Multi-Body Dynamics Analysis of UAV Propeller Testing Fixture

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Abstract - *The study focuses on the design and analysis of a UAV propeller testing fixture using both CAD software and multi-body dynamics analysis via MSC Adams software. The fixture, which accommodates all four propellers of a quadcopter simultaneously is developed to measure pitching and rolling moments under controlled conditions. Experimental tests were conducted to validate the simulation results, showing a minimal variation of approximately 3 degrees between the experimental and simulated data, attributed to motor positioning. This fixture provides a robust platform for testing various propeller sizes and configurations, offering valuable insights into propeller dynamics without the influence of wind. The results indicate that the testing setup is effective for real-world applications, providing a foundation for further optimization and research in UAV propeller performance analysis.*

Key Words: UAV propeller, Multi body dynamics, thrust, Pitching, rolling

1. INTRODUCTION

Testing of the UAV propellers is very important as we can understand the working of the propellers along with the specific motors. We can figure out how different motors work with propellers. UAVs have become a very important part of the aviation industry now and in the future, it will be a very demanding industry where even the delivery of items will be done using UAVs, and no doubt in that. In this fast-moving technological advancement testing of the UAV propellers also plays a very crucial role. To test these UAV propellers many companies are developing testing rigs and fixtures to test the compatibility of the propellers with the motors and how the propellers work in the different maneuvers.

Gene Patrick Rible et. al. [1] focused on exploring alternative and cost-effective methods for modelling a quadcopter using basic tools and electrical measuring devices. The study delves into quadcopter kinematics, making assumptions about geometric centre, total mass, moment of inertia, drag torque, and rotational dynamics, employing mathematical methods for calculations. The research provides alternative approaches for determining relationships such as thrust vs. PWM command, thrust vs. angular speed, and reaction torque vs. thrust for the quadcopter's propellers along with coefficients for aerodynamic drag. The dynamic model obtained is then used to design and simulate a basic flight controller. The experimental section outlines the hardware design, quadcopter modelling, and simulation of the basic flight controller. The study utilizes a DJI flame wheel 450 with a commercial DJI E600 propulsion system employing a cost-effective setup involving a tachometer and a weighing scale to measure angular speed and thrust respectively. The simulation phase involves determining PID parameters serving as starting points for the implemented controller with subsequent tests demonstrating the expected stable flight of the quadcopter. Patrik Kosa et. al. [2] experimentally studied the various parameters like, battery voltage, temperature, and humidity for accuracy employing an ATmega2560 microcontroller-based processing circuit to acquire, measure, and store data on a micro-SD card of UAV propellers. The equipment used includes a motor with a dragonfly propeller, a Li-ion battery, and an ACS 770 hall-effect current sensor suitable for measuring DC currents up to 100 A. A customizable stand facilitates the testing of different motored quadcopters, and a force sensor attached securely measures vertical thrust. An optical RPM sensor placed on the motor side allows RPM measurement with precautions taken to minimize ground effect influence. The custom circuit and algorithm are designed to process and store the measured data providing insights into the relationships between thrust and RPM under various input conditions as well as the propeller's behaviour. The results highlighted the feasibility of using cubic functions to approximate dependencies and predict propeller behavior under unmeasurable circumstances addressing the challenge of obtaining experimental measurements for various motor and propeller combinations not included in product descriptions. J. C. Bell et. al. [3] developed the test rig that customizable for different small unmanned air vehicles with adjustable screws and other components. The mathematical calculation of torque is also explained with formula. Two tests have been conducted on the rig initial test and fine grade test. Test have measured torque and performance of rig. There has been a failure in one of the tests which was reasoned to the lack of component in yawing motion in the system. Stephen D. Prior et. al. [4] designed the torque test-rig used to measure the reaction of torque, which provides the basic understanding about the experimental setup employed for evaluating co-axial rotor systems on SUAVs. Series of tests were analysed for various co-axial configurations to determine the optimal motor and propeller arrangements. In that the highest performing one placing the motor on the outside of each mounting arm using pusher propeller and lower tractor propeller setup also the comparison with singular rotor systems showed lower average thrust output for co-axial configuration. Inter rotor spacing tests indicated limited effects on total thrust. Varying pitch angles effected on the thrust/power ratio. Formula for accurate torque measurement was confirmed with min average error. By varying the H/D ratio showed the increase of torque variation. Overall, the results are leading towards the higher performance. Z S Islami et. al. [5] made efforts to build up small propeller test bench fit into a wind tunnel. Authors were made a setup test bench to obtain readings of thrust, torque and rpm, also varied RPM values to obtain thrust and power coefficients. This test bench experiment results are compared with Brandt's experimental results. To check theoretical and numerical methods, reverse Larrabee method and computational fluid dynamics model was used. With the use of this creative method, it was possible to measure the dependencies between thrust and RPM at various input circumstances, current and RPM, and the propeller's behaviour. The measurements have demonstrated that cubic functions can been used to approximate the dependencies. The propeller's behaviour under unmeasurable circumstances can be predicted by mathematical descriptions. Since the information about the combination of various motors and propellers is in the most cases not included in the product description, it is necessary to obtain this data with experimental measurements. K. Siva Prasad et. al. [6] developed a finite element model to analyse the vibration behaviour of aluminium propeller blade and compared the numerical results with experimental results based on mode shapes. Authors found that at lower modes the obtained natural frequencies and mode shapes agree well with the experimental results. Zhiting Jia et. al. [7] explored a novel instrument designed to measure static torque in composite variable pitch propellers, which is crucial for the safe and efficient operation of aircraft engines. Traditional methods typically measure only axial torque and often overlook the variations in radial torque at different angles, particularly in more complex propeller designs. While current techniques based on the torque balance principle are generally accurate and reliable, they fail to effectively measure radial torque at various angles. This research introduces a new device that accurately measures both axial and radial static torque enhancing our understanding of propeller performance. Tests conducted with a specialized gauge and actual propeller blades demonstrate the device's reliability and effectiveness making it suitable for modern propeller systems. This advancement aids in the optimization of aircraft engines with future research aimed at improving the device and exploring new materials for even more precise measurements. Dongdong LUO et. al. [8] analysed the foldable propellers that can improve UAVs by making them more portable and efficient. The considered propellers have a central hub with blades that can fold up or down, and it tilts rotor UAVs and making more aerodynamically efficient by increasing speed and time. They helped for better control and stability of the vehicle. Mohamed H. Eldegwy et. al. [9] discussed about the increasing demand for unmanned aerial vehicles (UAVs) and the importance of propeller-driven propulsion systems. Propellers are commonly used in UAVs because they are reliable, easy to install, and efficient during flight. However, accurately predicting propeller performance especially at low Reynolds numbers. The paper aims to develop a tool to improve propeller performance predictions for low Reynolds numbers. The propeller tests provided a valuable resource for designers during propeller selection and contribute to the development of data-driven models in the future. Adam Smedresman et. al. [10] explained about how important propellers are for the unmanned aerial vehicles. The researchers in this study made a way to build and test small propellers in a wind tunnel. They found that the actual performance of the propeller they tested was different from what was predicted by existing theories. They think this difference could be because the numbers used in the theories were not accurate, or because the way the propeller was made affected its performance. Willem A. Anemaat et. al. [11] concentrated on the quadrotor, a type of unmanned aerial vehicle (UAV) similar to a helicopter but with enhanced stability. It is operated remotely, eliminating the need for an onboard pilot. Quadrotors have diverse applications including agriculture, package delivery, military operations, and fire detection. The propeller is crucial for a UAV's flight, and they design propellers that can adjust speed to improve flight performance. Authors examined factors such as drag (the force that decelerates the propeller), lift (the force that elevates it), and thrust (the force that propels it forward). This analysis aids in selecting the appropriate motor for the UAV and designing efficient propellers. By studying aspects like thrust force, air pressure, airspeed, and air density, they can choose the best materials and shapes for the propellers, ensuring they are effective and practical for UAV flight. Rokvam et. al. [12] designed the propeller blades made of composite materials that can both bend and twist efficiently. Four different design ideas are tested first on simple blade structures to see how well they work. Then, these ideas are tried on real propeller blades to see if they can change the pitch (angle) effectively when the propeller is under different loads. The aim is to create a propeller design that can handle load changes better than current designs improving overall performance.

In the present work the design of the propeller is done using CAD software and the multi-body dynamics of the same and the experimental analysis of the fixture to find out the pitching and rolling moment by measuring the angles by using various means. This experimental analysis gives us the exact real-life situation study analysis results. The results taken from this experimental work are analyzed with the software analysis and the results that we got both in the experimental work and software analysis show nearly the same with 3 degrees variation from experimental and analysis work. This offset is because of the positioning of the motors at a certain angle and this motor positioning has made to get very little offset of the work results what has been got. Wind on the other hand plays a very crucial role while analyzing anything that flies, here in our analysis we have wind has not played any part as the work is done in closed environmental conditions and the results for open conditions may vary from that of the closed condition as the variable wind intensity may vary for both situations.

In our study, we tried to find out the pitching and rolling moments of the propellers using testing fixture CAD model by multi-body dynamics analysis in MSC Adams software and the analysis results are compared with the experimental results. This analysis allowed us to study the behavior of the propellers on how the pitching and rolling moments vary the force and torque in the propeller holders or the hands of the propeller holder and the size of the propellers can be varied. Here in our study we have used 10-inch propellers but if we have to test for a bigger or smaller propeller that can be made and if necessary the size of the upper holding fixture can be changed according to our needs and get the results. Other than the pitching and rolling moment analysis the angular velocity, angular acceleration, force on each body, and torque in each direction can be calculated using the analysis software. In this study we have used all 4 propellers to study the rolling and pitching moments as we can see in the paper by Z. S. Islami et. al. [5] authors developed a small test bench to test the propellers which accommodated only one propeller to test and derived their results from those tests, and the study by Prior et. al. [4] authors have studied coaxial rotor system for unmanned aerial vehicles which is also same as the other where only one propeller has been tested. But here in our design we have the facility to study all 4 propellers of the quadcopter UAVs which can be mounted all together at a time and can be tested. This testing gives us the real-life flying experience and the results where we can exactly get the feel of all 4 propellers. This testing is designed to understand the basics of the propellers as well as the force and torque playing around them. By changing the input r.p.m. we can realize the models with different test outputs which can be optimized in the future. Here r.p.m. change is done using the powerful motor, but in actual case the UAVs are run using the batteries where the power depends on the battery's mAh. The more powerful the battery the better would be the thrust.

2. DESIGN DETAILS

2.1 Upper holding and rm support

Upper holding as shown in figure 1 is an upper propeller holding fixture, a key part of a UAV propeller testing setup. This fixture provides a stable and secure platform for mounting the propeller during tests. Its strong design ensures the propeller stays in place, preventing any movement that might affect test accuracy. it can handle the forces produced during propeller operation. The fixture is versatile, fitting different propeller sizes and setups. It's also easy to assemble and disassemble, allowing for quick setup and adjustments during testing. This upper propeller holding fixture is crucial for accurate and reliable propeller performance tests.

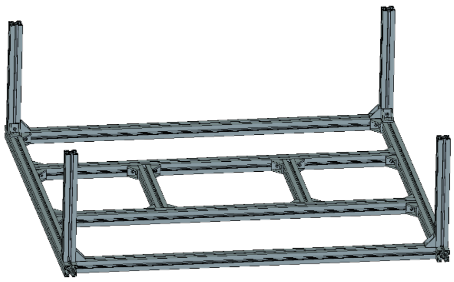


Fig 1: Upper holding of the fixture

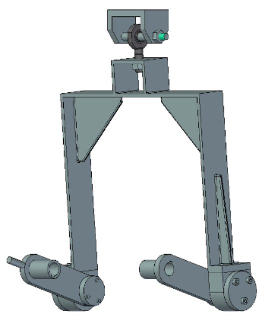
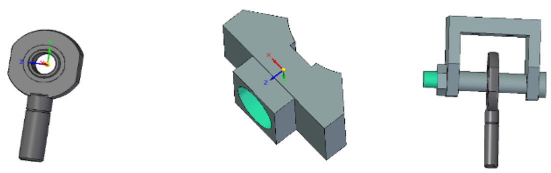


Fig 2: Arm support

Arm support as shown in figure 2 is a strong frame that ensures the propeller is firmly in place during tests. Because of the fixture's adjustable mounts make measuring aerodynamic forces and precisely aligning the propeller simpler. Constructed from robust materials such as stainless steel, the frame has sufficient durability for testing. Different propeller sizes and positions can be accommodated with the adjustable mounts. To quantify critical forces like thrust and torque and gain insight into the propeller's performance load cells are added. This arm is mounted to the gearbox to get the required motion which has to be given to the upper holder of the fixture.

2.2 Rose joint, T-joint and support clamp

It can be known as a Rose joint or spherical bearing is essential in a fixture for the movement of the arm and the upper holding of the fixture while keeping it aligned and reducing friction. The spherical design can handle slight angular misalignments, ensuring the upper holding turns freely during tests. By reducing friction, it ensures accurate and reliable test results as shown in figure 3(a). T-joint as shown in figure 3(b) keeps the upper holding of the fixture stable and properly aligned. It has a round opening. The design includes specific shapes and supports to provide strength while keeping the part lightweight. This ensures the upper holding is securely attached, reducing vibrations and improving the performance. The material and build of this part are crucial to handle the stresses and conditions during flight.



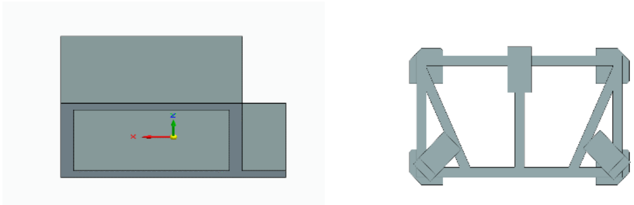
a) Rose joint b) T-joint c) Support clamp

Fig 3: Different joints and clamps

The C clamp (fig 3(c)) in the support clamp is assembled with the rose joint with the support of a nut and bolt to hold it steadily. That support clamp assembly is the connection between the arm support and the upper holding of the fixture. This is a major load-bearing component in this assembly, where it bears the load of upper fixture along with motor and propellers.

2.3 Motor mount and bottom mount

A motor mount as shown in figure 4(a) is attached to a gearbox mount, which is attached to the motor. This setup is important to hold the gearbox and motor while keeping everything aligned and stable. The mount is designed to be securely attached to the bottom mount providing strong support. The gearbox helps adjust the speed and torque to fit the propeller's needs. This component is built to be durable and reliable which is crucial for maintaining good performance and handling the stresses during UAV flights.



a) Motor mount b) Bottom mount

Fig 4: Different types of mounts

The bottom mount of a UAV propeller fixture as shown in figure 4(b) holds the motor and supports the upper fixture providing a stable base for the whole testing setup. Its design ensures a solid foundation reducing vibrations and movement during tests. The bottom mount securely holds the motor, which is important for keeping the propeller aligned and the tests accurate. It fits well with the upper fixture creating a reliable testing environment. In summary, the bottom mount is crucial for the stability and accuracy of the propeller tests, supporting both the motor and the upper fixture.

2.4 Final assembly of fixture

The assembly as shown in figure 5 includes both the upper and bottom mounts, forming a complete structure that securely holds the propeller during tests. It provides a stable base and strong support for the motor and propeller minimizing vibrations and movement to ensure accurate and reliable test results. Made from durable materials like aluminium or steel, the fixture can withstand the forces generated during testing maintaining its strength and performance. The design of the fixture allows it to accommodate different propeller sizes and configurations, making it versatile for various testing setups. Additionally, it is easy to assemble and disassemble, allowing for quick setup and adjustments during testing. Overall, this final assembly is crucial for providing a reliable and precise testing environment ensuring the propeller is securely and correctly positioned for performance evaluations.

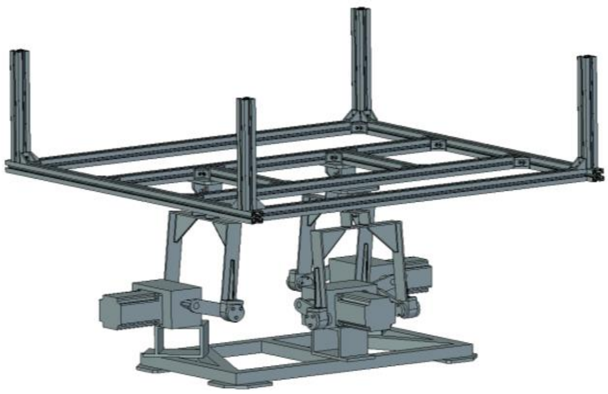


Fig 5: Final assembly of propeller fixture

3. PROCESS OF SIMULATION ANALYSIS

The real-time multi-body dynamics of the UAV propeller fixture is carried out using the MSC Adams software where the results have been extracted which are very near to the experimental results. Once the 3D model of the design has been designed using the Siemens Solid Edge software the model is imported to the Adams software first, then bodies are defined as fixed or flexible. Once that is done, the materials are assigned along with the joints and constraints, where constraints like revolute joints, prismatic joints, or spherical joints are assigned. Next, the external and internal forces such as gravity, aerodynamic forces, and spring forces are applied.

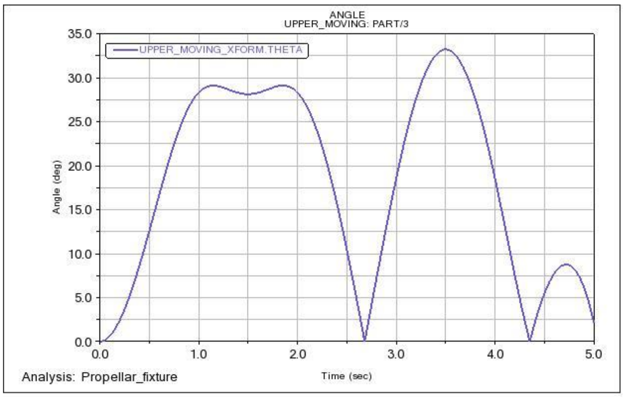
Simulation setup is done by specifying the positions, and orientations of the bodies. Boundary conditions are defined with the constraints and drivers that dictate how the system can be controlled and how the system will be moved. Dynamic analysis to examine the system's responses to the angular velocity, forces, and torque which gives us the real-time simulation of the forces and motion. Adams uses numerical analysis to solve the different governing equations to get the motion of the system. Post-processing consists of the visualization of the simulation through graphs, animation, and various plots and representations and analyzing the data such as velocities acceleration force, and moments and the reports along with the images and analysis results.

4. EXPERIMENTAL SETUP

The aluminum frames are used to build the upper body of the fixture and the other parts are mostly made up of stainless steel. Once the setup was ready we attached different force, torque, and motion sensors to find out the pitching, and rolling movement. The other sensors are also used to find the force and torque acting on the propellers. The power was given to the motors to give the movement for the upper holding of the fixture where we altered the power to each motor according to our needs to find out the pitching and rolling movements.

5. RESULTS AND DISCUSSION

The first simulation result is discussed for the pitching and rolling movements in the upper moving part of the fixture where it is compared with the experimental values. In simulation we got 28° during the pitching movement and 17° during the rolling movement and the experimental values are 30° and 20° respectively. This result helps us to analyze experimental values with the simulation data and compare the aerodynamic forces acting during pitching and rolling moments. The data obtained here can be utilized to validate and optimize the system if needed in the future for comparing and making the changes in the design of the fixture. Here the curve reaches the maximum of 30° in 1 second during the pitching movement, then it declines near to 0° within 3 seconds. All these changes depends on the power of the motor being used. Same happens during the rolling movement as well just the degree of change is different in this case.



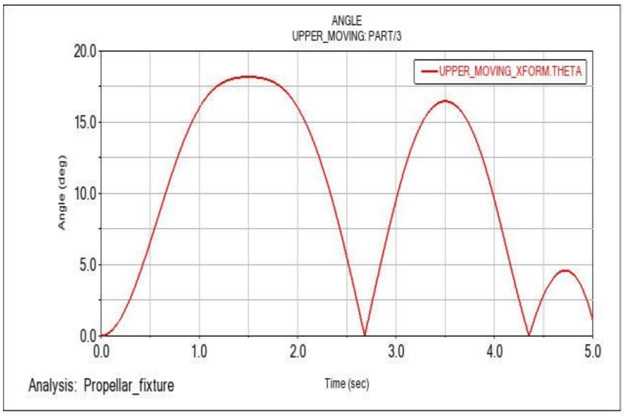


Fig 6: Angle vs time graph of pitching and rolling movement demonstration.

The forces that were analysed during the simulation are shown in figure 7 are different in each joint. Out of 3 joints one joint touched a maximum of 415 N in the negative direction and 300 N in a positive direction during the pitching movement and 45 N in a positive direction and 140 N in the negative direction during the rolling movement. The forces acting on each joint are constantly being varied in the joints over the period of time. This helps us to understand the dynamic behaviour of the fixture under the various loads and by identifying the force at each point helps us to understand the stress points of the fixture and take the necessary action if required. During the full run, the force seems to be most stable along the time at most of the points.

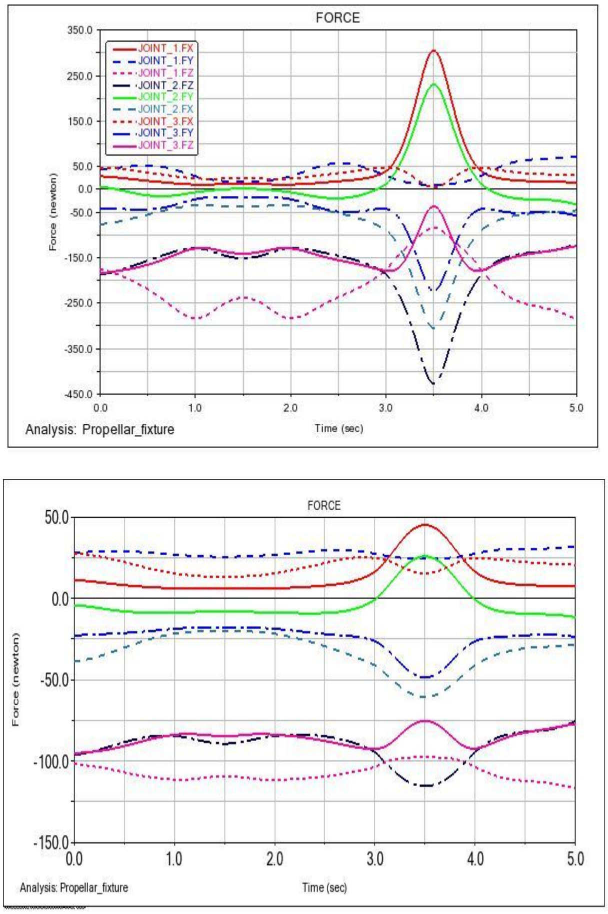


Fig 7: Force vs Time graph for joints 1,2, 3 during pitching and rolling movement demonstration

Coming to the torque which is shown in figure 8 is 21000 N-mm in the positive direction and 36000 N-mm in the negative direction during the pitching movement and 12500 N-mm in the positive direction and 12000 N-mm in the negative direction during the rolling movement. All the data is analysed for 5 seconds run during the simulation and the time can be changed for higher or lower time for future simulations or trials. During the pitching movement, all three arms are operational and show different torque in each arm which indicates the oscillatory behaviour and observes the vibrations in the arm. When it comes to rolling motion, only two arms are operational and the phase relationship helps us to understand the vibrational characteristics of the system, this is very crucial during the designing of the systems which helps us to minimize the vibrations and synchronize the motions. Overall, the graphs show performance and identify potential issues and optimize the design.

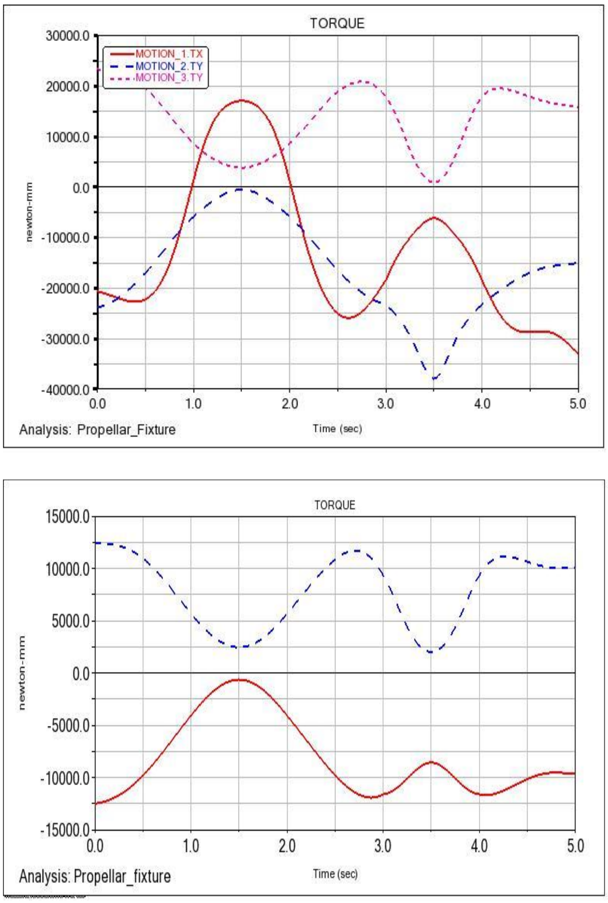


Fig 8: Torque vs time graph in the arm during pitching and rolling motion demonstration.

Table 1: Experimental and simulation values for pitching and rolling moments

	Experimental Value (deg/sec)	Simulation Value (deg/sec)
Pitching Moment	30	28
Rolling Moment	20	17

Table 2: Simulation values for the pitching moment

	Load (N)	Potential Energy (N-mm)	Kinetic Energy (N-mm)	Angular Velocity (deg/s)
Joint 1	285	-	-	-
Joint 2	40	-	-	-
Joint 3	40	-	-	-
Arm 1	-	-4800	80	-
Arm 2	-	7000	38	-
Arm 3	-	7000	38	-
Motion 1	-	-	-	90

Motion 2	-	-	-	90
Motion 3	-	-	-	90

Table 3: Simulation values for rolling moment

	Load (N)	Potential Energy (N-mm)	Kinetic Energy (N-mm)	Angular Velocity (deg/s)
Joint 1	115	-	-	-
Joint 2	88	-	-	-
Joint 3	88	-	-	-
Arm 1	-	0	0	-
Arm 2	-	6000	47	-
Arm 3	-	6000	47	-
Motion 1	-	-	-	0
Motion 2	-	-	-	90
Motion 3	-	-	-	90

The values of the load acting in the joints, Potential energy in each arm Kinetic energy and the angular velocity which is given as input is listed in the table 1, 2 and 3 for pitching and rolling movements. The angular velocity is decided from the chart which is taken from the standard motor and gearbox combination. This angular velocity can be changed and simulate to find out the various possible outcomes.

6. CONCLUSIONS

In conclusion, the comparison between experimental and simulation results for pitching and rolling movements, as well as the forces and torque exerted on the arms during these movements, has provided valuable insights into the performance of the propeller testing fixture design. For pitching movement, the experimental and simulation results showed close agreement, with values of 30 deg/sec and 28 deg/sec, respectively. Similarly, for rolling movement, the experimental and simulation results were in good agreement, with values of 20 deg/sec and 17 deg/sec, respectively.

Additionally, the analysis of forces and torque during pitching movement revealed variations from -400 N to 300 N and -35,000 N-mm to 20,000 N-mm, respectively. Similarly, during rolling movement, the forces ranged from -115 N to 48 N, and torque ranged from -12,500 N-mm to 12,500 N-mm. The consistency between experimental and simulation results, along with the observed force and torque profiles, demonstrates the effectiveness of the propeller testing fixture design. These findings provide a strong foundation for further research and validation opportunities.

Future research could focus on refining the design parameters of the propeller testing fixture to optimize performance, enhance stability, and ensure safety. Additionally, further validation studies could be conducted under different operating conditions and environments to assess the robustness and versatility of the fixture design. Overall, the promising results obtained from the simulations open avenues for continued research and development in propeller testing methodologies, ultimately contributing to advancements in UAV technology and aerospace engineering.

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