Achieving a More Electric Aircraft: a comparative study between the concurrent and traditional engineering models

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Abstract*: The paper presents a model of concurrent engineering implemented in the life cycle of an electric motor as part of an electric aircraft with major advantages over traditional engineering. The paper also shows the 2D modeling of the electric motor using the FEMM program. The results of 2D modeling will be additionally used to the electromagnetic design of the electric motor. ENOVIA, a PLM (Product Lifecycle Management) software product for project management and engineering processes that integrates other 2D / 3D design software will also be used to implement concurrent engineering.*

Key Words*: Concurrent engineering, conceptual model, numerical modeling, electric aircraft, electric motor*

1. INTRODUCTION

Concurrent engineering is a working method used in product development where design engineering, manufacturing, and other functions are simultaneously integrated (Simultaneous Engineering) to reduce the time required to achieve and market a new product [1].

At an economic level, the need for concurrent engineering is steadily increasing in the implementation of complex projects as it leads to improved quality, reduced total cost and durability, but also an increased competitiveness, as compared to traditional engineering.

The concept of concurrent engineering is widely applied in various areas of electrical engineering, aerospace, IT, telecommunication, etc., based on five key elements: a process, a multidisciplinary team, an integrated design model, a facility and a software infrastructure.

For a systematic approach to designing and developing a product, all elements of its lifecycle, from conception to withdrawal, should be taken into account, ensuring an engineering, cooperative, collaborative, collective and simultaneous work environment [4, course].

Streamlining process of product development to a quality/ price high ratio within companies plays a very important role for business profitability, taking into account the challenges of the current trend.

The defining feature of concurrent engineering studies [2] is working in a guided process, concurrent access of all experts to a shared database, and direct and effective communication between all subsystem experts.

The major advantages of concurrent engineering are: high efficiency of project cost and results in early design phases, close collaboration with direct communication facilities, fast data exchange, as well as easy tracking of the design process by the team members which can also increase understanding and identification of issues that can be discussed in group; this can leads to new points of view and possible solutions and also helps to identify and solve the problems, [2].

Figure 1 shows a comparison between the concurrent engineering model and the traditional product model.

As one can see, there are huge time savings when concurrent engineering is implemented in the design-manufacturing cycle of the product. Also, the concurrent engineering method does not lead to design implementation issues in product manufacturing as it happens with traditional engineering modifications which are very expensive; thus the total cost of the product is reduced [3].

After the design completion, in the traditional model one can expect that all departments involved in the product consider the design, although these departments have a very small contribution to the product design input data.

A frequent issue refers to the design utility without the involvement of experts in the field. Very often, the design team of the traditional model does not have the knowledge and skills necessary to achieve a functional, high quality and manufacturable product. The traditional model is vulnerable, being susceptible to costly and error-prone products [3].

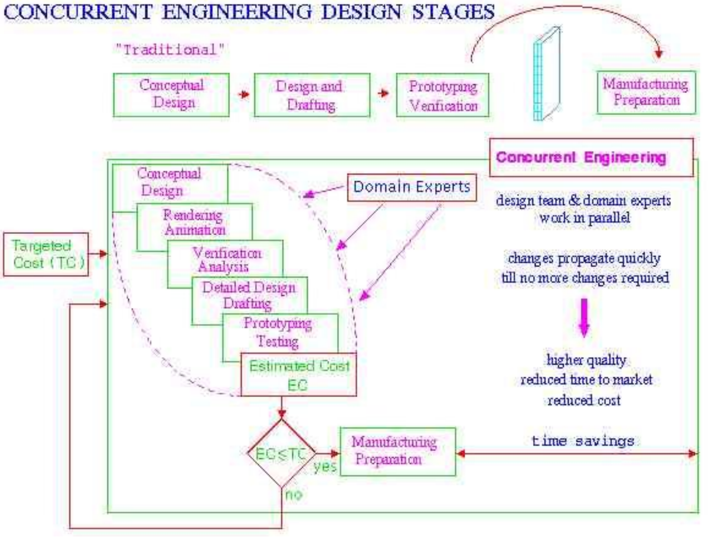

Fig. 1 Concurrent engineering design stages [3]

From Fig. 1 it can be noticed that while the concurrent engineering design method starts with the cost of the product, the traditional method does not have such a reference. After the design phase, the concurrent engineering team compares the resulting cost of the product design with the target cost. Product production can start only if the estimated cost is less than or equal to the target cost.

Such a design discipline is essential to ensure that the product price is competitive on the market.

It is obvious that, following the concurrent engineering model, all the drawbacks of the traditional model can be avoided. The difference between the two approaches will be more apparent after studying the total production cost of the product lifecycle. The marketing department usually initiates new product ideas. Such ideas are based on market research, after studying customer needs.

The marketing department is not totally independent in conducting this marketing study. Different other departments contribute with information such as the production capacity of a particular product proposal and help the marketing department to formulate a more accurate idea for a new product.

Finally, the idea is presented to the design team that has goals and design objectives more clearly defined. A result of the marketing analysis is to determine the sales price and the target of production costs [3].

The main difference in concurrent engineering design as compared to traditional one is the approach to design. With concurrent engineering, at the design stage, a suggested design is sent to the engineering team.

The advantage of involving the concurrent engineering team in the design phase is that the experts in engineering, production, marketing, sales, packaging, inspection, service, assembly, and environmental engineering will improve the product design by using their knowledge and working simultaneously with the design team.

A good feature of this concurrent engineering phase is that by designing the product, the concurrent engineering team also designs the product manufacturing process. The team decides what kind of equipment will be used, the layout of the machines, etc. In the traditional model, at this stage, only people in the design department are involved, and major decisions are largely left to a designer.

One type of design that can be integrated in concurrent engineering is the electromagnetic design of electric motors, based on classical mathematical models that can use additional custom software.

In this way, a consistent set of design parameters can be defined that can be changed during the study according to the desired efficiency. This is an integral part of concurrent engineering with major advantages over the traditional model.

This paper aims to implement concurrent engineering in the production cycle of an electric motor as part of a More Electric Aircraft, (MEA), with major advantages over traditional engineering.

2. THE CONTENT OF THE WORK

A concurrent engineering model is based on a team that is responsible for the entire life cycle of the product, from idea to finite product. Such a team brings together experts in design, engineering and manufacturing [3].

A concurrent engineering model is presented below. Our model refers to the design of an electric motor for a small electric aircraft, usable by one person.

The engine has a power of 15 kW and is designed using concurrent engineering. Instead of sequencing the stages (study, design, production, marketing, operation, dismantling), all stages are done in one step.

This procedure leads to two major advantages over traditional engineering results, namely the reduced product lifecycle and the low price of the end product.

The aircraft will have two AC electric motors. Each electric motor will be powered by a 24 volts battery that will be coupled to the electric motor via an inverter to convert the DC into AC.

These components make up the propulsion of the electric aircraft. The electric motor data are shown in Tab. 1.

Table 1. Parameters of the electric motor

Electric power	15 [kW]
Electrical voltage	230 [V]
Speed	3000 [rpm]
Nominal frequency	50 [Hz]

For the choice of the engine, a market study was carried out showing that, for small aircraft, the electric motor has the electric power in the range of 10 - 20 [kW] [4].

The electric motor was designed using a classical electromagnetic design algorithm [5] to which application-specific elements was added. Some design elements of the electric motor are shown below:

- Rated power P_N = 15 [kW].
- Number of pairs of poles p=1.
- Frequency f = 50 [Hz].
- Rated voltage U_N = 3 x 230 [V].
- Rated current per phase:

$$I_{NG} = \frac{P_N}{\sqrt{3}U_N} = \frac{15000}{\sqrt{3} \cdot 230} = 38\,[\text{A}]$$

Number of slots

$$Z_1 = 2pmq = 2 \cdot 3 \cdot 1 = 6$$

where:

- $q = 1$ is the number of slots per pole and per phase.

The electromagnetic voltage k_b form factor and the α_i ideal polar pitch coefficient are chosen from the curves diagrams for electric machines:

$\alpha_i = 0.75$, $k_b = 1.05$ and the air gap $\delta = 2$[mm].

CALCULATION OF MAIN DIMENSIONS

The internal diameter of the stator $D = 0.14[\text{m}] = 140[\text{mm}]$ is chosen from tables.

$k_D = 1.4$ = the ratio between the outer and the inner diameter of the stator.

The stator outer diameter: $D_e = 0.14 \cdot 140 = 196[\text{mm}]$.

The polar step:

$$\tau = \frac{\pi \cdot D}{2p} = \frac{\pi \cdot 140}{2} = 220[\text{mm}]$$

The machine length:

$$l_i = \frac{60P}{k_{CA}\pi^2 D^2 n_1 A B_\delta} = 123[mm]$$

From the value tables the following are chosen:

- Electric current layer, $A = 42\left[\frac{\mathrm{A}}{\mathrm{mm}}\right]$
- Air gap induction $B_\delta = 0.75\,[\mathrm{T}]$.

The optimal form factor (dimensionless) is calculated with the formula:

$$\lambda_{optim} \approx 0.5\sqrt{p} = 0.5$$

From our values, the form factor is

$$\lambda = \frac{l_i}{\tau} = 0.56$$

The value of the form factor calculated with the dimension is very close to the optimal value.

For technological reasons, the geometric length l_g of the core is chosen to be $l_g = l_i = 120[\mathrm{mm}]$.

ELECTROMAGNETIC STRESS OF THE MACHINE

Electrical Stress

We have chosen the electric current layer according to the curves diagrams in the electric machines literature: $A = 42[\mathrm{A/mm}]$ (anyway, it will be checked afterwards).

The current density will be calculated afterwards.

Magnetic Stress

- According to the graphs, the air gap induction (maximum value) is $B_\delta = 0.75[\mathrm{T}]$;
- The pole core induction is: $B_m = 1.15[\mathrm{T}]$;
- The rotor yoke induction is: $B_j = 1.3[\mathrm{T}]$, the yoke being made of steel.

STATOR WINDING AND SLOTS

Simple-layer windings are used with round copper wire coils, the slot being closed, with parallel walls.

Number of stator slots:

$$Z_1 = 2pmq = 2 \cdot 3 \cdot 1 = 6$$

Circular pitch:

$$t_1 = \frac{\pi \cdot D}{Z_1} = 73[\mathrm{mm}]$$

Stator winding elements (armature):

The initial number of turns in the coil per phase results from the relationship:

$$w = \frac{k_E \cdot U_{1N}}{4k_B f_1 k_w \Phi} = 85 \text{ [turns / phase]}$$

where the preliminary value of the maximum magnetic flux is:

$$\Phi = \alpha_i \, \tau \, l_i B_\delta = 14.8 \cdot 10^{-3} \text{[Wb]}$$

The number of effective conductors in a slot is:

$$n_c = \frac{2maw}{Z_1} = 85 \text{ [wires/ slot]}$$

Required checks:

For the definitive values of n_c and k_w the following checking calculations are required:

a) The final determination of the actual number of turns per phase:

$$w = \frac{Z_1 n_c}{2ma} = 85 \text{ [turns / phase]}$$

b) Check of the electric current layer:

$$A = \frac{n_c I_n}{a t_1} = 44259 \text{ [A/m]}$$

c) Maximum effective flow rated load

$$\Phi = \frac{k_E \cdot U_{1N}}{4k_B f_1 w k_w} = 14.8 \cdot 10^{-3} \text{ [Wb]}$$

Rated flow at no-load work: $\Phi_{0N} = \frac{\Phi_N}{k_E} = 13.7 \cdot 10^{-3}$ [Wb].

Fundamental wave flux for nominal voltage:

$$\Phi_{1N} = \frac{U_{1N}}{\pi\sqrt{2} f_1 w k_w} = 13 \cdot 10^{-3} \text{ [Wb]}$$

d) Check of maximum air gap inductance (in the pole axis) at the rated load.

$$B_\delta = \frac{\Phi}{\alpha_i \pi l_1} = 0.73 \text{ [T]}$$

It can be observed that B_δ is close to the initially calculated value.

Winding type and slots dimensions

Current density: J = 3.5 A / [mm^2].

It results that: $s_{Cu} = I_N / J_1$ = 38 A / 3.5 A / mm^2 = 10.86 [mm^2].

The surface is too large for a conductor and therefore we will use several small wires for a wire in the slot.

The diameter of the round copper conductor is 0.65 [mm], which has s_{Cu} = 0.332 [mm^2].

It follows that the number of small conductors in a large conductor is: 10.86 / 0.332 = 32.7. We choose 34 small conductive components of a large conductor from the slot.

The dimensions of the slot are established depending on the wire dimensions and the n_c:

b_c = width of the slot = 36 [mm]

h_c = length of the slot = 14 [mm]

The surface of the resulting slot is s_{cr} = 36 x 14 = 504 [mm^2].

Thus we have

s_{cr} / s_{Cu} = 504 / 10.86 = 46.41 [conductors / slot].

It follows that the elementary conductors in the slot are: 34 × 46.41 = 1578. We choose 1600 small conductors in the slot.

The external diameter of the stator was established at D_e = 196 [mm]. From the formula $D_e = 2 \cdot h_{j1} + D$ results that the height of the stator is: $h'_{cr} = 28$ [mm].

The value of the air gap was previously chosen from the curves diagrams for electric machines at δ = 2 [mm].

SIZING OF THE MAGNETIC CIRCUIT

Sizing the stator and the air gap

The dimensions of the stator and the air gap have been set previously: $D_e = 196$ [mm], $D = 140$ [mm], $l_i = 120$ [m], $\delta = 2$ [mm].

Sizing of the rotor

The outer diameter of the rotor (magnets outside): $D_{rm} = D - 2\delta = 140 - 4 = 136$[mm]

Polar piece width (permanent magnet from NdFeB): $b_p = \alpha_p \cdot \tau = 0.75 \cdot 220 = 165$[mm] (at the interior of the stator).

Polar piece width (permanent magnet from NdFeB): $b_p = 160$ [mm] (at the exterior of the rotor).

Thus, $h_m = 5$[mm] is chosen for economic reasons (NdFeB magnets have a high price), because the air gap induction does not need to be greater than 0.75 [T] and for technological reasons (sizing of the rotor is made from 5 in 5 [mm]).

The rotor is provided with 2 mm depths for better fastening the magnets on the rotor. In conclusion, the magnets will exceed the outside of the rotor yoke by only 3 mm.

Outside rotor diameter (without magnets): $D_r = D_{rm} - 2h_m = 136 - 2 \cdot 3 = 124$ [mm].

The length of the pole piece is equal to the geometric length of the machine:

$l_m = l_g = 120$ [mm].

For the electromagnetic design of the electric motor, 2D FEMM modeling software was used to confirm some parameters; a modeling result is shown in Fig. 2.

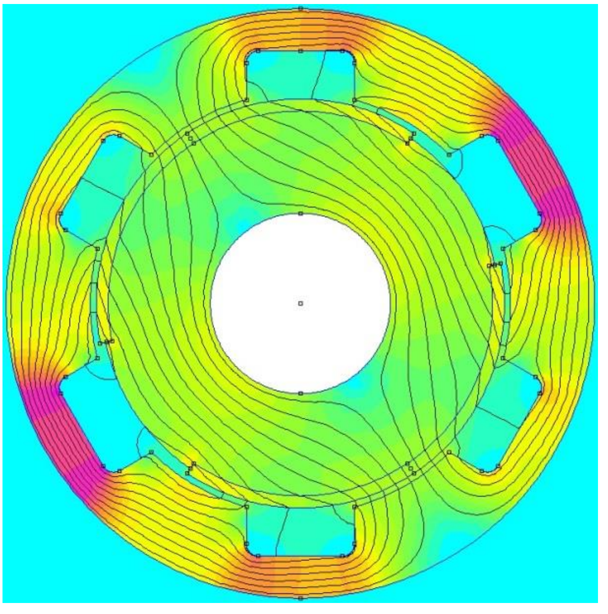

Fig. 2 The magnetic field colour map of the electric motor

The three institutions that are part of the project consortium: INCAS, BEIA and ICPE-CA will participate in the implementation of concurrent engineering. Each institution will have some attributions in the implementation of concurrent engineering in the life cycle of the product, as follows:

INCAS - airplane design;

BEIA - management, marketing, end user;

ICPE-CA - design of the electric motor and its related system (accumulators, connecting cables).

ENOVIA, a product lifecycle management (PLM) software for project management and engineering processes that integrates other 2D / 3D design software, will also be used to implement concurrent engineering. ENOVIA provides a collaborative framework for the PLM software of the involved institutions. It is an online environment that involves creators, collaborators and consumers in the product lifecycle.

3. CONCLUSIONS

The project implements a concurrent engineering model, a method used to develop products where engineering, design, manufacturing, management, marketing, maintenance, and other functions, are integrated simultaneously.

Thus this new type of engineering of simultaneous type has two important advantages over the traditional engineering, namely the reduced product life cycle and the low end product price.

At an economic level, the need for concurrent engineering is steadily increasing in the implementation of complex projects as it leads to improved quality, reduced total cost and durability, as well as increase of the competitiveness of these projects, as compared to traditional engineering model.

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