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Subject: Completed Aerodynamics and Structural Evaluation: Reporting Successful Computational Testing of System Design and Materials and Recommendation for Materials Procurement, Assembly, and Hardware Testing

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Foreword

Electric remote control aircraft are a cornerstone of a comprehensive aerospace engineering education due to their accessibility and ability to be designed, built, tested, and flown by students. A crucial component of these aircraft is their electric propulsion system which generally consists of electric motors and propellers. Electric motors and propellers come in an extremely large variety and varying the combinations of motors and propellers will result in different levels of performance. A variety of student teams are currently participating in the *Aerospace 495 Systems Engineering Leadership Course* taught by Professor George F. Halow. These teams are creating quadcopter drone racers (Michigan Drone Racing), an electric vertical take-off and landing (e-VTOL) aircraft (Michigan Vertical Flight Technology), and a conventional take-off and landing aircraft (MACH). All of these teams need to test their propulsion systems to ensure their motor and propeller combinations meet the needs of their architecture. As such, Professor Halow has tasked us with designing, building, and testing a modular electric motor dynamometer and thrust test stand capable of covering the range of motor and propeller requirements that are covered in the Aerospace 495 course. We have accomplished design of the system and computational testing of the structural and aerodynamic properties of our design. To validate that our system will be capable of handling the loads exerted on it we have used Finite Element Models with equivalent forces to those exerted by the variety of motors we expect to test. We then used Computational Fluid Dynamics to determine the optimal fairing shape for our structure to minimize the aerodynamic forces that may impact our readings and then iterate over potential test scenarios to ensure minimal aerodynamic impact. This memorandum details the rationale behind the conclusions drawn from our analysis, supporting data, and our recommendations for proceeding with the manufacturing of our design and subsequent testing of the full system.

Summary

We have successfully implemented a structural design that will withstand the forces acting on our structure and minimize its aerodynamic impact on our test results and have confirmed its feasibility, reliability, and effectiveness. This conclusion was achieved through finite element analysis and computational fluid dynamics modeling the specific forces and environments that our structure will endure. We determined that our system design is feasible by using trusted modeling software and ensuring that all our parameters were set with actual conditions in mind and ensuring that those forces and environments do not exceed the capabilities of our structure. Our system is also

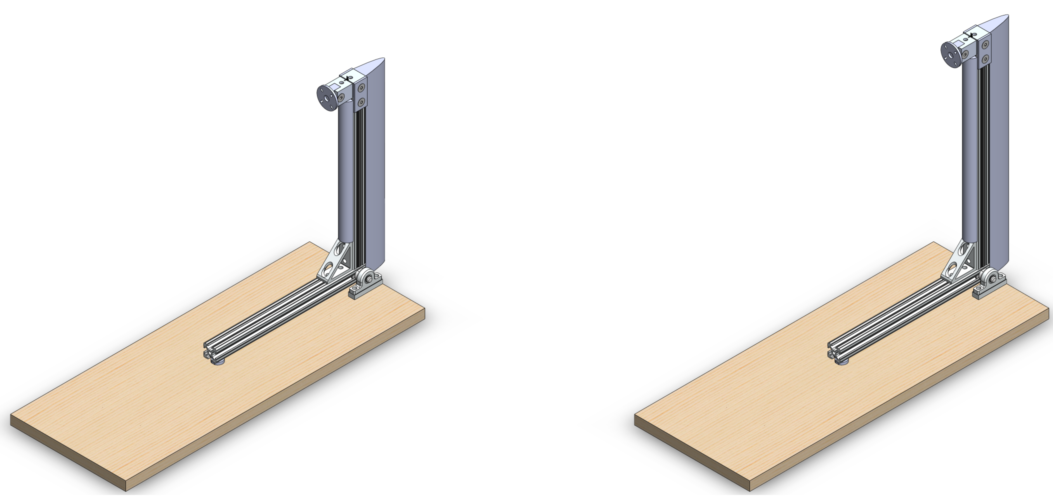
reliable as we ensured that our maximum expected stresses on the structure only cause minimal deflection in the beam and that our fairing is designed to minimize aerodynamic impacts on our readings. Finally, our system is effective because the modular design with interchangeable vertical arm allows for a large range of motor and propeller sizes and allows our system to fit within a wind tunnel. Our system is also designed to easily accommodate many motor types and easily run a variety of tests on them. After confirming the viability of our design through these tests, we have concluded that all our criterion have been met and recommend materials for assembly be procured and assembly to commence and static and dynamic testing of the system to begin.

Detailed Discussion of Computational Analyses

The following sections introduce the motivation for the problem, the experiment hypothesis, the criteria necessary to support our analysis, and quantitative support of the conclusion.

Introduction

In this report we present our method for determining the capabilities of our system design using Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD). To accomplish this, we first developed a detailed computer aided design (CAD) model of our thrust stand assembly. The CAD for the thrust stand was designed with manufacturing in mind. These computational analyses were done to demonstrate that our design, material choices, and manufacturing processes would produce a system that was feasible, reliable, and effective. Then, we selected most of the components we plan to purchase which allowed us to generate an accurate Bill of Materials (BOM) and ensure that our entire design will meet our budget constraints. Our design has two different interchangeable vertical arms for our thrust stand, one short and one long as shown in Figure 1. The actual construction of the thrust stand will be based on dimensions and drawings from this model so we ensure that the simulations we run will accurately represent our final product. For the finite element analysis, the complex portions of the assembly were simplified to reduce computational time. In particular, the flexure torque sensor was modelled as a rectangular block, and the bearing shaft was modelled as a bearing fixture. In addition, the load cell was modelled as a roller fixture such that it was constrained to the plane but was free to move laterally. For the fluid dynamics, various beam cross-section shapes were tested in a simulated wind tunnel using CFD software to determine a design with minimal drag for wind tunnel testing.



(a) Thrust stand with the 12 in arm (b) Thrust stand with the 15 in arm

Figure 1: Comparison in size of the two configurations of the thrust stand

Criteria Rationale

The criteria that must be met to determine the viability of our system design are feasibility, reliability, and effectiveness. We addressed the feasibility of our system design first, as we needed to ensure that our structural design, material selection, and overall approach did not result in system failures when the system is used at the limits of what is intended for the system. Reliability was another important factor, as we needed to confirm that our system design minimizes the impact of the structure on the measurements the system takes during both static and dynamic testing and thus provides reliable results. Finally, effectiveness is necessary as the primary purpose of this system is to provide a capable test stand for a wide range of electric propeller motors for use in and out of the wind tunnel.

To verify the feasibility, we ran FEA simulations at our maximum expect load of 20 lbf thrust and 15 lbf-in torque to ensure that our design was well below the yield stress of our chosen material. For the process to be reliable we used the same FEA model at max loads to verify that there was very little deflection in the system, which would impact the accuracy of our measurements. Another accuracy concern is the drag produced by inlet air during wind tunnel testing, particularly on the vertical arm of the test stand. The load cell measuring thrust will not be able to distinguish between this drag force and a thrust difference, thus reducing accuracy. To make sure that our measurement is as accurate as possible during these testing circumstances, we surveyed various cross-sectional shapes of the vertical beam using CFD simulations. Our design focused on modularity to increase the effectiveness for all the teams involved in Aerospace 495. Our interchangeable vertical arm and motor mounting plates allow for various sizes and brands of electric motors. Our torque measurement flexure device is compatible with all sizes of motors. These choices increase the effectiveness of our thrust stand for the teams involved in Aerospace 495.

Support for Thesis

Our design is feasible, reliable, and effective. These three criteria are analyzed and discussed in greater detail below.

Verification of System Design Feasibility

In order for our system design to be feasible, we need to ensure that it will be able to perform over the entire range of expected load. To do this, our FEA model was run with a range of thrusts and torques and the maximum stress in each run was identified. In doing this, we verified that the yield strength of the materials were never reached, allowing us to be confident in the feasibility of this design. Shown in Table 1 below, this was done with the full range of torques and thrusts for both the short arm and long arm model.

Thrust (lbf)	Torque (lbf-in)	Long Arm Max Stress (MPa)	Short Arm Max Stress (MPa)
20	15.0	105.641	91.098
18	13.5	93.877	81.988
16	12.0	83.446	72.879
14	10.5	73.015	63.769
12	9.0	62.584	54.659
10	7.5	52.154	45.549
8	6.0	41.723	36.439
6	4.5	31.292	27.329
4	3.0	20.861	18.220
2	1.5	10.431	9.110
1	1.0	5.224	4.566

Table 1: Maximum Stress of Both Long and Short Arm FEA Models

The yield strength of aluminum 6105-T5, the material used for our 80/20 aluminum extrusion, is 240 MPa at 23° C [1]. We find this to be a reasonable temperature for our operations, and have used this number as a baseline. From Table 1 above, none of our max stresses from either the long arm or short arm model reach 240 MPa. This increases our confidence in the feasibility of our design, as even our largest max stress in the long arm model still has a safety factor of almost 2.4.

Expected Reliability of Results Produced from Test Stand

To evaluate the reliability of the results from the thrust stand, we need to keep in mind two factors that would affect the accuracy of our measurements. First, any significant displacements in the thrust stand system would lead to inaccurate readings. Additionally, any drag on the stand when dynamically measuring thrust would also lead to inaccurate readings.

To investigate possible displacements in the system, the same approach was taken when looking at maximum stresses. An FEA model was evaluated over our entire expected operating range for both the short and long arm models. The maximum displacement in the model was recorded for each run. The results of this study is shown in Table 2. From these results, the maximum displacement for either model is at most under three hundredths of an inch. We determined that this is a very small in comparison to the lengths scales of our design. In fact, in comparison to the arms of the thrust stand, the displacements seen are about four orders of magnitudes smaller. We believe this is a small enough displacement to lead reliable results.

Thrust (lbf)	Torque (lbf-in)	Long Arm Max Displacement (in)	Short Arm Max Displacement (in)
20	15.0	0.0271	0.0194
18	13.5	0.0244	0.0175
16	12.0	0.0217	0.0155
14	10.5	0.0190	0.0136
12	9.0	0.0162	0.0117
10	7.5	0.0135	0.0097
8	6.0	0.0108	0.0078
6	4.5	0.0081	0.0058
4	3.0	0.0054	0.0039
2	1.5	0.0027	0.0019
1	1.0	0.0014	0.0010

Table 2: Maximum Displacement of Both Long and Short Arm FEA Models

To analyze drag on the stand, we used STAR-CCM+ CFD simulations. For the purposes of this experiment we wanted to look into the effects of different vertical beam cross-sectional shapes. Practically, this would be accomplished by putting a fairing over the front and rear faces of the vertical beam. Simulations were performed using the beam by itself, semicircular fairings, and one semicircular fairing on the front face with an elliptical section on the rear face to give the overall cross-section an airfoil shape as seen in figure 1. The results of this survey was that the airfoil style fairing performed the best, followed by the uncovered beam, and then the rounded fairings performing worst as seen in figure 2. The differences in drag between each beam increases as inlet airspeed increases. For this reason, we determined that the airfoil would be the most reliable design with a drag force of 0.79 pounds of force at 56 miles per hour inlet airspeed.

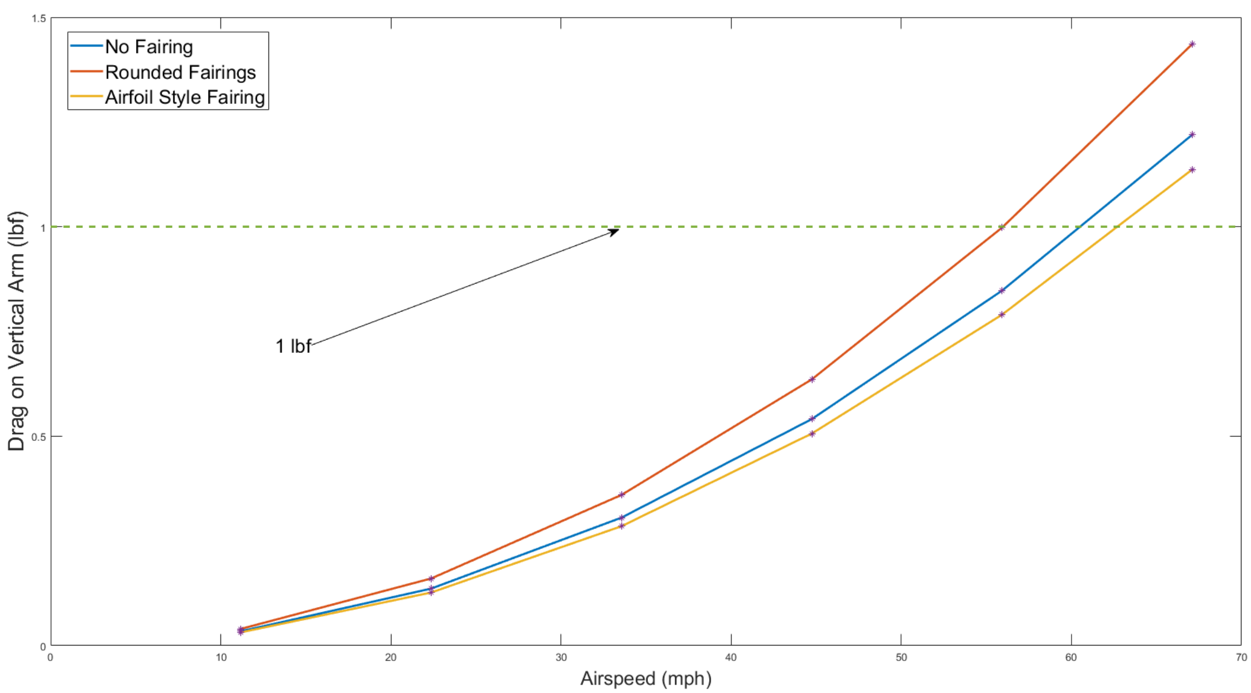


Figure 2: Drag of Various Vertical Beam Cross-Sectional Shapes Showing Increasing Benefits of an Airfoil Fairing as Velocity Increases (Raw Data on Table 3 of Appendix A)

Effectiveness of System Design
Our thrust stand has been designed with modularity as the main objective. The interchangeable vertical arm lengths allow for testing to occur for a variety of propeller and motor sizes. This also allows for the thrust stand to operate in both large and small wind tunnels, making test scheduling more convenient for the users. Our motor mounting plates will allow for the mounting of various motors with different bolt patterns. The various sizes of these plates will allow for testing on small motors and large motors on the same stand. Our unique flexure torque measurement device allows for torque data to be collected from all ranges of motor sizes that fit on the thrust testing stand. This innovation increases the effectiveness and accuracy of the data from other more traditional torque measurement solutions. These system design choices increase the effectiveness of our thrust stand and allow it to meet a wide variety of team's thrust testing needs.

Testing and Empirical Data
As stated before, in order to model the thrust stand system in FEA many of the complex structures were simplified. This included the flexure assembly being modelled as a rectangular block and the bearing pivot being modelled as a bearing fixture. The CAD model was done in Solidworks and the FEA was done in the Solidworks built-in simulation tool. The load cell and the sides of the pivot were modelled as roller/slider fixtures so that they would be constrained in the plane but can move laterally. The built-in 6061 aluminum alloy material model was applied to the model due to convenience, which has the same properties as the 6105-T5 alloy, just a lower yield strength. The mesh was generated using Solidworks' automated mesh tool, but mesh control was applied in order to ensure that there were at least 3 elements across each dimension to accurately model the problem. In Figure 3, a zoomed in display of the maximum stress point is shown along with the mesh for the max loading condition of 20 lbf of thrust and 15 lbf-in of torque on the long arm model. The maximum stress ended up being in the same region for all the simulations, right where the 90° bracket met the horizontal arm.

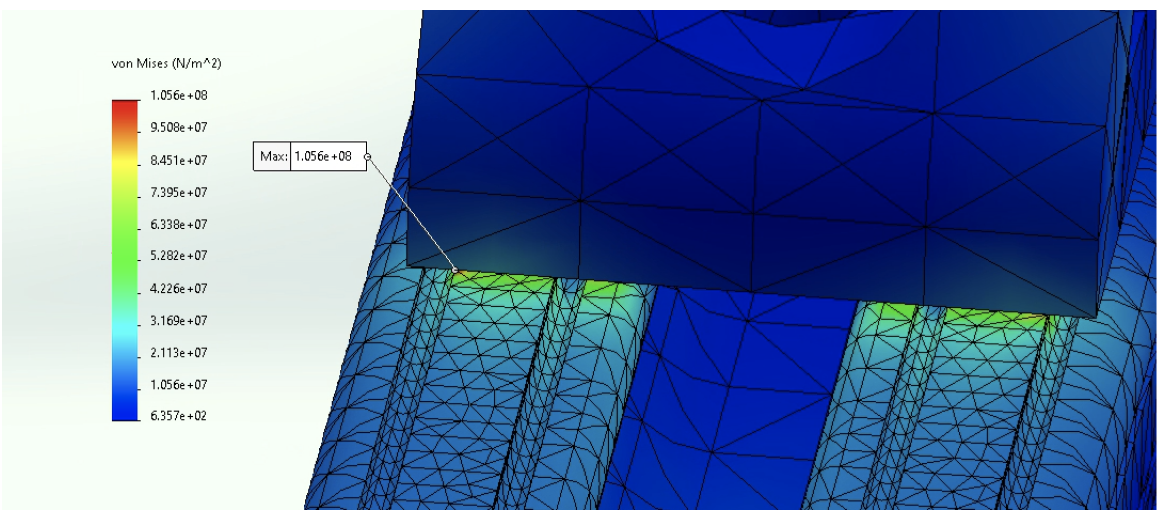


Figure 3: Max Stress for Max Load Condition on Long Arm

As previously mentioned STAR-CCM+ CFD simulations were used to model the drag of the stand. Because the only variable between these design is the vertical beam cross-section, simulations were performed using the 15 inch beam by itself, with semicircular fairings, and with one semicircular fairing on the front face and an elliptical section on the rear face to give the overall cross-section an airfoil shape. The simulations were then run with the respective beam suspended, centered in a simulated 2 foot X 2 foot wind tunnel using iterations with intake airspeed of 11, 22, 34, 45, 56, and 67 miles per hour.

Proposed Testing of Fully Assembled System

Our future testing will include the testing of the physical structure, once assembled, and the software package to be included with this structure. This testing will use calibrated weights and measures in order to better understand the reliability of the system as well as to calibrate our various measurement systems. We will also be putting our structure, shrouded with an aerodynamic fairing, into the wind tunnel and testing the amount of drag that the system generates with the goal of minimizing this effect. We are confident that the testing that has been done so far using computational methods will allow us to minimize initial testing of the system. Once this initial testing, as described above, is complete, we will move to testing known motors. We will start with those available via the Aerospace 405 Laboratory and comparing to results from existing thrust test stands and manufacturer specifications. Then we will move on to motors used by the teams participating in the Aerospace 495 course. These motors will have relatively well-known performance characteristics and will help us determine the reliability of the test stand across different motor types and sizes. We will use all of these test campaigns to test our hardware and software, calibrate all of our measurement systems and thoroughly test the usability of our system.

Omissions, Errors, or Limitations

In the testing done for this phase of the report we have omitted analysing the direct forcing of our load cell and torque measurement system. This is because we have a good understanding of the forces that these components will see and we will be procuring these components. As these components will be purchased and not designed and built by this team, we can ensure that they are capable of withstanding the forces that we will be applying to them.

During this analysis we understand that our method for generating these computational results invoke some level of error. These errors likely arise from discrepancies between the materials used within the Finite Element Analyses, differences between our CAD model and our actual structure, and potential user errors in setting up the models. However, we do anticipate these results to be very similar to what we will see on our hardware and we have ensured that we have gone above the actual expected forces and wind tunnel speeds that our system will see to ensure we have enough margin for error in our analysis.

This analysis will also have various associated limitations. Primarily, there are limitations from the computational models used both for FEA and CFD and limitations in our experience setting up and using these models. These omissions, errors, and limitations will not prevent us from confidently using our analyses to verify that our design is feasible, reliable, and effective as we understand that they exist and have ensured that our analysis mitigates them as much as possible and will do physical testing on a completed system before our system can be deemed complete.

Conclusion

From our results, we conclude that our system system design is feasible and capable of withstanding all of our expected forces, the overall system is reliable and will produce repeatable results as the system design introduces minimal impacts on the readings, and our system is effective as it will be a capable test stand that will accommodate a large range of motor and propeller sizes which is the overall goal of this project. Since this analysis indicates our design is valid, we will now begin materials procurement, manufacturing, and static and dynamic testing of our thrust stand and its associated software.

Appendix A: Raw Drag Data From CFD

	Drag (lbf)		
Airspeed (m/s)	No Fairing	Rounded Fairing	Airfoil Fairing
5	0.0345	0.0400	0.0318
10	0.1362	0.1604	0.1269
15	0.3056	0.3598	0.2851
20	0.5408	0.6356	0.5062
25	0.8475	0.9979	0.7901
30	1.2197	1.4362	1.1368

Table 3: Drag Results of Various Cross-Sectional Shaped Beams

References

[1] ”AA Standards Grade 6105 T5.” Matmatch Available: https://matmatch.com/materials/alky16105229t50-aa-standards-grade-6105-t5