EXPERIMENTAL CHARACTERIZATION OF ELECTRIC MOTORS AND JET ENGINES FOR BLENDED WING BODY FLIGHT TEST MODELS

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November 2019

Abstract

In recent times, Unmanned aerial vehicles (UAVs) have demonstrated a significant potential as mean of concept validation in aerospace domain, an essential step before proceed with real scale testing. The Center for Aerospace Research (CfAR), specialized in production of Flight Test Demonstrators, recently has focused most of its efforts on the Blended Wing Body (BWB) scaled models on behalf of Bombardier. This new planes configuration consists of an hybrid shape with unique features able to match benefits from both flying wing and traditional aircrafts, making it a worthwhile object of study in the last few years. A first prototype made by CfAR is the 7% scale model (FTV7%) which is already under flight testing, while the other, the 16.5% model (FTV16.5%), is not ready to fly yet. Each of this models is a combination of numerous systems and subsystems that need to be tested and validated in order to get the predicted results. The objective of the present dissertation is to carry out a parallel design and development of propulsion system characterization for both FTV7% and FTV16.5% models. The first one mounts a pair of Electric Ducted Fan (EDF), while the other a couple of Jet turbine engines. The EDF motor have been ground tested obtaining useful performance maps and detecting unexpected vibrations. Concerning the 16.5% model, the efforts were addressed more on the design and development of an instrumented test bench, including a Labview Graphic User Interface (GUI). A preliminary design of the upcoming tests has been done too.

Keywords: UAV, Propulsion System, EDF, Jet turbine,Testing.

1. Introduction

Aerospace engineering sector at its side, has always demonstrated to be at the forefront in development of new concepts, showing consistent flexibility towards new technologies and new aircraft configurations, respecting though safety standards. ”For years, the airline industry has been seeking game-changing aircraft”, says John Grant, London-based senior analyst at OAG, the airline research and publishing firm. “Now they're finally arriving and are genuinely changing the way that carriers are able and willing to launch new services and frequencies”. Specifically, Grant says the latest machines can take us farther, faster, and move us in greater comfort than ever before. And in the process, they'll burn less fuel—meaning that even if airfares don't drop as a result, they probably won't go up as fast as they would otherwise [3].

BA in particular, is working on developing new BWB business jets, with an estimated entry into commercial service in 2035 [1]. The charge of building up Flight Test Vehicles (FTV) has been shared recently with the Center for Aerospace Research (CfAR) of University of Victoria (UVic), delegating most of design and manufacture tasks. The center of research,in collaboration with Quaternion Aerospace, has shown high professionalism in UAV design, production and testing.

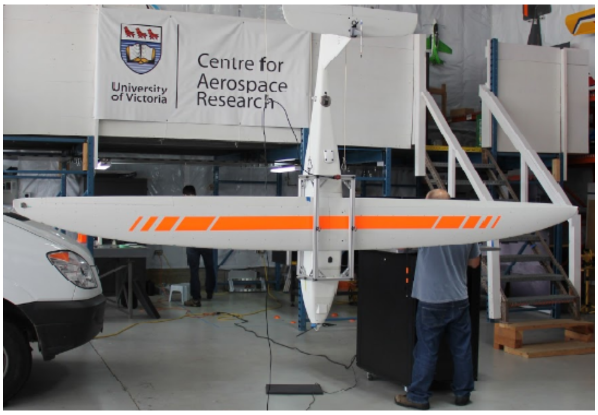

Figure 1: Uvic Center for Aerospace Research.

The first scaled model of the new generation aircraft so far described has materialized in the 7% scale of the large-scale aircraft. Along with this model testing, the CfAR has started working on the design and development of a larger scale flight test demonstrator, the 16.5% model, in order to get closer to what are the real physics and issues of the full scale aircraft.

The principle purpose of this dissertation is that of setting up suitable test benches for the propulsion systems of the two models. Moreover, it is intended also to accomplish ground tests for both systems, and analyze the collected data.

2. Engine Characterization

2.1. Electric Ducted Fan (EDF)

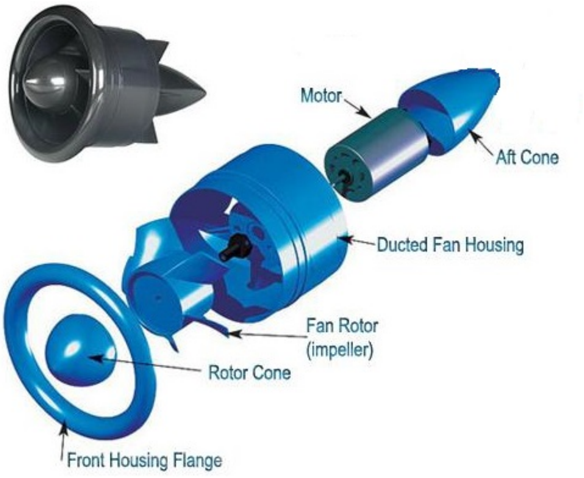

Figure 2: Electric Ducted Fan components.

Electric Ducted Fans (EDF) are widely used as propulsion systems in vertical and/or short takeoff and landing (V/STOL) uninhabited aerial vehicles (UAVs), and that because they offer a higher static thrust/power ratio for a given diameter than open propellers. Furthermore, due to operational requirements (LiPo batteries, constructive simplicity, high reliability) and the cost price, this type of motors are being increasingly used to power various types of unmanned aircrafts respect to small engine jet.

The analytical approach of a 3-D rotor flowfield is pretty complex, and is quite often replaced by a simplified, inviscid actuator disk model. The latter is originated from the combination of the radial equilibrium equation, energy equation, and the conservation of angular momentum principle across the fan rotor. The first equation consists of the force balance in the radial direction at a given axial position, balancing the pressure forces in the radial direction with the centrifugal force. The following assumptions are made:

- The airflow is incompressible;
- The effective size of the EDF unit is determined by the Fan Swept Area;
- The ducts are frictionless (neglected boundary layer effect);
- Ducts can be assumed to be circular in cross section;
- Vorticity due to rotating parts is ignored;
- The bifurcation and joining of ducts can be ignored.

In this approach, a pressure change term is computed from the first principles at each radial position of the rotor from hub to tip. The final result is expressed as pressure jump between the rotor inlet and exit:

$$\Delta p = p_2 - p_1 = \rho \left[U c_{\theta 2} - \frac{1}{2} \left(c_2^2 - c_1^2 \right) \right] \qquad (1)$$

Equation (1) allows the enforcing of a prescribed pressure jump p in the function of density, radial position, rotor angular speed, rotor exit swirl velocity $c_{\theta 2}$, c_1, and c_2.

The "efficiency" of the fan is the nearness to which the energy required is matched by the energy provided, or $Efficiency = P_{flight}/P_{fan}$.

The main researched curves during the characterization of an EDF motor are:

- Thrust curve known also as "performance curve", that shows the variation of the thrust through time;
- Thrust to throttle curve that shows the variation of the Thrust as a function of the commanded throttle;
- Thrust to RPM curve, that is quite similar to the previous one, having as x-axes the revolutions per minute instead of the command;
- Torque to RPM or to throttle curves;
- Consumed power with respect to time or to RPM;
- Efficiency curves.

2.2. Gas Turbine Engine

Development of Micro Turbine Engines (MTEs) began from attempts of application of that propulsion source by group of enthusiasts of aviation model making. Nowadays, the domain of micro turbojet engines is treated on a par with “full size” aviation constructions. The dynamic development of these engines is caused not only by aviation modellers, but also by use of micro turbojet engines

Figure 3: Modern jet engine "JetCat P80".

by army to propulsion of contemporary drones, i.e. Unmanned Aerial Vehicles (UAV) or Unmanned Aerial Systems (UAS) [2].

The analytical approach uses different thermodynamics law as well as dynamic's. The main output of this analysis is materialized in the equation of thrust expressed as:

$$F = \dot{m}_e u_e - \dot{m}_0 u_0 \tag{2}$$

is useful though to obtain the expression for the exhaust velocity u_e . That proceeds from the conservation of energy between after turbine and exit (stage 5-9). The exhaust velocity is hence:

$$u_e = u_g = \sqrt{2c_{pg}\left(T_{t5} - T_9\right)} \tag{3}$$

Looking at the parameters that best describe the performance of a turbo jet, the main ones are :

- Specific Thrust (I_a):

$$I_a = \frac{T}{\dot{m}_a} \cong u_e \tag{4}$$

- Thrust-specific fuel consumption ($TSFC$):

$$TSFC = \frac{1}{\alpha I_a} \tag{5}$$

The common outcomes from a Jet engine characterization are disposed below with some examples in Figure **??** .

- "Performance curve", that shows the variation of the thrust through time;
- Thrust with respect to throttle curve and the inverse curve ;
- Thrust with respect to RPM curve and rhe inverse that are quite similar to the previous one, having as x-axes the revolutions per minute (RPM)instead of the command;
- Torque with respect to RPM (or to throttle);
- TSFC with respect to time (or to RPM);
- Specific thrust curves;
- Exhaust Gas Temperature (EGT) to RPM (or to throttle);
- Efficiency curves;
- Thermal analysis either through sensors or Thermal cameras;
- Vibration analysis;
- Wind tunnel analysis for further aerodynamic mapping.

3. EDF Testing

The selection of the propulsive system has been done during the design phase, and the chosen one for the FTV7% consists of a pair of "Schubeler" EDF motors. These motors are known for their high performance and reliability, however, it's good practice to test them on ground before proceed with fly tests.

3.1. Test Rig Design

The test bench must be designed so that it is possible to accurately characterise different types of UAV engines, and it is good practice if it could accommodate both electric motors and tiny internal combustion engines. However, here in CfAR it has been chosen to test the electric motors inside the shop, therefore no tests with internal combustion engines are allowed. Regardless the kind of engines in question, the test rig must be portable and simply installed to simplify assembling/disassembling, as well as storage of the components. At last, it must be said that output parameters of the test have always a direct dependency on the set installed in the test bench, and this reflects clearly on the deign .
After discussing all these points with the rest of the team, it has been decided to use the same test stand used for a previous work. The stand was used to test a propeller driven by an electric motor with same power range of Schubeler EDF motor.
As first thing, it has been verified that the stand respects all the mentioned requirements, and it was found that the only modification that need to be done, was on the engine mount. To perform a more accurate testing it was found preferable to design and 3D print a mount that contains the shape of FTV7% nacelles.

3.2. Experimental Set Up

After planning everything, and purchasing all the missing components, it was time to finally set up the test bench. The installation of all the components was done on one of the available optical tables at

CfAR's shop. The main components of the EDF test rig are :

- the Engine Mount;
- the Electric Speed Control (ESC);
- the Power box;
- the Data acquisition system;
- the EDF power source;
- the Safety equipment.

The assembled test rig is shown in Figure 4

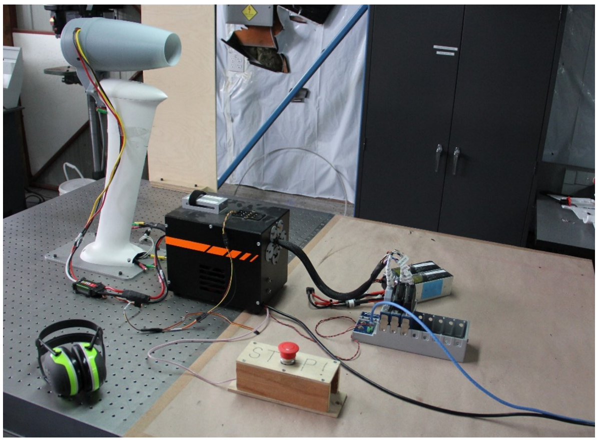

Figure 4: EDF test rig assembled.

3.3. Testing and Results

In this section will be presented the results obtained after having elaborated the data acquired from testing EDF motors. Moreover, It would be useful to take a look to the scheme in Figure 5 to have an idea on how work has been organized.

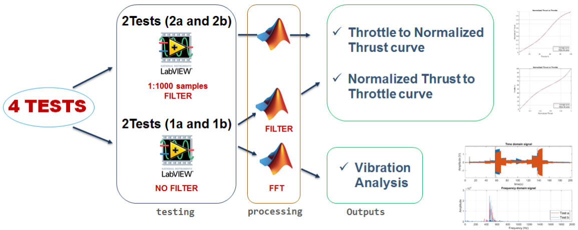

Figure 5: Scheme of the performed tests and analysis .

Before start running the engine, it was mandatory to test the ESC first. Although most of CfAR prototypes uses the same device as speed controller, it was proved that not all of them have the same upper and lower limit for arming, and thus send the signal to run the engine.
These have been found successfully.

Concerning the thrust test outcomes, these can be presented in the three different froms given below:

- average thrust curve with correspondent fitting one (Figure **??**); normalized$_{t}hrust_{t}o_{t}hrottle.pngnormalized_{t}hrust2.png$

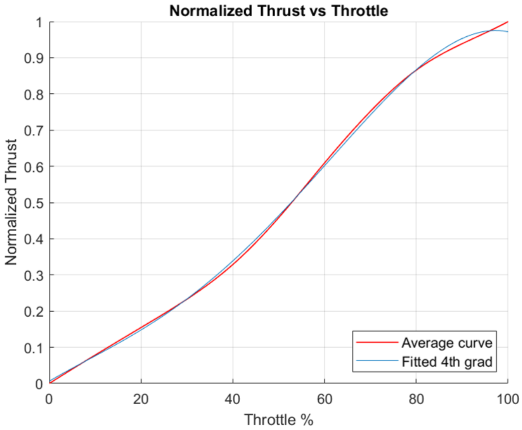

Figure 6: : experimental thrust curve fitted.

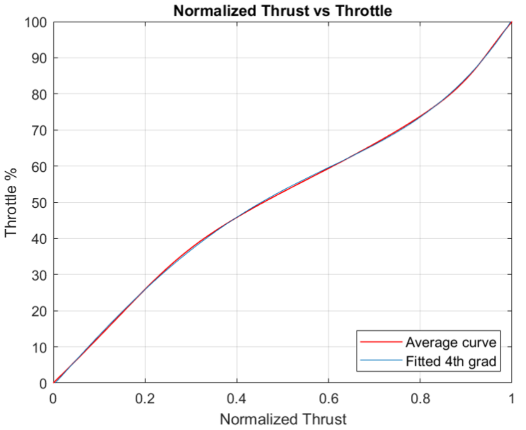

Figure 7: experimental thrust curves fitted.

- equations:

$$y = -2.4e^{-0.8}x^4 + 3.4e^{-6}x^3 - 7.4e^{-5}x^2 + 7.4e^{-3}x - 6.5e^{-3} \tag{6}$$

$$y = 16x^4 - 19x^3 + 12x^2 + 14x - 0.63 \tag{7}$$

- tables with relevant values (not shown here).

All the values presented above have been given to the flight team, and they are ready to be implemented on Simulink.
Another study performed is the Vibration Analysis. This part was not included in the planned tests, but since curious vibrations occurred during the tests, it has been decided to investigate the phenomena.

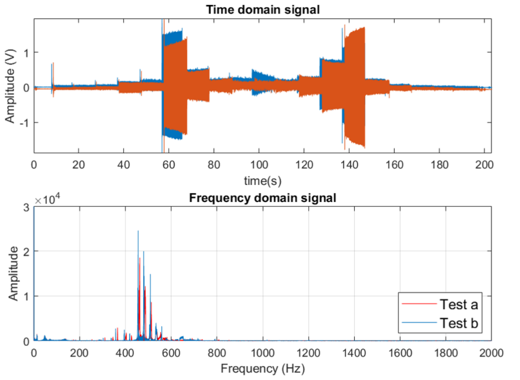

Figure 8: Vibration detection in two different tests.

The main results are that the values of 40%,50%,60% an 70% are the main responsible of this behaviour. The corresponding frequencies are given in Table 1

Throttle	RPM	Frequency
40%	22000	360 Hz
50%	25700	420 Hz
60%	29300	480 Hz
70%	32300	530 Hz

Table 1: Values responsable of vibrations.

After careful investigation, it was possible to state that the electric motor was the responsible since the values derived from ESC and FFT analysis, follow in good approximation the relation given below:

$$f = \frac{RPM}{2\pi \times 60\,(s) \times 6\,(poles)} \tag{8}$$

4. Turbine Jet Testing

Unlike the previous prototype, this new 16.5% scale model is powered by two gas turbines instead of EDF motors. The reason lies on the fact that the full scale aircraft will be mounting gas turbines and not electric motors, thus the scale model is much close to the full scale one. After selecting the propulsion system, the next step for the designers was that of selecting which one in particular will power the plane. The research ended with choosing two JetCat turbines, in detail the "P500/P550 PRO" model.

The functional requirements for JetCat testing were given by Bombardier guidelines documents. In brief , it has been decided to focus all the efforts on the following tasks:

- Design a jet engine Test bench;
- Select and purchase the required sensors;
- Design and test the software graphic interface;
- Set up the test bench and test sensors;
- Check the engine response to the command sent (without firing the engine);
- Check the correct operation of the feed system.

4.1. Test Bench Design and Equipment Selection

4.2. Software Development

Before start describing the software development, it is appropriate to take a look to the diagram present in Figure 9.

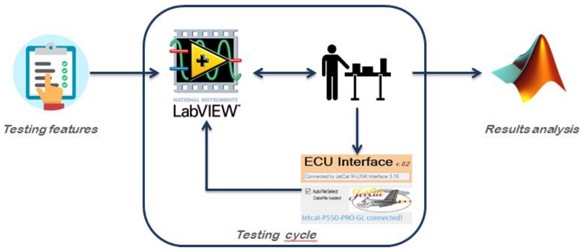

Figure 9: Multidisciplinary procces for JetCat tests.

In this project, there was the necessity of creating a new GUI since it was not made one for this typology of tests. The process of software design had also the purpose of provide CfAR a useful tool to be used whenever similar tests are made, reason way is it must be as accurate as general to fit any future application. The principal components of this GUI are:

- Throttle knob. Using this gadget it will be possible to send signal to the Pro interface that in turn will send to the engine. All the values used during the tests are recorded if button "LOG" is pressed;
- EGT Temperature thermometer;
- RPM indicator;
- Fuel tanks indicators;
- LOG button and file path;
- Thrust, EGT and TSFC Charts;
- STOP, TARE and CLEAR CHART buttons.

4.3. Experimental Set Up

After planning everything, and purchasing all the designed components, it was time to finally set up the test bench. This is shown in Figure **??**

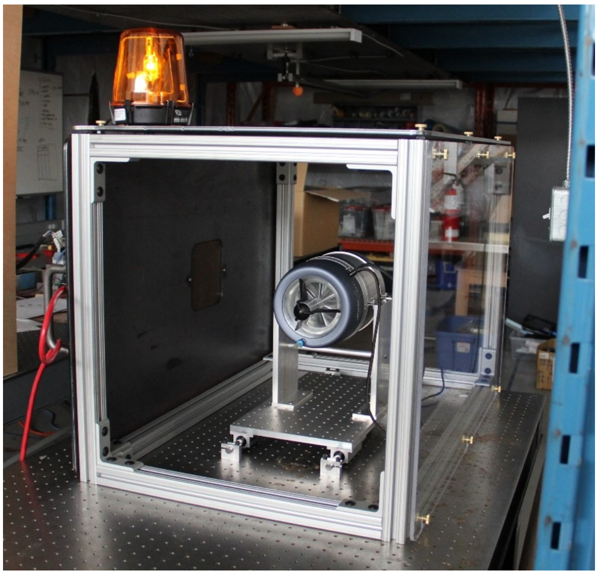

Figure 10: Jetcat Test rig.

5. Conclusions

Is always a good practice to give an idea about the future advancements, both to use it as a starting point for the upcoming project tasks, but also to complete the picture of argument treated.
This chapter will be presenting possible improvements and continuation regarding what have been already done for both propulsion systems. Each section will give an overview of both testing and software expected developments.
The main adviced updates on the EDF side is regarding the data acquisition system, in particulare to be using a cRIO instead o the previous cDAQ. The benefit from using this new device of the National Instrument is the possibility of working with real time signals both in Input and output, without the constraint of dealing with computer processor lags. In detail, this new data acquisition apparatus allows the user to send signals that are not affected by delays or lags thanks to the presence of a little processor inside the board itself, enabling the device to make its own time sampling.

Figure 11: cRIO data acquisition system.

Regarding the JetCat engine, it si presented a roadmap of the upcoming tests:

- Single Engine Thrust Test;
- Feeding System Tests
- Nacelle Tests;
- Dual Engine Control;
- Integrated Engines Thrust Test.

In overall, the present thesis work started with the objective of testing and characterize the two propulsion systems of both FTV7% and FTV16.5%. To achieve that, it was required to start a test bench design and development for both systems. In the case of EDF motors, luckily the test was almost ready, and few adaptions have been made before proceed with testing. From the other hand, the JetCat test rig did not exist yet, and was made from the bottom brick. However, at the end of the work, both test rigs were ready and have met all the pre-established requirements.
Unfortunately, although all the efforts on the readiness of the JetCat rig, it was not possible to start testing within the available time for the present dissertation. Nevertheless, a little chapter has been dedicated to describe the upcoming tests.
Returning to the EDF part, here the test have been performed with success, and lots of fascinating results have been achieved. Despite this good results, it was appropriate to suggest further developments in order to improve even more the model already made.
In conclusion it must be admitted the difficulty of designing respect to testing, at least in this experience after the enormous effort and time dedicated to JetCat project. All this may not stop CfAR engineers from moving forward on their design tasks, making every challenge encountered, just a step before triumph.

Acknowledgements

The author would like to thank all the members of family, friends and classmates who have stood beside me along this long journey. Warm thanks also go to the professors and Institutions who gave me an invaluable support in building myself. Particular thanks to the CfAR team for their acceptance and help along the composition of this research.

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