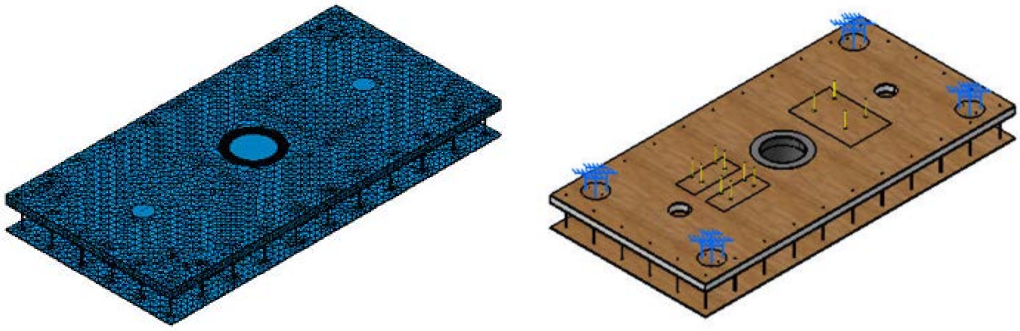


Fig. 5. Finite element hull model with boundary conditions

The hull material made of wood / foam sandwich structure has a good strength to weight ratio. The wood / foam core panel is capable of withstanding the payload, battery weight and other electronic modules without exceeding its yield strength and breaking limit.

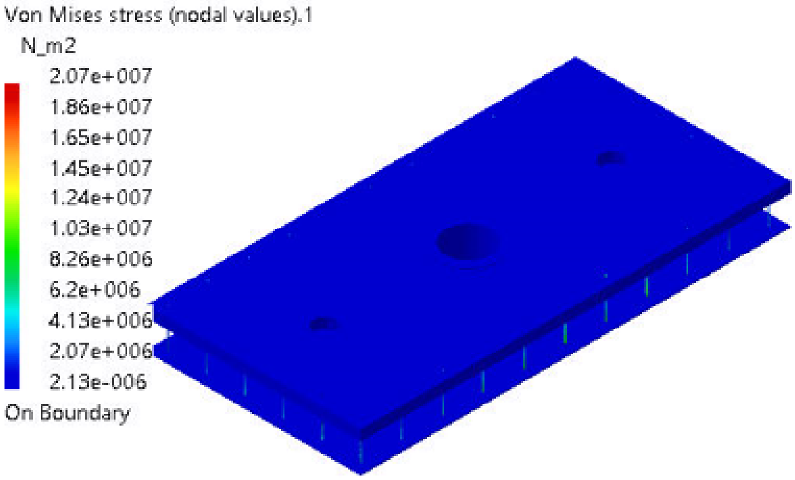


Fig. 6. Stress contour of Hull

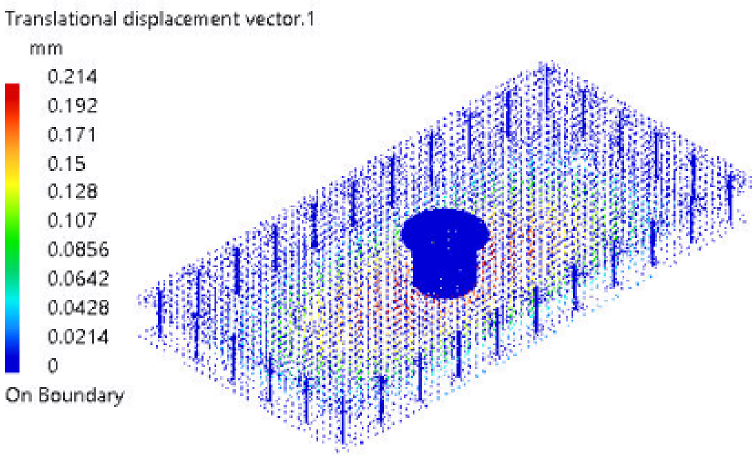


Fig. 7. Deformation of Hull

3.3. Skirt

The bag skirt [19] is considered to be an effective way in producing cushioning effect for smooth gliding along the water surface. A duct fan located at the centre is used to produce required air flow to exert the pressure on the side walls of skirt to inflate it that provides lift of the hovercraft.

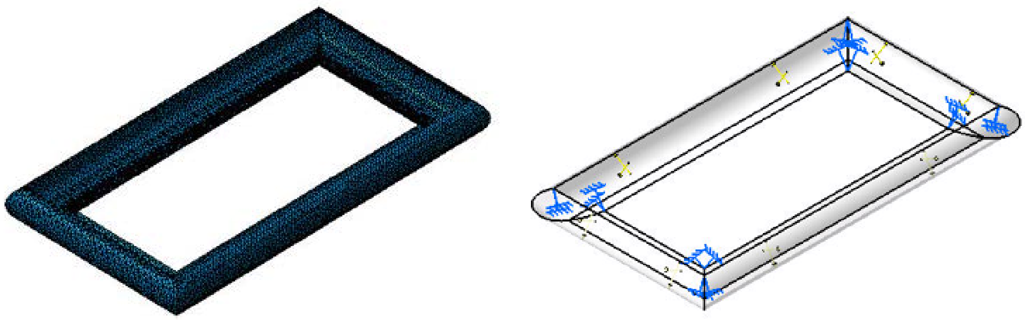


Fig. 8. FE skirt model with boundary conditions

The skirt is only inflated during hovercraft mode and it creates cushioning effect between the vehicle and water surface. Supposing there is no pressure loss in the plenum chamber, the same internal pressure of 731 Pa is applied along the periphery of the structure and static analysis is performed for diverse materials as given in Table 2. In this case, thickness of the skirt is almost negligible compared to the size of the component and therefore 2D triangular element is used to keep aspect ratio closer to 1. The skirt finite element model is of 7279 nodes and 14054 elements. The FE model has obtained an excellent mesh quality with an average skewness of 0.179, an average aspect ratio of 0.524 and an average shape factor of 0.878.

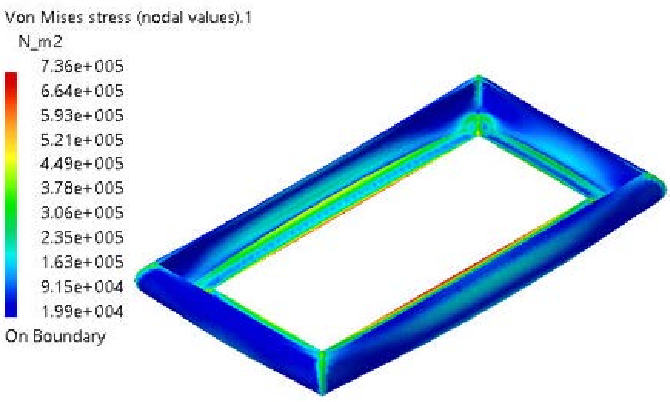


Fig. 9. Stress contour of skirt

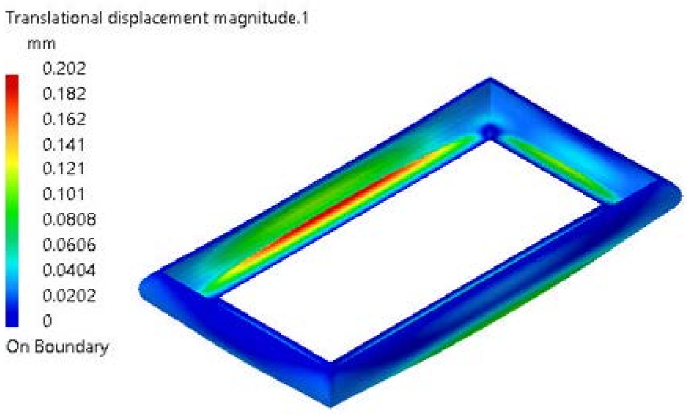


Fig. 10. Deformation of skirt

Table II
Structural analysis results for various skirt materials

Materials	**Max stress (MPa)**	**Max displacement (mm)**	**Structure mass (kg)**
Natural rubber	0.74	0.35	0.97
Nylon impregnated with urethane	0.74	0.31	1.20
Urethane nylon	0.74	0.43	1.33
Neoprene coated nylon	0.74	0.20	1.28

FEA is carried out for various skirts materials and it is observed that (Table 2), the performance is quite similar for nylon family materials except for natural rubber. Neoprene coated nylon is an all-purpose elastomer and an extremely versatile synthetic fabric capable of resisting degradation from sun, ozone and weather and performs well in contact with oils and chemicals. It is widely used in hovercraft skirts, industrial aprons, spray deck and adventure clothing.

3.4. Integrated structure

After integrating UAV frame, hull, and skirt with the selected material and applying appropriate boundary conditions, FEA is carried out to evaluate the integrity and strength of entire amphibious structure.

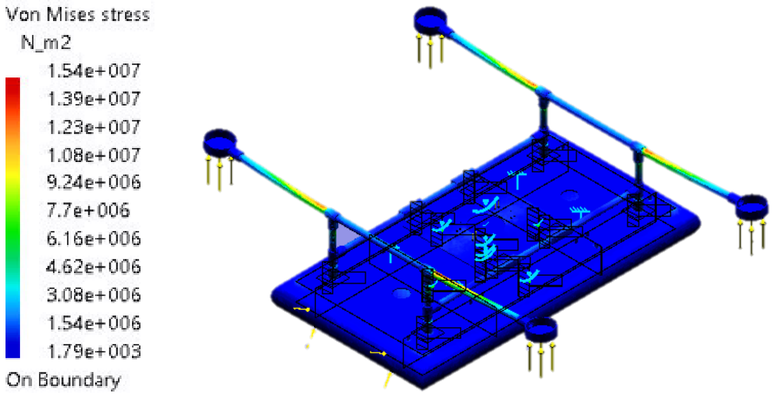


Fig. 11. Stress contour of amphibious structure

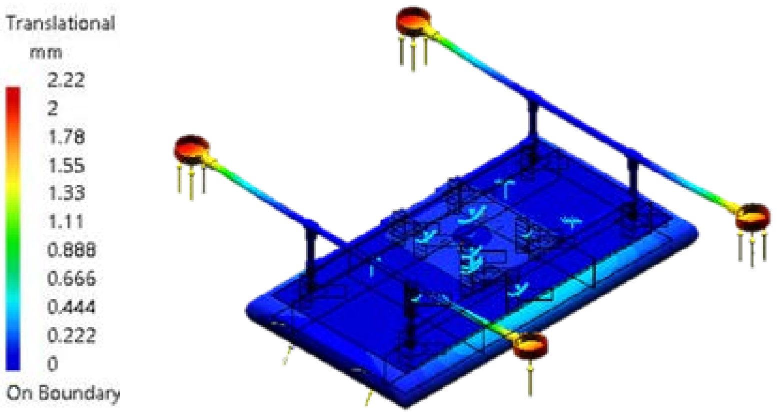


Fig. 12. Deformation of amphibious structure

Static analysis results indicated that, the designed structure experience very minimal stress of 1.54 MPa which is well within the allowable stress (Fig. 11). A maximum deformation (Fig. 12) of 2.22 mm can be seen at the four corners where the thrust from the propellers are acting due to cantilever structure.

4. Modal Analysis of Amphibious UAV

The study vibration characteristics is considered to be an important aspect of all designs because, the mechanical systems have natural modes and may cause control disturbances. In order to determine the natural frequency of amphibious structure, modal analysis is performed. When a specific load is applied to the mechanical system, the natural mode can be excited which can lead to catastrophic failure of the system. This leads to the importance of studying the resonance frequency of the UAV frame, which is the frequency that the system will be exited, to ensure that the natural modes will not be disturbed. The natural frequency of amphibious model is computed and compared to the vortex shedding frequency of the propeller. These results are used to determine the physical operational speed limits for effective maneuvering.

Identifying the sources of vibrations from the mechanical system is an important requirement to perform modal analysis. In the case of amphibian vehicle, the main source of mode excitation comes from the propulsion system (brushless electric motors and propellers). Since 30.5x9.7 (30.5-inch diameter, 9.7-inch pitch) propellers are chosen to lift the entire huge vehicle, and assuming standard sea-level air density, the vortex shedding frequency of the propellers can be deduced by using the information given for the motor rating (KV) and supplied voltage (V). The Strouhal number of the propeller is estimated at 0.2 in our study. The dimensionless Strouhal number is used to determine the frequency induced by the propeller at different RPM which is given by,

$$\mathrm{St} = \frac{fL}{U} \tag{1}$$

St is the Strouhal number
f is the vortex shedding frequency of the propeller
U is the velocity of the flow through the propeller
L is the characteristic length of the propeller

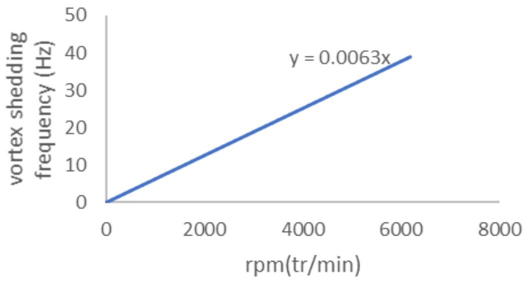
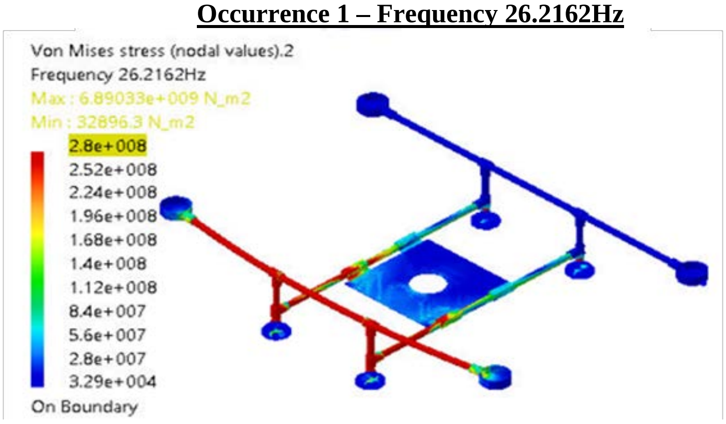


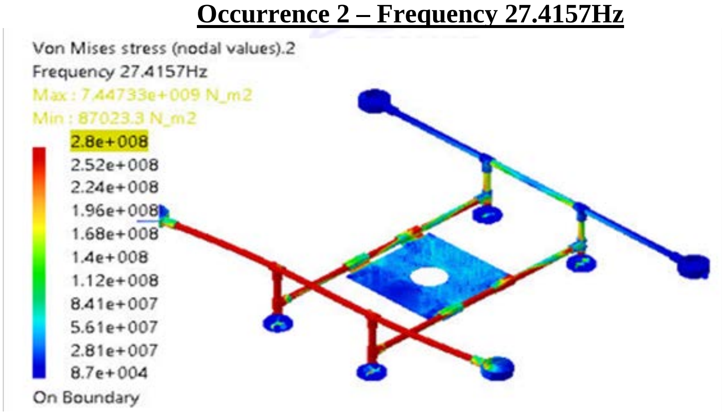
Fig. 13. Linear correlation between vortex shedding frequency and motor RPM

A linear correlation between vortex shedding frequency and increase in motor RPM is observed in Fig. 13. Meanwhile, the natural frequency of the aluminum frame is estimated as follows:

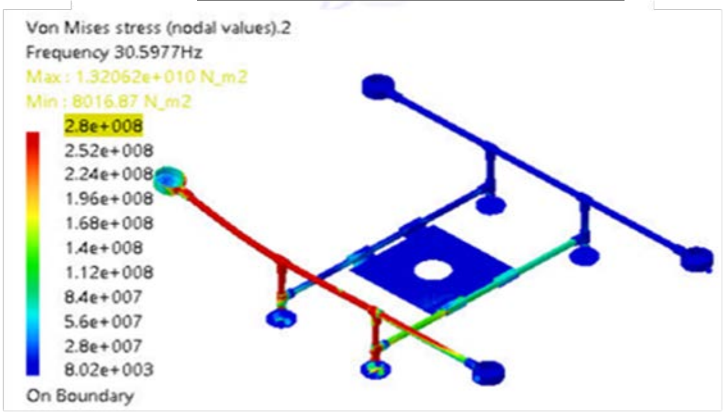
Occurrence 1 – Frequency 26.2162Hz



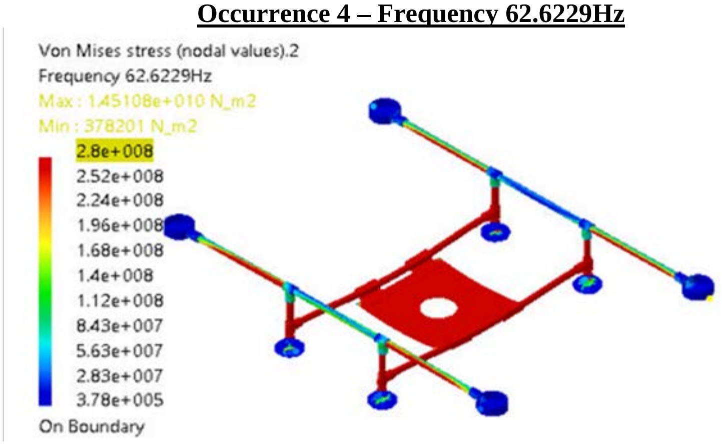
Occurrence 2 – Frequency 27.4157Hz



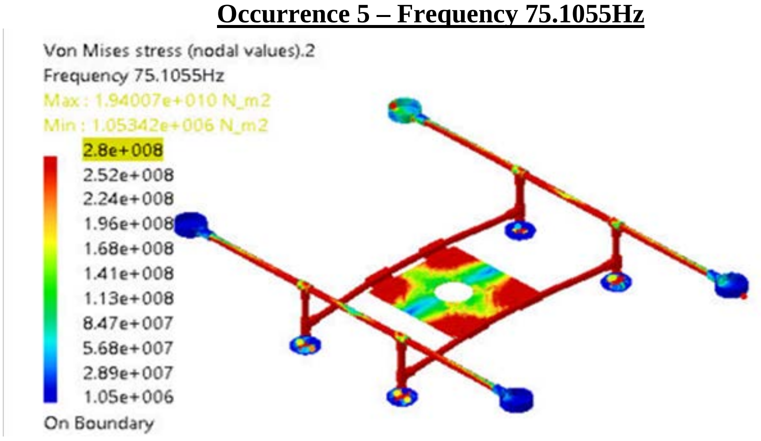
Occurrence 3 – Frequency 30.5977Hz



Occurrence 4 – Frequency 62.6229Hz



Occurrence 5 – Frequency 75.1055Hz



Occurrence 6 – Frequency 104.404Hz

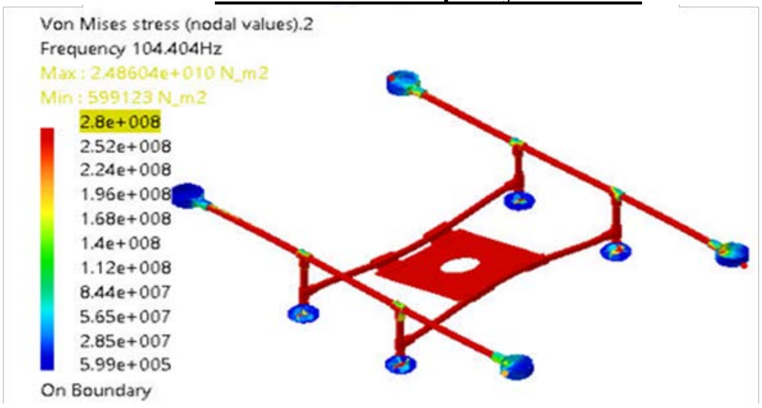


Fig. 14. Estimated natural frequencies of amphibious structure

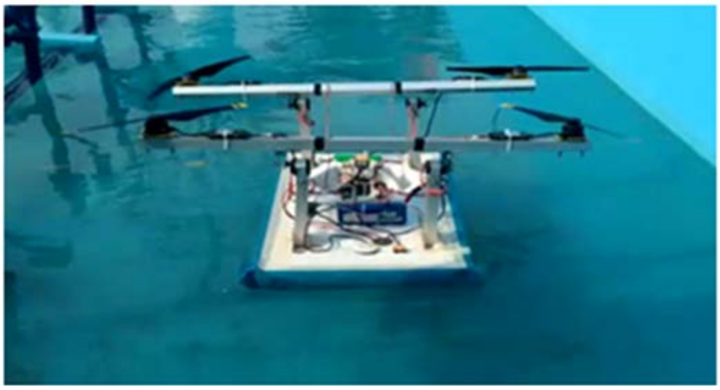
It is observed from Fig. 14 that, first two modes are of bending of frames and then twisting is experienced. Other modes of vibration are occurred in the centre plate of the structure. Comparing the vortex shedding frequency with the natural frequency of the aluminum frame it can be determined that about 4200 rpm can excite vibration severally. Modal analysis results predicted that, the first three natural frequencies of the frame are near to the vortex shedding frequency at higher speed of the motor. In order to keep the structure safe from resonance, the speed of the brushless motor has to be limited to below 4000 rpm.

5. Fabrication and Testing of Amphibian Structure

A hollow aluminium structure is considered as a UAV frame to obtain maximum strength to weight ratio. They are cut into required dimensions using grinding wheel and assembled with screws and nut. A high density polyurethane foam and wood plates are integrated with fabricated frame through bolts and nut. According to the scaled down amphibian model, motors, propellers and electronic speed controllers are selected. They are assembled in the UAV in the respective positions. In this model, a duct fan is mounted at the centre to show case the performance of hovercraft system. The duct fan is used to generate sufficient cushion pressure on the periphery of skirt to achieve hovering of amphibian vehicle. A small air gap is achieved between the skirt and the surface to avoid friction. The forward motion of the vehicle is achieved through rotating the frame 90^0 as shown in Fig. 15 and propelled. Similarly, reverse motion is obtained through rotating the rear frame 90^0 and control the vehicle for moving along any surface. Compared to other existing amphibian vehicle [19] it has multifunctional capability. The constructed prototype is tested for its functionality such flying (Fig. 16 a), gliding along the land and water surface (Fig. 16 b). Vibration of the vehicle is major concern and it is minimized through strengthening the UAV frame through additional support.

Fig. 15. Constructed amphibious structure

a) Amphibious UAV (Air Borne)



b) Amphibious UAV

Fig. 16. Field testing of amphibious UAV

6. Conclusion

A conceptual model of amphibious vehicle with integrating the features of multirotor and hovercraft systems is designed. Structural analysis is performed for various parts of amphibious structure. FEA results for UAV frame suggested that carbon fibre and aluminium are obtained minimal stress and displacement. Aluminium is considered due to ease of availability and low cost. High density polyurethane foam in combination with wood experienced minimal displacement and selected for hull. In nylon family, neoprene coated nylon is accounted as skirt material because of its excellent material characteristic with reference to its strength, flexing, twisting and elongation over a wide temperature range while having outstanding physical toughness. Frequency spectrum through modal analysis suggested that around an operating speed of 4000 rpm resonance may occur and the amphibious UAV is to be propelled below and above this speed. Scaled down amphibious model is developed through selecting motors, propellers and other electronic modules appropriately. Field testing of amphibious UAV in air, land and water borne operations achieved good performance characteristics vehicle in stability and control. The prototyped amphibious vehicle can be utilized to perform multifaceted operations including water sampling and naval applications.

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