CONVERSION METHODOLOGY OF AN AUTOMOTIVE ENGINE INTO AN AERONAUTICAL ENGINE

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Abstract. *This work shows a report about a project to convert an automotive engine to an aeronautical engine. A review is presented and the economic relevance is pointed out. The conversion procedure is detailed along the text. During the project, were developed: a propeller test stand to measure engine thrust and torque; a software to simulate internal combustion engines; a reduction gear suitable for in-line cylinders engines; a methodology to obtain performance maps of turbocompressors and a procedure to calibrate a engine electronic control unit. The main result is a prototype ready to be tested onto propeller stand. The estimated engine cost is US$ 8,000.00 and the Brazilian market size is estimated in US$ 2.66 millions for the next three years.*

Keywords*: Propulsion, Aeronautical Engine,Conversion*

1. Introduction

The first conversion of an automotive engine into an aeronautical one was done by Santos Dumont, in 1898, to equip his Number 1 blimp (Villares, 1957). The conversion was made over an Otto cycle engine, with one cylinder, that powered a tricycle carriage. The engine, called Dion-Button, had 3.5 hp (2.6 kW) of power at 120 rpm. The main changes were the use of two cylinders, one over another, with a common crankshaft. The exhaust pipe was directed downside to prevent sparks from reaching the hydrogen balloon. The propeller was only two plates onto a transverse bar. The previous conversion trials were unsuccessful due the high weight/power ratio of the engines used: Gifard, 1852, with a steam engine; Tissandier brothers, 1883, with an electrical motor; and Renard e Krebs, 1884, also with an electric motor.

The development of the Otto cycle aeronautical engines was tremendous from the beginning of the XX century to the end of 1940's. During the 1950's the engines reached 2,000 hp (1,500 kW, Griffon V-12), but jet engine technology stop the research of aeronautical reciprocating engines. Since then, the landscape looks unchanged with small aircrafts with power requirements of less than 450 hp (335 kW) using piston engine and large aircrafts using turbopropellers or jet engines (Shiembob, 1995).

Today, piston engines equip aircraft classified as General Aviation and Experimental Aviation. This means all one engine aircrafts and some two engines aircraft using propellers. All aeronautical engines were projected at 1950's, most with a power output of 220 hp (164 kW). For experimental aviation there are engines with a power output of 80 to 180 hp, where there were a lot of converted automotive engines from 90 to 400 hp.

The conversion of automotive engines to aeronautical ones was very used until the 1930's. During the II World War this practice was suspended. Only with authorization to operate civil experimental aircrafts at 1960's, the conversion had started again. The most common conversion was of Volkswagen four cylinder boxer engine, air cooled. More recently, the V-6 and V-8, water cooled, engines (GM, Ford and Volkswagen) and Subaru four cylinder boxer engines were preferred for conversion (Finch, 1991).

Dix e Gissendanner, 1985, presented a work describing the criteria to select an aeronautic engine over new projects or derivative ones. The objective was discussing the criteria for military aviation and jet engines, though some aspects are also valid for general aviation. They said the engine is half the aircraft weight and more than half the aircraft price. The life cycle is said to be 35 years: 5 for development, 10 for production and 20 for operation. The present aeronautical engines are with 50 years. The Dix e Gissandanner criteria are political, economical and technological. The political aspect is subjective and aims short and long term views. The economical aspect is the development costs, return rate and operational and maintenance costs. The technological aspect evaluates the performance and the technical development risk. All three aspects are important to make a decision about a development.

The recent research focus is the Diesel cycle for aeronautical engines. The NASA approach is a two stroke, two cylinder engine into a boxer configuration (Willis et al., 1980). The NASA research program, called GAP (*General Aviation Propulsion Program*), aims to develop a Diesel cycle aeronautical engine with low initial and maintenance cost. Another Diesel engine was developed by a French company SCOMA, in 1999.

Knepp e Mullen, 1993, presented a description of a V-6 automotive engine conversion to aeronautical use. The result was a 550 hp (410 kW) engine, turbocharged, with a reduction gear that keeps propeller below 2,100 rpm and with 327 kg of total weight. The criteria for engine selection were maximum power and piston mean velocity below 15 m/s. The authors had made minimum modification at the engine to maintain reliability.

Shiembob, 1995, describes a Chevrolet V-8 engine conversion. This engine has 8,112 cm^3 of displaced volume, water cool system, fuel injection system and an aluminum block. The resulting engine, called Orenda, has 600 hp (447 kW) at take off and 500 hp (373 kW) of continuous power. With the turbocompressor the specific fuel consumption was 0.19 kg/hp/h and the propeller rotation speed was 2,057 rpm with a 2.14:1 reduction gear. The objective was replacing turbopropeller engines (PT6 engines, with 250 hp (186 kW) at 7,620 m) used in King Air aircraft. This power output is enough to propel the aircraft to a final velocity of 644 km/h. Until 1995, there were at Unites States 25,000 general aviation aircrafts with a potential market of 5,000 engines. The author reported that the present piston engine power varies from 65 to 400 hp at 7,620 m (maximum altitude), with a TBO (time between overhaul) from 1,500 to 2,500 hours. The most frequent maintenance problem was poor cooling. The aeronautical piston engine mean cost was US$ 250/hp and the aeronautical turbine mean cost was US$ 450/hp, with an overhaul cost of 30 % of the initial engine price.

A book by Finch, 1991, presents an extensive analysis of automotive engine conversion to aeronautical use. The estimated cost was US$ 20/hp, less than 10 % of a typical aeronautical engine. The difference of price was explained by volume of production. During 50 years, the Textron-Lycoming has produced 230,000 engines and meanwhile, the General Motors produced 250,000 engines per year for only one automobile model (Chevrolet Corvair, 1960). The author work covers engine reliability, engine selection criteria, main modifications, injection and ignition systems, exhaust systems, engine fixing structures, reduction gear, radiators, engine covers, engine weight, static tests, flight tests, certification and United States components manufacturers.

Data from the Brazilian government (MAer, 2004) counts 3,292 piston engine powered aircrafts. The experimental aircraft fleet is growing at 300 units per year. So, the total market is 350 engines per year for selling and replacing piston engines, giving a total market of US$ 3.2 millions per year.

Then, is possible to affirm that the conversion of automotive engines is economic and technical viable as approach to develop new aeronautical engines.

The most used conversion at Brazil is made over the air cooled Volkswagen engine (1,300 cm^3). One certified engine is produced by RETIMOTOR (JANE'S, 1990-91). Nowadays, the SUBARU, water cooled, boxer engine with an aluminum block is being more used. Some developments were done, like Silva, 1993, work that described a marine engine conversion. The aeronautical engine version was two stroke, water cooled and equipped with a new reduction gear of 2.57:1. The power output was improved by 30 %, by scavenging optimization, reaching 40 hp (30 kW) at 4,400 rpm.

Since the end of II World War, Brazil is training experts into aeronautics and astronautics. As a result, we could say Brazil has know-how to design fixed wings aircrafts of small and medium size. There are more than three aeronautical centers to teach experts. But the propulsion system is still treated as specification, selection and maintenance problem. There were no planning or long term policies to develop automotive, aeronautic or space propulsion system. The Brazil small aircraft industry world competitively will miss a local and cheaper propulsion system.

One important point is the present automotive engines are changing in a very fast way by integrating new technologies, as electronic injection and supervisor systems similar to that used in large aircraft jet engines. Though, these technologies are not spread into general aviation and could be a factor to reduce accident risk. This work intent to gather information to apply these new technologies to small aircraft engines aiming to improve safety.

2. Relevance and Objectives

The most successful engine development program, at BRAZIL, was the ethanol fueled engine in 1980's. Some local engine project, like the GURGEL case, had not a solid technological base leading to noncompetitive engines. The same happened in the aeronautical sector, where most engines do not passed certification tests. Only at the end of 2004 the first ethanol fueled aeronautical engine was certified, but it was a modification of a Lycoming engine. The Volkswagem 1,300 cm^3 converted engine is still used to propel most Brazilian ultralight aircrafts. This system has low reliability, low power output and is technological old compared to modern automotive engines. Then, it is necessary that new project uses modern engineering tools to maximize efficiency and reliability.

This project is a systematic study of a conversion of an automotive engine into an aeronautical one using modern testing procedures. The electronic sensors play an important role in such tests. The project aims to create, as a secondary target, an infrastructure of equipments and personal needed to develop aeronautical engines with the same performance and reliability reached by automotive engines.

The economical aspects could be seen by comparing final cost of today's aeronautical engines at market: A certified aeronautical engine cost almost US$ 30,000. A non-certified engine costs US$ 15,000; and an automotive engine converted costs US$ 10,000. If one includes the certification costs the converted engine price goes to US$ 15,000. Should be notice, the elimination of import taxes improves competitiveness of the converted engine in Brazilian market.

The proposal is to analyze the conversion procedure of a four cylinder FIAT automotive engine, water cooled. This engine presents low production cost, good performance and incorporates modern technologies. The final objective is to equip a very light airplane projected and build at Aeronautical Studies Center (CEA-UFMG).

3. Methodology

The stages to make a conversion proposed are detailed in this section. The endurance tests, flight tests and certification are not included in this work.

- **Engine selection**

In this stage was selected the automotive engine model to be converted based on power requirements of light aircrafts, engine weight, cost and availability. The FIAT FIRE 1,242 cm^3 engine, with four cylinders, 16 valves and water cooled, was selected following the above mentioned criteria.

- **Engine modelling**

It's a conjunct of tasks to predict the engine performance curves needed to analyze the aircraft/engine/propeller behavior. The objective is to develop a model able to calculate the brake power output (bhp) as a function of operational conditions (environmental, rotation speed and load).

The development line was: First was elaborated an algebraic model to establish a relation between the performance parameters and the cycle parameters (Barros and Valle, 2003). Second, was implemented the one zone, zerodimensional model. The differential equation terms had asked to engine components details. So, object models (classes) were constructed for cylinder, connecting rod, piston, crankshaft, cams, valves, etc. It was followed by models for ideal gas, isentropic flow, friction, heat transfer, manifolds, etc. After testing each component separately, the first results are taken. Third, a two zones onedimension model was implemented. During the model tests a new model for combustion was proposed and implemented. The model output was made compatible with the experimental data obtained at dynamometric tests. The human interface was not improved during this stage. The computational model implemented has the following characteristics (Barros, 2003 and Barros and Valle, 2001):

- The model uncertainty for engine performance parameters was 4 %, similar to the experimental uncertainty;
- The computational code is object oriented and presented flexibility and reusability. The encapsulating of data and methods allows to reduce errors related with input data;
- The one zone model was limited because required a lot of experimental parameters inputs;
- The momentum conservation equation was used for the first time to engine simulation and allowed to calculate the mean gas velocity in the cylinder as a function of mechanical movement of piston, connecting rod and crankshaft;
- The two zones model is able to predict the interaction between burned and unburned gas in a physical coherent manner. The model implements a hemispherical wave front with complex contour conditions (finite and variable geometry and volumes, heat loss, friction, mass flux, mixture combustion with composition variation);
- The two zones model automatically respect the pressure equilibrium between the burned and unburned gas as a result of the contour conditions;
- The detonation point detection could be made using the two zones model;
- A combustion model was proposed to estimate the turbulent flame velocity as a function of admission Reynolds and cylinder size. A combustion mechanism transition was predict to occur at 25,000 of admission Reynolds, this is, between 2,550 and 3,000 rpm;
- The geometric combustion chamber model was implemented in a way to became independent of burning phase;
- A new model for discharge coefficient for butterfly valves was proposed as a function of aperture angle;
- A Venturi effect was implemented to simulate valve overlapping;
- The model predicts pressure variation at carter and the blow-by mass flow;
- The model allows frequency analyses of engine running;
- An exergetic analyses was implemented into the computation code;
- The simulation cost was 50 % less than dynamometric test cost for one configuration.

The uses of the model could be:

- To optimize engine configurations;
- To develop a new engine;
- To evaluate different fuels;
- To analyze the performance of converted engine at aircraft altitude range;
- To analyze valve timing;
- To analyze various valves strategies;
- To analyze advance map;
- To analyze partial load engine running;
- To analyze dynamic behavior;
- To analyze supercharging.

The use of analyses object oriented was chosen to allow the model to grow without changing codes at basic classes' models, reducing code modifications. Some pre and pos-processing code should be developed due to the complexity of analyzing a large volume of output data. The computational code proved useful to teaching engine related matters.

- **Dynamometric tests - Reference**

In this stage the automotive engine was integrated to perform a series of static dynamometric tests. The results were used as a reference to compare the effect of the conversion modifications. The test stand allows measurement of torque and consumption at a constant rotation. The engine configuration was that for automotive use. A digital acquisition system was installed at the dynamometer to replace the manual readings. Eighteen variables were monitored: torque, rotation speed, fuel consumption, air flow, throttle, crankshaft angle, admission temperature and pressure, cylinder head temperature, in-cylinder pressure, exhaust temperature and pressure, water in and out temperatures, oil temperature e pressure, detonation signal and mixture ratio. The results were compared with the manufacturer data and showed good agreement, within the uncertainty allowed by test standards (Barros, Rodrigues and Valle, 2001 and 2002).

- **Engine conversion**

This stage was divided into 8 tasks for engine modifications to suit the aeronautical use, as follow (Santos, 2003; Brant, 2004):

- *Reduction gear* – design and construction of a reduction gear to rotate the propeller, since its maximum rotation speed is 3500 rpm;
- *Turbocompressor* – selection, acquisition and installation of a turbocompressor kit;
- *Air intake* – design and construction of air intake manifold due to usage of a turbocompressor and an intercooler;
- *Exhaust pipe* – design and construction of an exhaust pipe shorter, lighter and with a less efficient muffler;
- *Radiators* – selection and acquisition of two radiator, built of aluminum, to engine cooling and receiving air from propeller;
- *Weight reduction* – weight minimization of block and flywheel;
- *Engine structure* – design of a structure to support the engine at aircraft front;
- *Engine instrumentation* – specification and assembling of a minimum engine instrumentation that allows the pilot to control the propulsion group. Should be noticed that this engine has an automatic mixture control.

- **Dynamometric tests - Conversion**

After the conversion, the engine was tested at a dynamometric test stand to compare performance with the original automotive engine and with simulation runs (Silva, 2003).

- **Propeller test stand design, construction and calibration**

For the propulsion group test was design and built a propeller test stand. This test system allows measurement of thrust and torque at the same time as a function of the rotation speed. The instrumentation were designed and calibrated. Then, the propeller test stand was verified with an aeronautical engine ROTAX 532 equiped with a CEA two blades propeller, 1.4 x 0.7 m, (Castro, 2004 e Bach, 2004). The tests results proved that the stand is able to make the measurements needed to evaluate the performance of the propulsion group up to 164 kW (220 hp). (Barros, Valle and Figueiredo, 1999; Figueiredo, 1999; Figueiredo, 2000; Alves, 2003; Castro, 2004; Bach, 2004)

- **Engine tests at propeller test stand**

The propulsion group composed of the FIAT FIRE motor and the propeller is tested at this stage. The first test is a performance test, which .take two weeks. The others tests are of endurance, as specified at FAR 33.29 standard. The endurance test last 150 hours, divided into runs of 20 or 30 hours. The results are a measure of propulsive efficiency at take off conditions. This stage is being prepared to start this year.

4. Results

Figure 1 shows the converted engine prototype and performance data compared with data from the automotive engine. The main modifications made during conversion are:

- Garret GT12 turbocompressor installation after experimental mapping procedure of GT12 e T2 turbocompressor assemblies;
- New exhaust manifold;
- Flywheel weight reduction;
- New oil and water circuit;
- New air manifold between compressor, intercooler and original manifold;
- Turbocompressor electronic control valve;
- New electronic control unit (ECU) after mapping at dynamometric test stand;
- New wiring;
- Colder spark plugs;
- Smaller muffler;
- Reduction gear (2:1).

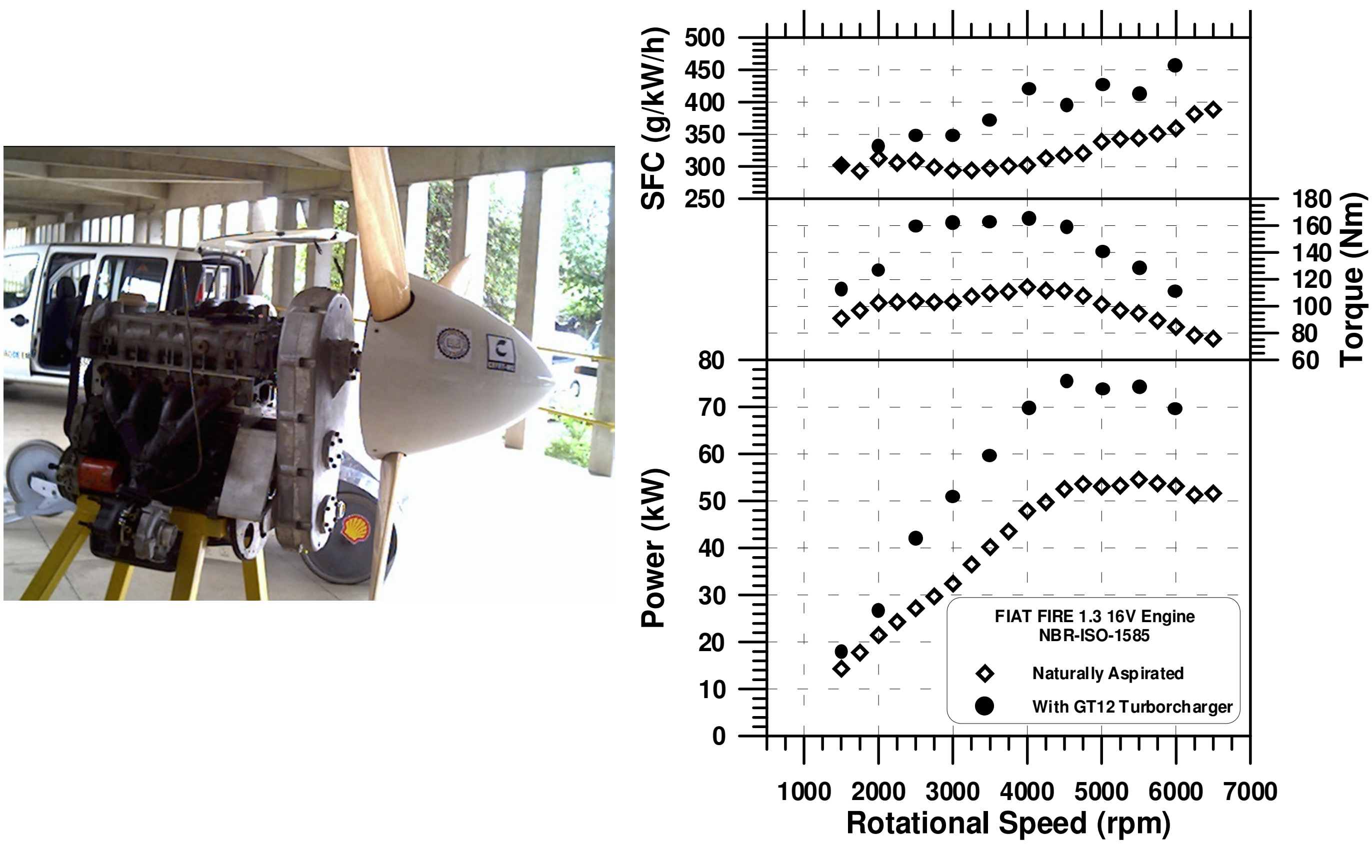

Figure 1. Converted engine view and performance data

News radiators should be prepared to the test at propeller stand, with a new thermostatic valve. A new propeller will be needed to increase the propulsive efficiency, since the actual was not projected to be used with this engine.

The propeller test stand was projected and constructed. The instrumentation was implemented, tested and calibrated. The stand has two degree of freedom allowing measurement of thrust and torque at the same time. An improvement is being planed to simulate flight conditions with a blower.

The reference tests were executed and included new quasi-static and dynamic test procedures. The results fit the manufacturer data and allowed to evaluate the limitations of the dynamometer test stand.

Two turbocompressor assemblies, GARRET GT12 e T2, were tested at a cold flux test stand to construct the map flow of each component (compressor e turbine). The GT12 assembly was selected because its flow parameters fit better to the engine working range. Also, two models were developed to calculate the maps flow (Rodrigues et al., 2002; Rodrigues, 2003; Wardil, 2004).

The new ECU, Motec M4, was able to control the engine with the turbocompressor. The mapping procedure was accomplished without problems (Valle, Barros and Baeta, 2004).

The reduction gear was design and constructed. At assembly stage suffered from typical holes misalignments, but it was corrected. It was pointed that some regulation system was needed to overcome misalignments. The full speed working test will be done at propeller stand.

The simulation software was developed and is named as C.A.R.E (Cycle Analysis of Reciprocating Engine). The code was object oriented and allows calculating the performance curves as function of engine geometry, fuel and environmental conditions. Another analytic model was implemented to be used in simulating engine control system that asks for real time processing.

The project took 3.5 years and was needed more six months to finish the first stage. The turbocompressor assembly took one year. The reduction year design took 1.5 years and more 6 months of fabrication. The propeller stand took one year of design and another year to be set up. The tests of the propeller stand took 3 months. The dynamometer tests took 320 hours (2 months) and spent 400 liters of fuel. All project cost was US$ 70,000, partially supported by FAPEMIG research support agency.

5. Conclusions

The estimated cost of the converted engine is US$ 8,000.00 and when compared with the lowest market price of US$ 15.000,00 for an aeronautical engine of same power output, it shows that the engine is economically viable.

From a technical point of view, the converted engine should be proved in an endurance test and flight tests before start industrial production. Though, the engine proved to be robust during the dynamometric tests and reach the specified power with a turbocompressor, without a reduction of any engine component life. The original engine reliability was reduced by mechanical components related with the turbocompressor. The new electronic control unit was adapted to the engine without major problems and proved reliable. The reduction gear was simple and safe, but added 20 kg more to the propulsion group.

The Brazilian market grows at 300 small aircrafts per year. Then, taking 10 % of the total market the production rate could be 30 engines per year. If we take a 5 % of replacing the Brazilian actual small aircraft fleet (4.000 units, MAer, 2004), is possible to sell 200 engines. Then, the estimated market in a three years period is US$ 2.66 millions.

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