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NEW PROPOSAL FOR THE FEASIBILTY OF DEVELOPING OF A AIR COMPRESSED ENGINE USING RAPID PROTOTYPING

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Abstract. *The development of new products has always demanded the production of prototypes in order to test concepts and verify the functionality of the design. The rapid prototyping technology has brought a variety of manufacturing processes in order to lead the project from the virtual world to the real world. The possibility of using rapid prototyping technology to produce functional parts of small dimensions is the focus of this work. It was chosen a compressed air engine as the functional system to be developed. This device has features fully known as its dynamic equations and structural parts integrated for its operation. Provided it is not a commercial purpose design, it is not of primary importance whether this product will have good market acceptance or market share. However, the product design methodology must be applied in order to organize and show the best solutions, which are not always easy see or to choose. This work presents the first stage of development, which consists of the feasibility study, exploration of the systems involved and testing of solutions.*

Keywords*: rapid prototyping, project development, air compressed engine*

1. INTRODUCTION

The ability to perform a work from different energy sources is a constant search for the modern world. The search for environmentally sustainable energy sources, which can reduce dependence on oil, has motivated the industry to develop new technologies especially regarded to automobiles, such as biodiesel, hybrid cars, fuel cell and air compressed engines.

The use of compressed air used in the current pattern, was first conceived by Denis Papin (1647-1712) the concept of transmission of compressed air in a pipeline, thenceforth many industrial applications with this type of energy has been used in all segments of the industry, services and trade (Filho, 1983).

The development of new products has always demanded the production of prototypes in order to test concepts and verify the functionality of the project. The rapid prototyping technology has brought a variety of manufacturing processes to the project to transform the virtual world into the real world in a easier way (Volpato, 2007). The possibility of using rapid prototyping technology to produce functional parts with small dimensions is the focus of this work. Aiming the production of a fully functional product, was chosen a compressed air engine due to completely known features like dynamic equation as structural parts necessary for its operation.

This work presents the development of a compressed air motor using the deposition manufacturing method, relatively new method, thus evaluating the advantages and disadvantages of using this method.Since the development of this product has not a commercial purpose, is not a primary importance whether this product will have good acceptance in the market or it is in an untapped market niche. However, a design methodology must be applied in order to organize and lead to the best route to follow, which is not always easy decision, and visualization.

2.OBJECTIVE

This study aims to understand the development process of functional mechanical models made by additive manufacturing. As a tool it is used the design methodology PROCRIA to monitor the project development. The mechanical model chosen is a compressed air engine because the mechanical behavior fully known reducing the quantity of variables to analyze.

3.METODOLOGY

Project Development

The process of product development can affect the cost of production by 50% or more, then we can conclude that the decisions made during the development process has a great effect with very low the cost over the product (Ullman, 2003). The process of developing new products can be divided into three basic stages: feasibility study, preliminary design and detailed design. In the stage of feasibility study, is done the market research focused on knowing in which niche a company should invest their time and capital, and thereby obtain greater success in sales and acceptance of its product. An example of this step can view in the case of Embraer, the company has evaluated the need for aircraft capable of transporting intermediate capacity (90 to 150 passengers) thus was developed the ERJ family of aircraft. Then the production process must also be taken into account in product development, since the production process directly influences the product cost. At this stage are created and defined concepts that will be taken into account throughout the project. You can then outline various solutions, and then check which of these are physically and economically feasible.

The preliminary design is the next step is to define the best model developed in the feasibility study and the model dynamic equations of the system. To choose of the best solution is made according to the performance of the prototypes. Aspects such as operation, durability and ease of assembly should also be considered. Beyond the dynamic behavior, the mathematical model describes relationship between geometric parameters and the cost of the project. At the end of this stage is defined the operating characteristics of the product and its main parameters of the project. The completion of the project development is done with the project details. Here are defined tolerances and details for orient the production. Detailed list of components, manual assembly and the systems are interconnected. These steps can be followed using the software developed in the doctoral work of Delgado Neto at 2009, called the PROCRIA.

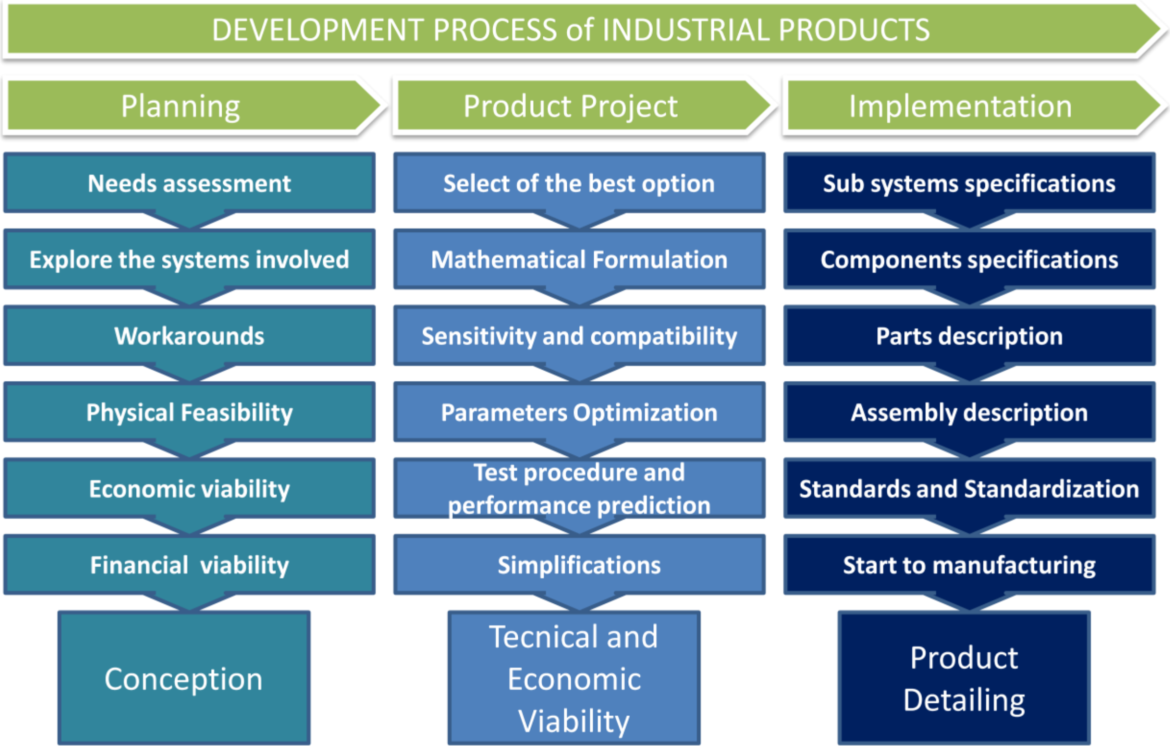

Figure 1 - Development Process of the Product

Computed Aided Design (CAD) modeling

The three-dimensional modeling of the components was made using SolidWorks ® 2007 and Rhinoceros ® 4.0 software. For most of the components, SolidWorks is more suitable because it use features and parameters concept in its structure creation, making the change of dimensions much easier. The Rhinoceros software is much more suitable for the development of complex geometries with curvatures as in the propeller. Parts coming in contact in the assembly are designed with 0.1 mm of interference, to reduce the gaps that could be generated by dimensional variation caused by the process of prototyping. Depending of the interference between the parties, the adjustment is made with a thin sandpaper or let to fit itself by the wear of the use.

After completion of the modeling, the CAD model is transformed into a format called STL format (.stl) which was established by 3D Systems in 1987 by the Albert Consulting Group. An STL file represents an object by a mesh of connected triangles. This type of file can be called tessellated object or as a faceted object (Lee, 1999).

Prototyped parts

The proposed rapid prototyping applied to the production process open a new range of possibilities in both design and technical specification of the product. The equipment available for testing are the FDM-Vantage from Stratasys Inc.® and the Sinterstation 2000 from DTM Corporation and Fab@CTI developed at Division of Three Dimensional Technologies at Renato Archer Information Technology Center (CTI), Brazil. The FDM-Vantage and Sinterstation 2000 have intermediate precision qualities compared to others equipments in the market, while Fab@CTI has a poor dimensional quality. Most of the prototypes will be made using the FDM-Vantage which use fused deposition modeling (FDM®) technology because has better dimensional qualities.

The prototyping process by FDM® is developed by Stratasys. Inc produces each layer by extrusion of thermoplastic material in liquid form. The part is built by successive layers extruded just above the solidification temperature. This process is limited to use only thermoplastic materials. The height of each layer (Z axis) depends on the injection nozzle used. The nozzle used is the T10 and it enables the cutting of smallest thickness of 0.127mm. The accuracy of the layers in the plane (XY plane) is 0.01mm as described in the FDM User Guide.

The second used method is developed by DTM Corporation which use the selective laser sinterization (SLS) method like its production method, and the precision of this machine is 0.5 mm in height (Z axis) and 0.1mm in the plane of the layers (xy plane). Among various materials that can be used, DuraFormTM Polyamide is used as raw material. Those techniques do not produce parts with mechanically isotopic properties and it depends according to spatial orientation in the build (DTM, 1999). Another warm is the dimensional quality by geometry cutting in layers imposed by the process. There must be a balance between mechanical properties and dimensional quality, since the direction of greater strength and better dimensional quality are in the same way.

The device manufacturing fab@CTI additive has one difference among other commercials devices, is the ability to use different materials, since it is open source so it is only necessary to change the control parameters of the production process (Filho 1999, Neto 2007 and Malone et al. 2007). The product of interest in this project is the possibility of production with the use of viscoelastic materials such as silicone. When properly molded, silicone can be used as seals in structures such as the union between head and cylinder and between housing and block.

5. Mathematical Modeling

Kinematic analysis of the components can be made from the analysis of position, velocity and acceleration of the components that make up this engine and can be found easily. Since this is the system used in almost all types of engines that need to transform linear motion into circular motion, the crank rod system is easily described with only one degree of freedom. Using the angular position of rotation center of the handle as the degree of freedom, we can describe the position, velocity and acceleration as a function of piston position and the angle between the rod and the direction of movement of the piston. This equation system can be observed in the next equation (Eq. 1) to (Eq. 7). With the knowledge of the kinematic structure, it is possible to perform calculations of internal forces and reactions of support from the Newton's second law (Dougthy, 1988).

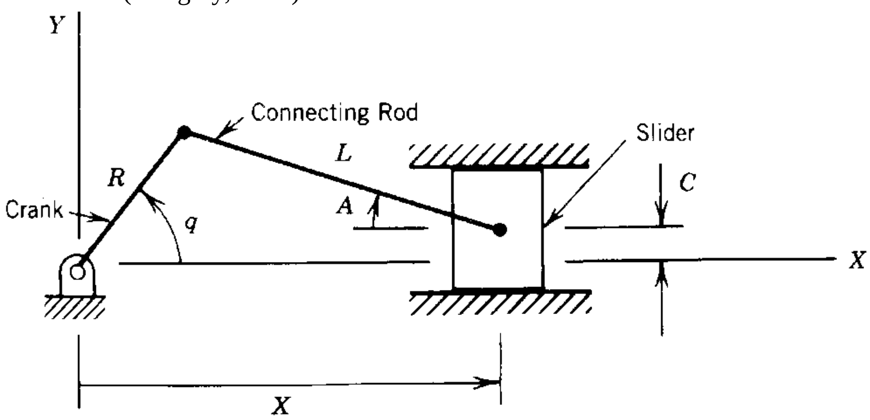

Figure 2 - Crank Rod System

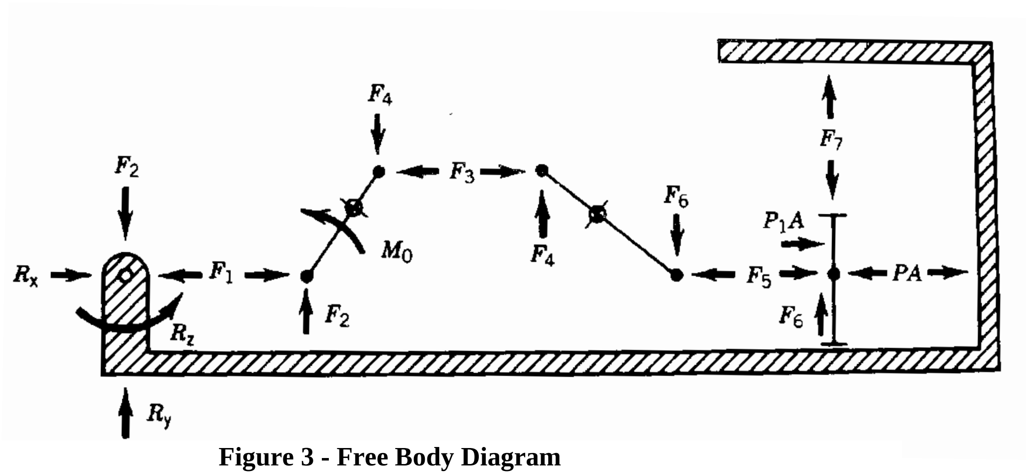

Figure 3 - Free Body Diagram

$$F_5 = M_3(\ddot{q}K_{x3} + \dot{q}^2L_{x3}) + (P - P_1)A_c \quad (1)$$

$$F_3 = F_5 + M_2(\ddot{q}K_{x2} + \dot{q}^2L_{x2}) \quad (2)$$

$$F_1 = F_3 - M_1(\ddot{q}U_1 \sin q + \dot{q}^2U_1 \cos q) \quad (3)$$

$$F_6 = \frac{\left(-F_3U_2 \sin A - F_5(L-U_2) \sin A + I_2(\ddot{q}K_a + \dot{q}^2L_a) - M_2(\ddot{q}K_{y2} + \dot{q}^2L_{y2})\right)}{L \cos A} \quad (4)$$

$$F_4 = F_6 + M_2(\ddot{q}K_{y2} + \dot{q}^2L_{y2}) \quad (5)$$

$$F_2 = F_4 + M_1(\ddot{q}U_1 \cos q + \dot{q}^2U_1 \sin q) \quad (6)$$

$$F_7 = F_6 \quad (1)$$

The calculation of internal forces and reaction forces of the bearings are essential for the proper design of structures such as the axis of the crankshaft and the bearing support. The calculations of these forces can be taken in three different ways, namely: static, dynamic and cinetostatic. In this case, the cinetostatic model was chosen because the static model does not take into account the inertia of the components, and that the low variation in the speed of rotation does not explain the dynamic analysis of the model.

This analysis assumes that engine runs at a constant speed, thus considering the acceleration of the axis of rotation will be zero in the equations of motion, but forces from the inertia of the system will be considered. With the solution of the equations of internal forces, from the equations of equilibrium of the system, we can find the bearing reaction forces. The control of intake valve of the engine can be controlled in several ways. However, the most used in the control of the opening is the use of the cam. The most common types of cam are: Ramp cam, cam and frontal drum cam and cam disk. For this specific engine, because of the small size of the cam followers it was not possible to use roller carriages, then, was used tip followers type. The best definition of the profile is given by the tests of motor operation.

An important consideration in the design of the cam profile is your state of tension. If tensions are high, there will be signs of fatigue and fragmentation of the surface caused by contact stress. That phenomenon should be avoided, since the deformation of the cam profile causes changes in the performance of the engine and increased engine wear. This tension is also known as hertizian contact tension, since it was first studied by Heinrich Hertz. Usually the cam is relatively thin when it is compared with radial dimensions, so the stresses that are found in the cams can be considered plane stresses. The derivation of plane stress (Budynas, 1977) can be found below (Eq. 8).

$$\sigma_0 = \sqrt{\frac{F\, E_1\, E_2\, (R_1+R_2)}{\pi\, t\, P\, (E_1+E_2)}} \quad (2)$$

The development of bearings starts with the used theory: full-film lubricant, mixed film lubricant and boundary lubrication. The most common lubricant used in the engines is full film, where the surfaces are separated for a film of lubricating oil. The full film lubrication can be hydrostatic, hydrodynamic or elasto-hydrodynamic. For the main bearings of an engine, it is preferred to hydrodynamic bearings where a flow of oil feeds the loss of lubricant by sides of the bearing without the injection of pressurized oil in the bearing. For bearings where the ratio between length and diameter are less than two, the theory Ocvirk (Eq. 8) is more appropriate for the design of bearings. The Sommerfeld's method is more suitable for long bearings because it provides loss of oil from the sides of the housing. The solution Ocvirk is solved for angles between 0 and π, since values between π and 2π, the pressure is held void, because the loss of oil from the sides reduces the pressure in this region of the housing. The number of Ocvirk (Eq. 9) is calculated with parameters in which the designer has control and shows that any combinations of those parameters that produce the same number of Ocvirk have the same ratio of eccentricity. Experimentally, the theory underestimates the magnitude of the eccentricity ratio, and then an empirical curve can be written as the following equation (Eq. 10). (Norton 2003, Juvinall et al. 1999 and Bosch 2007).

With the knowledge of the internal forces and the reaction force of bearings, you can use other tools like finite element analysis for design structures with complex geometries and hard modeling by conventional methods. The difficulty in using the finite element analysis is the lack of mechanical properties of materials used in manufacture additive.

Engine development is based on a similar engine with scaled dimensions. So the size of the motor is started by the mathematical modeling of internal forces and obtaining the forces of reaction. This equation can be inserted in software like Matlab so that data can be treated more agile.

$$p = \frac{\eta U}{r c_r^2}\left(\frac{l^2}{4} - z^2\right)\frac{3\varepsilon \sin\theta}{(1+\varepsilon\cos\theta)^3} \quad (9)$$

$$O_N = \left(\frac{p_{média}}{\eta\, n}\right)\left(\frac{d}{l}\right)^2\left(\frac{c_d}{d}\right)^2 = 4\pi K_\varepsilon \quad (3)$$

$$\varepsilon_x \cong 0{,}21394 + 0{,}38517\log O_N - 0{,}0008(O_N - 60) \quad (4)$$

6.RESULTS

At this particular case, the analysis of market and economic climate are not fundamental since the project tries to develop solutions make manufacturing parts produced by additive mechanisms in functional and not sell the final product. The transformation of energy is always an issue where people are interested, and where most of the mechanical systems are inserted. That was the reason to choose the engines as mechanical systems to be simulated by rapid prototyping. Analyzing the types of existing engines, the air compressed engine has the most interesting features, it is the system that generates less heat, and do not need further knowledge in thermodynamics and electronic like electric motors. Product using rapid prototyping is aimed for customers who require unique product of medium accuracy but with the possibility of high geometric complexity. It is hoped that these types of products are mainly used in laboratories where it is necessary to use innovative products, where normally there are no commercial products that satisfy their needs. The economic climate is not viable for mass production due to its high cost and low production speed. As an advantage of this process is that generates highly customizable products without the need of producing a mold. At this stage, it conducted a search of similar products on the market. The production process is also a key factor, so it was included an analysis on which prototyping process would be most suitable for the production of parts under mechanical stress. It is possible to find an engine completely produced by plastic injected, producing enough thrust to fly a toy airplane. Without a technical specification, this single-action engine consists in a pressure vessel that supplies compressed air to a piston engine with one cylinder and opens with the intake valve actuated by a rod attached to the piston head. With this engine as a basis for developing the next versions were tested five models for testing.

Model number 1

The engine model number 1 has double proportions similar to models found in the market. The valve proved to be inefficient and difficult for calibration. The operation of this type of valve allows the valve opening only with positive angle, resulting in loss of speed, since the valve releases air before the piston reaching the top dead center (TDC), pushing the piston against the direction of motion. It is necessary to seal the engine head, since the process generates porous part. The sealing was done with the application of cyanoacrylate on the outer surface of the head. The seal between the piston cylinder and head was made with the application of silicone. The axle of crankshaft, proved too small, leading to fracture due air expansion forces. The bearing with excessive length and without any lubrication, leads to great loss of energy through friction.

Model number 2

The main difference of this model with the previous model is the inclusion of the cam for better control of the injection of compressed air into the engine. The profile used is shown in figure 4, where its regulation in relation to the

TDC can be done in steps of five degrees by the "gear" which fits with the crankshaft. For the follower, we used the metal tip of a ballpoint pen, trying to simulate a follower reel. The follower roulette perfectly when there is ink in the tip. After the end of ink cartridge, the ball locks and acts as a simple follower. The thin edge ends up wearing the cam profile and affects the amount of air entering the engine. The valve opening is given by the elastic deformation of the follower, which raises and releases the pin passage of air into the engine. To reduce the friction were included rings that reduce the contact area between the crankshaft and the engine block. But due to friction, and the lower level of the support melted, causing large misalignment of the crankshaft. The motor has great vibration losses and air leakage especially where the pin enters the engine head. The pin-ball engine has not been demonstrated with great effectiveness.

Figure 4 - internal components of engine model 2

Model Number 3

The cam follower does not have the tip of a ballpoint pen, which is replaced by a simple prototyped tip. The crankshaft has two bearings fixed between to the rod. This configuration enables the crankshaft to reduce the shaft length in cantilever where the inertia disc is fixed. This length reduction aim to minimize the stresses and deflections. Sleeve bearings have been replacing the fixed bearings and were prototyped in orientation that optimizes the geometry. The bearing is placed back on the amount, making this a key to the operation of the engine. This type of arrangement allows a break in the longitudinal direction of the crankshaft.

Model Number 4

In order to reduce the slack in the longitudinal direction of the crankshaft, the crankcase is split on the line corresponding to the axis of crankshaft. The number of prototype is increased whit the piston and the piston ring. It requires the sealing of the upper surface of the piston for not lose air pressure by the porosity of the material. The cam profile was redesigned so the valve stays open in reduced time. The lubricant considerably leaks through the region by the joining of the blocks. The balanced crankshaft reduces vibration and is perceptible increase of engine speed.

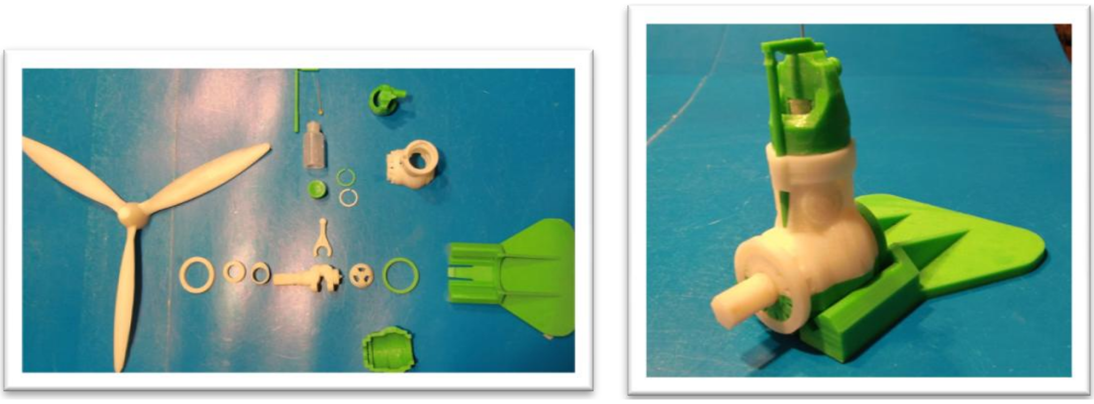

Figure 5 - Exploded and Assembled View of engine number 4

Model Number 5

The main change in this model is the inclusion of a reservoir of PET bottle of compressed air to the system. It was included a Schrader valve for the operation of the engine. In this configuration, the valve is positioned horizontally, requiring the modification of the valve opening. This system leads to a head much more compact and can be prototyped with the engine block. The mounting of engine houses the Schrader valve and serves as the cap of pressure reservoir at the same time.

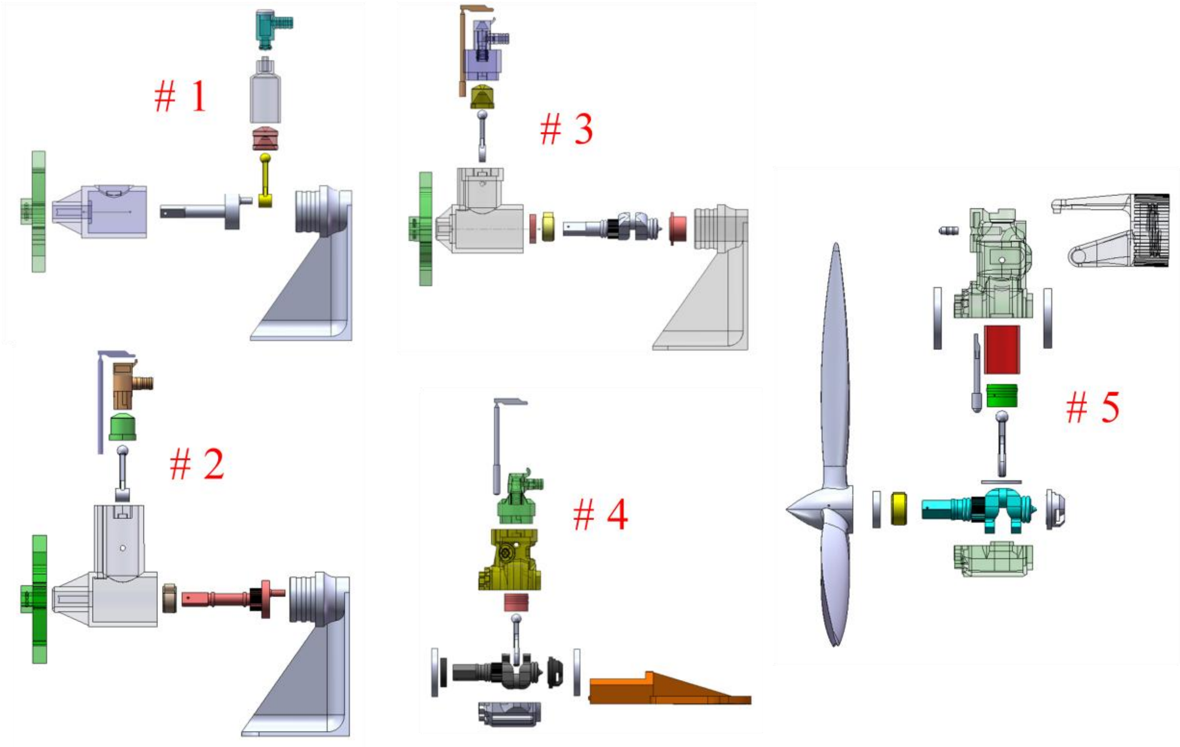

Figure 6 – Exploded version of the five models developed

7. DISCUSSION

The performance of each engine was evaluated in a qualitative manner. The main features were: vibration, wear, breaks, and leakage in the system, rotational speed and maximum operating time until the breaking of some component. Engine vibration is coming from the movement of the masses. There was a large reduction of vibration with the balancing of the crankshaft. The wear of parts was caused by the lack of an efficient lubrication system. The breaks occur mainly by under sizing of components, and can easily be corrected in later models. The tightness of the system as a whole is evaluated to see if the system loses energy due to the air leakage while it traverses the system.

Figure 7 - Breaks due to under sizing, poor lubricating and load in weak resistance direction

The rotation measurement of model 5 was not possible due to the malfunction of the system, in which the rotation was not constant to make it. The running time indicates the duration of engine operation without breaking or malfunctioning.

Failures can be explained primarily by three phenomena: element undersized, melting or component wear due to high friction and low lubrication and loads applied in the directions which the geometry has a lower mechanical strength due to the manufacturing process i.e. orthogonal to the plans of prototyping.

The best performance of the feeding system was observed when a pin is the valve and a spring forces the close of it while it is not driven by the follower.The handling of the engine became easier when the mounting base was only used for fixture, not when it suits covering the block and mounting base simultaneously.For the piston head and piston cylinder the prototyped ones were used, because it allows the dimensional variation, and it does not restrict the diameters of head piston, what it is not possible with the commercial syringe.The bi-supported crankshaft has better mechanical strength and wear characteristics.

The choice of those settings took into account parameters such as ease of assembly, system robustness and efficiency in operation. To solve problems encountered in all models mainly related to the mechanical strength, new solutions have been included in previous models. A better fix can be obtained by use of a support which unites all components pressing against each other. This makes all the parts work in compression. This support is produced by SLS process, which has higher yield strength. So it allows for orient the parts produced by the FDM process to gain geometric quality instead of mechanical strength. The crankshaft is the only component which was given the preference for mechanical property instead of the dimensional quality.

The cam and crankshaft were made into a single piece because the profile used in the last three versions have proven to be very effective and would not need to change this solution. Analyzing the equation for the contact stress, a larger radius of curvature on contact surfaces, induces lower stresses values. So the primitive radius of the cam profile was raised in order to achieve lower hertizian stresses, allowing the cam profile to become in contact with the oil deposited in the sump.

This configuration allows the bearings to be scaled to a larger diameter, allowing part of the bearings to remain dipped in crankcase oil. The outer part of the bearings was produced separately so the circularity was better than that found if it were produced along with the crankshaft. It is known that nylon is a plastic self-lubricating, so it makes in the best choice for the bearings.

Table 1 - Performance of Tested Engines

	vibration	Wear	Crack	Seal	Maximum rotation	lifetime
model #1	ND	ND	rod	low	ND	zero
model #2	high	cam and bushing	crank arm	low	800 rpm	2,5 minutes
model #3	high	rod	crank arm	medium	1800 rpm	10,0 minutes
model #4	medium	bushing	conection between head and cylinder	medium	2200 rpm	17 minutes
model #5	medium	bushing	did not happen	medium	not measured	not achieved

This new design required the inclusion of a new piece between the cylinder and head. This new component is used as a valve seat and as a separating wall between the head and cylinder.

The O-ring seal of this new component has been prototyped using the Fab@CTI with silicone. This choice is due to physical characteristics of silicone like filling the gaps when compressed by engine assembly, preventing air leakage.The same silicone is used for sealing the contact interface between the block and the sump.

Figure 8 - O-ring made by silicone

8.CONCLUSIONS

The conclusion of this work is that it is possible to use additive manufacturing in creating functional products. The care in the production of these mechanisms is mainly related to the orientation of the deposition layers for the manufacturing process, because it is critical to maximize mechanical strength and dimensional quality at the same time in final model.

The use of design methodology to develop a project improves the ability to organize information, so the decisions can be taken with efficiency and technical basis. Although important, this technique was not applied at all stages, since the purpose of this project was not aimed at the marketing or production of this engine series for instance. In this context, results of the stages of economic and financial evaluation did not change the focus of research. The performance and robustness of engines have been increased as the problems of previous models were observed and resolved. The main results that led to this conclusion were the increase in the rotation speed and increase in the operating time.

The fifth tested model had several changes especially in the valve control system and in the cylinder that was prototyped for the first time. This model showed rotation speeds lower than the previous. A careful analysis of reasons for this reduction in performance led to the conclusion that the low flow of air from the Schrader valve was the main responsible.

The four previous engines have shown a reduced life span, in which wear and breaks were found. It is clear that the catastrophic failures occurred when there were shear forces acting parallel to the layers deposited by the additive manufacturing process. These are the directions in which the mechanical properties are weaker. This weakness is more visible in the works produced by the FDM process, in which the union between layers is not as efficient as in the SLS process. Finite element analysis could be used in the development of this material it the mechanical properties such as elastic modulus, Poisson's ratio and yield strength of the material were available. The difficulty in obtaining these values is due to the high variability of these properties, since the manufacturing parameters are adjusted according to the geometry and dimensions of each piece.

In the case of the FDM process, major adjustments are given by the thickness of the wire, path of the deposition nozzle, and distance between the paths of deposition. In the case of SLS, other factors are beyond the operator such as polymer degradation, since the raw material is reused several times. The processed material degrades with the heat that can change in addition to mechanical properties, the dimensional quality of the final model. The post-processing with the use of cyanoacrylate and chloroform is sufficient to achieve sealing and sealed parts. However, the use of cyanoacrylate increases the thickness of the wall because it adds a thin layer of polymer to the surface of the component, while the chloroform dissolves the surface of ABS and reduces the wall thickness of the material.

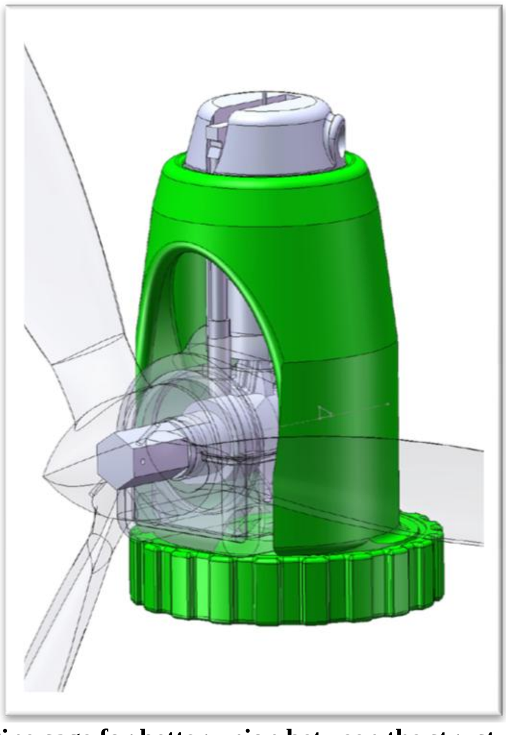

Figure 9 - Engine cage for better union between the structures (green)

The containment cover was designed for the last model and it was made by the SLS process. It works by compressing all the pieces vertically from the head to the crankcase and is more reliable than the other methods, while enables the control of applied pre-stress, since locking is given by the torque screw located at the base of this cover.

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