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The Construction and Flight Testing of a Scaled, Remotely-Piloted, Flight-Test Vehicle

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Abstract

The high cost of prototype flight testing can be a limiting factor in the optimization of new designs as they proceed from the drawing board to the flight line. The use of low-cost scaled models to predict full-scale prototype performance is the focus of this project. It will be shown that by strictly following geometric and dynamic scaling criteria, the scaled aircraft's flight performance can be predictably related to the full-scale aircraft's performance. Although many companies have performed scaled flight-testing of Remotely Piloted Vehicles (RPV's), published non-proprietary information about low-cost, scaled flight-testing is essentially non-existent. The focus of the project at hand, therefore, is to compare the in-flight performance characteristics of a 1/3-scale flying "prototype" of a Cessna 172P to the well-documented in-flight performance characteristics of a full-scale Cessna 172P. Much flight testing has been done by the Aerospace Engineering department at ERAU, using the 172P, such that using this aircraft as the model for determining the validity of the scaling hypotheses is considered technically sound. The author, with the aid of students from capstone design classes at ERAU, designed and constructed a 1/3-scale replica 172 as the flying test-bed from which a series of future scaled prototype projects will draw vital conceptual and procedural ideas. The model 172 will be flown by remote control and will have an array of on-board sensors to collect information about key flight characteristics. Along with the on-board data acquisition system and real-time display ground base, the craft will also have a real-time video/audio link to the ground to allow the pilot to fly maneuvers using visual flight cues comparable to those he would have in the real plane.

Introduction

A new aircraft often spends many years progressing through the stages of conceptual and preliminary design. After a prototype is built, the aircraft begins the long process of flight testing. Depending on the size of the project and complexity of the aircraft, this stage usually takes years to complete. Whenever such amounts of time are spent on developing the aircraft, the costs quickly rise. If problems should arise during flight testing, the result could be an extension of the flight test plan and a further increase in the project cost.

There are, however, alternative methods to producing the desired data required to complete the analysis of a new design. One of these--wind tunnel testing--has been utilized since the days of the first aircraft. According to Eastlake[1], wind tunnel testing can be a quick and relatively inexpensive way of evaluating the performance of a new design. Wind tunnel tests can, however, be very extensive, and, considering the cost of time in a major tunnel facility, can still be very expensive. Perhaps the single greatest advantage of wind tunnel testing to flight testing is that, since the testing is done on the ground, the danger of a fatal crash is eliminated.

The other alternative method, while not entirely new, is growing in usefulness and accuracy. That is, flight testing, of remotely-piloted, sub-scale vehicles. Flight testing of RPV's is not a new concept. For many years, companies have used scaled versions of prototype aircraft to prove basic performance characteristics and, even sometimes, just to see if their design is airworthy. Only within the most recent design generation has the miniaturization of electronics allowed these companies to collect large amounts of data from an almost unlimited range of parameters. Because of this, flight-testing of scaled versions of prototype aircraft can be considered a viable alternative method for producing the data originally obtainable only from full-scale flight testing.

Each of the three methods mentioned here have their advantages and it is not the author's intention to discourage the use of flight testing or wind tunnel testing in assessing performance. It is, however, intended to show the advantages of using remotely-piloted, sub-scale aircraft for flight testing. The following table shows some of the advantages and disadvantages of each of the evaluation methods discussed.

Table 1: Performance Evaluation Methods

Type of Testing	Time Span Required	Project Cost ($)	Safety	Instrumentation Type	Data Accuracy
* Flight Test	Years	10^7-10^8	Dangerous	Packaging Difficult, Telemetry Required	Best Available
* Wind Tunnel Test	Months	10^6	Safe	Stationary, Fairly Easy	Good
RPV Scaled Flight Test	Months to Years	10^4-10^5	Safe	Packaging Difficult, Telemetry Required	Good to Best**

*- Taken from reference 1

**- Dependent upon the ability to produce precision maneuvers remotely

It is the intention of this project to show that the use of moderately large, sub-scale models can be used to gather data to evaluate a new design. It is assumed, though, that the model will be constructed and flown in a very precise manner. If care is not taken in the design, construction and flight testing of the RPV model, there is no guarantee as to whether or not the data will be useful.

Previous/Current Research

The Aerospace Engineering Department at Embry-Riddle has been conducting flight tests using a 1986 Cessna 172P as part of an elective lab course. From years of successful testing, ERAU has acquired a sizable knowledge of the basic performance and flight characteristics of the C172P. It is because of this large database of performance data on the C172P that the make and model of aircraft on which to start sub-scale flight testing was obvious.

As part of the Advanced General Aviation Transport Experiments (AGATE) projects over the last few years, aerospace engineering students at ERAU have designed a next generation general aviation trainer/moderate performance aircraft. In 1996, the author served as the lead engineer on the team responsible for the final configuration of the design. That year, the design took first place in the annual AGATE design competition. It was then decided that the continuation effort be placed into building and flying a 1/3-scale prototype model. The students quickly realized that to validate the sub-scale flight-testing of an unproven design, sub-scale flight-testing of a proven design would have to be conducted to verify the accuracy of scaling laws to be used in the AGATE project

Scaling the Aircraft

There are many types of scaling to consider when developing a scale prototype model. For the most part, all scaled aircraft used for flight testing should be accurately scaled in both geometry and dynamics. The first of these--a geometrically scaled model--is the simpler in concept but can sometimes be just as difficult to reproduce as a dynamically scaled model.

A geometrically scaled model is one where all linear dimensions of the aircraft are a scale factor of the original prototype. In the case of a 1/3-scale Cessna 172P, the full-scale aircraft has a wing span of 36 ft. Therefore, the model should have a wing span of 12 ft (L/3). Upon scaling all linear dimensions by 1/3, it can be seen that all areas then are scaled by 1/9 $(L/3)^2$ and all volumes are scaled by 1/27 $(L/3)^3$.

A dynamically scaled model is one that responds in a scaled manner--with respect to the full-scale aircraft--when subjected to inertial loads in addition to other aerodynamic loads. To do this, one must properly scale the weight--or mass--distribution of the aircraft. This is accomplished by scaling the mass moments of inertia about the three axes of rotation at the center of gravity. If done properly, the sub-scale aircraft should maneuver in dynamic scale of its full-scale counter-part.

The following table shows the scale factor used to adjust full-scale parameters to 1/3-scale parameters for the Cessna 172P. In each case, the multiplier is a factor of the scale factor, 3. Many of these factors are obvious, but some may require a bit of calculation to validate. This topic not in the scope of this paper but is explored further in reference 2.

Table 2: Basic Scaling Factors[3]

Parameter	Full-Scale Value	Multiply Full-Scale by:	1/3-Scale Value
Linear Dimensions	36 ft	1/3	12 ft
Area	174 ft^2	1/9	19.3 ft^2
Volume, Mass, Force	2400 lbs	1/27	88.9 lbs
Moment of Inertia	1346 sl-ft^2	1/243	5.54 sl-ft^2
Linear Velocity	120 kts	1/1.732	69 kts
Linear Acceleration	3.8 g	1	3.8 g
Power	160 Hp	1/46.77	3.4 Hp
Wing Loading	13.8 lb/ft^2	1/3	4.6 lb/ft^2
Power Loading	15.0 lb/Hp	1.732	25.9 lb/Hp
Angles	30 deg	1	30 deg
R.P.M.	2750 RPM	1.732	4763 RPM

There are some inherent problems with the scaling of an aircraft (that are also a concern when wind tunnel testing). The problem results from the differences in the nature of the aerodynamics at low and high speeds. The Reynold's number (Rn) is usually used as a standard of comparison here and can be used to account for differences in parameters like lift and drag on various objects. Wind tunnel and RPV models tend to have low Rn due their smaller size when compared to full-sized aircraft. The result of this difference in Rn is an increase in the drag coefficient along with a reduction in the lift coefficient. To avoid the problems with Reynold's numbers, it is important that the model to be, physically, as large as possible to keep the Rn as high as possible.

Another parameter to consider when scaling is Mach number. In this project, Mach number difference is not nearly as important as Rn, as both the model and the full-scale aircraft fly at speeds well within the incompressible range.

Turbulence in the air can also cause unwanted problems for a sub-scale flight-test vehicle. Since scaling an aircraft to produce a model does not reduce the scale of turbulent eddies and wind gusts in the atmosphere, the model must be built to accommodate larger g-loads. This should be accounted for in the analysis of the structure using the maximum g-loads from the V-n diagram. For the C172P model, the gust velocities required for consideration by FAR Part 23 were found to be able to produce as much as 5.8 g's on the structure, significantly greater than the 3.8 g's that the full-scale aircraft is certified for.

The RPV 1/3-Sale Cessna 172P

The construction of the model C172P represents a perfect marriage of standard model building technique and high-tech, high-precision manufacturing. The majority of structure of the aircraft is a mixture of aircraft-grade birch plywood and spruce. This made structure easier and faster to build. A high strength-to -weight ratio was another factor in material selection. Other portions of the aircraft are constructed from materials including 4130 steel, 6061 and 2024 aluminum, fiberglass, and carbon-fiber. Balsa was used for fairings and other non-structural elements.

Since the model C172P would be required to fly precision maneuvers, it is obvious that the model must be built as precisely as possible. This was accomplished by constructing jigs used to build the structure and perform wet lay-ups of the skins. The aircraft is designed to be modular and can be disassembled into four major components--fuselage, wing, horizontal stabilizer, and vertical stabilizer--and many sub-components. Items such as the engine mount and main landing gear were designed and built in-house by the author, along with students in the capstone design classes and the department’s machinist. Other parts such as the nose gear strut, brake system, engine, radio, and camera were purchased as off-the shelf items from various vendors.

The design of the RPV C172P has been used as design and manufacturing projects by a number of design teams in the capstone design classes at ERAU. The task of the preliminary design teams of the fall semester, 1997, was to conduct continue the AGATE effort using the C172P project. The students managed to acquire $7500 to pay for the construction of the aircraft. The detail design classes of the spring, 1998, conducted the stress analysis of the entire aircraft. The results of this semester began the actual construction of the model. The detail design teams of fall, 1998, designed and analyzed the landing gear and also finalized the weight and balance. Throughout the entire building process, various students learned to use the 3-axis CNC vertical milling machine to manufacture parts for the project.

When constructing a model which is intended to be dynamically similar to a full-scale aircraft, it is recommended that the empty weight of the model be kept to approximately half of its gross weight[3]. This is to facilitate the addition of ballast to the aircraft to adjust the moments of inertia (MOI). Ballast added along the x-axis of the aircraft forward and rearward of the center of gravity (CG) are used to adjust the MOI about the pitch axis. Similarly, ballast mounted left and right of the CG adjust the roll MOI. Both sets of ballast will adjust the MOI about the yaw axis and so it is important to plan ahead. The model C172P was specifically designed and constructed with this in mind.

On-Board Data Acquisition System

Any flight test vehicle needs to have a method of recording or presenting data to the flight test engineer. The use of a remotely-piloted vehicle requires that the data be taken and either stored to disk on-board the aircraft or transmitted down to the ground. Since feedback information from on-board sensors could be used to help fly precision maneuvers, it was decided to construct an on-board data acquisition and transmission system (ODATS). The author developed the preliminary layout of the systems and sensors in the spring of 1997 [2]. This was then further developed in detail by a group of avionics engineering technology students at ERAU under the advisement of Dr. Al Helfrick.

The final system can measure up to 60 different parameters from sensors mounted throughout the aircraft. The data is then assembled and sent to the ground via a 2.4 GHz wireless modem using standard transmission protocols. The model C172P only utilizes 12 of the channels of data. These are: engine RPM, cylinder head temperature, outside air temperature, total (Pitot) pressure, static pressure, vertical acceleration of the CG, aileron deflection, elevator deflection, rudder deflection, throttle position, angle of attack, and angle of sideslip. Some of these parameters are used to calculate (in real-time) basic flight parameters (i.e., velocity/airspeed) to help the pilot fly the aircraft.

ODATS Ground Computer

The ground-stationed pilot will be presented with a healthy array of information in graphical format by the ODATS computer. The ODATS signal is sent from the aircraft and received through the base unit of the wireless modem by a laptop computer. Using computer software custom written by CCT Coporation[2] to run on a Linux platform, the data is picked apart, preliminary analyzed, and presented to the pilot through a series of computer generated analog meters, strip charts, and real-time graphs. The data is displayed to the pilot in a familiar form, using gauges such as an airspeed indicator, a vertical speed indicator (VSI), a tachometer, and more. Along with presenting the data to the pilot, the function of the ODATS ground computer is to store the down-linked data for future analysis.

Flight with visual cues

To aid the pilot in flying precision maneuvers, it was decided that a visual down-link be established. A miniature color amateur TV (ATV) video camera was purchased which, when placed at the pilot’s-eye-view, shows the view looking out the front glareshield of the aircraft. This video signal (along with one for audio) is transmitted to the ground via a 915 MHz signal to a ground station and displayed on a 9" TV/VCR set. The pilot can use flight attitude cues given on the TV screen along with the flight data presented on the display of the ODATS computer, to fly precision maneuvers.

Future Work

Upon completion of the airworthiness tests, the ODATS system will be installed and flight tests will begin. The first stage of flight tests will require the pilot to conduct basic maneuvers to prove the aircraft and its systems are capable of collecting data related to basic performance parameters such as level speed, rate of climb, take-off distance, and more.

Future flight tests will broaden the spectrum of data collected and begin to explore other portions of the aircraft’s envelope. Tests will be performed to explore characteristics at different load factors and flight speeds. Since the ODATS allows for significant expansion possibilities, the aircraft could potentially be fitted with rate gyros about all three axes and linear accelerometers along the two remaining axes to perform dynamic response tests.

Because of the wealth of real-time information provided to the pilot of the model C172P, the aircraft could be flown from a portable sit-in simulator. This is an option which could lead to many useful projects including training and debriefing through flight recording (an area currently under examination through the Human Factors department at ERAU), and incorporation of the ODATS into other future sub-scale flight test vehicles.

Summary

Flight testing of sub-scale aircraft is a viable source of quality data. When the construction of the test aircraft is done using strict guidelines and flight tests are conducted in a precise manner , the resulting data should correlate well with full-scale data. Since this is the case with the 1/3-scale Cessna 172P , it is believed that its flight characteristics will be comparable to that of the full-scale aircraft. In the future, other sub-scale flight-test aircraft built at ERAU can utilize the ODATS and on-board TV technology to assist in other sub-scale flight-test projects. The development of this system has utilized the capstone design course work of 3 semesters and future developments will most likely be conducted in a similar arrangement.

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