DEVELOPMENT OF UAV ROTOR BLADES USING RTM PROCESS

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Abstract

Since 2010, KVE Composites Group (KVE) has been developing Unmanned Aerial Vehicle (UAV) rotor blades (RB). Typically, these rotor blades are developed with limited budgets but still require a sound engineered design to prevent resonance of the rotor system, withstand limit loads and have long fatigue lives. Based on the structural design concept, KVE has developed a cost effective manufacturing process using Resin Transfer Moulding (RTM) to manufacture rotor blades. This single shot technique allows high manufacturing rates and also allows the engineer to design blades with a continuous reinforced leading edge and trailing edge laminate. The process also allows KVE to reliably manufacture blades with integrated balance weights which need only limited balancing afterwards. An important aspect of rotor blade development is the validation of design. KVE has developed in house testing tools for rotor blade characterization and structural testing.

1. INTRODUCTION

The last twenty years, a large number of Unmanned Aerial Vehicle helicopters have been developed with and without success. Examples of successfully developed UAV rotorcraft are the Schiebel Camcopter S-100 (Figure 1), UMS Skeldar V-200 and the High Eye HEF32. The sizes of these helicopters vary from 20 kg to 200 kg and have rotors from 1 towards 4 meter diameter. Most UAV developments started in a backyard shed, where the helicopter structures were manufactured manually by a single person. Nowadays, professional, large companies manufacture UAV helicopters. 10 Years ago regulations from airworthiness authorities such as EASA were not present. Nowadays, these regulations are present and set strict requirements on the reliability of the system. These higher standards led to the demand for professionally developed rotor blades, since these are the primary load carrying items on a UAV helicopter. However, only limited development budgets are available. To put things in perspective, the budgets required to develop a manned helicopter rotor blade, with lengths from 2 to 6 meter, are typically higher than the cost for the development of a complete UAV rotorcraft. Being a design and build company of composite structures, with a track record in machine construction industry as well as in aerospace, KVE has specialized in developing rotor blades from 1 to 2.5 meter. The first developed blades were delivered in 2010. Since then, KVE has developed more than five different types of rotor blade of variable load capacities. Unique of these blades are that they have been manufactured using the RTM technique which allows higher production speeds and structural improvements over conventional manufactured bladed made with the prepreg press moulding technique. This paper describes the design process developed by KVE and the manufacturing for making these blades.

Figure 1 Schiebel Camcopter S-100 (Courtesy of Schiebel)

2. ROTOR BLADE DESIGN PROCESS

2.1. Design process

To limit the engineering costs of the development and not to perform extensive simulations, only the minimal requirements are considered which need to be met in a sound design. Four key aspects are determined of a rotor blade: resonance of the blades with the rotor system, limit load, ultimate load and fatigue strength. This UAV rotor blade design process is as follows.

1. Based on experience and the input from the customer, including the aerodynamic geometry, a global design is made. The materials, lay-ups and thicknesses are chosen based on experience.
2. From this model, stiffnesses are estimated (relative to previous developed RB's). These stiffnesses are input for the aero-elastic (AE)

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model. This model is described in a later section.

3. With the AE model, blade stability is calculated. If necessary, stiffnesses are adjusted by changing lay-up and thicknesses in the global design.
4. With the stiffness requirement set, an Finite Element (FE) model is made from the blade. Geometry is extracted from the CAD model.
5. With the FE model, the stiffness of the RB is verified and, if necessary, thicknesses are adjusted to match the stiffness of the AE model. In addition, root strength for centrifugal force is also validated, This is an ultimate load case.
6. With the AE model, a limit and fatigue load case is calculated, and the RB deflections per section (every 100mm) are calculated.
7. The calculated RB deflections from AE model are fed into the FE model to simulate the deformation of the RB during limit and fatigue load. From FE the stresses and strains are calculated.
8. If necessary material thicknesses are adjusted and from step 5, the process is done again.

The process is shown in a flow chart in *Figure 2*.

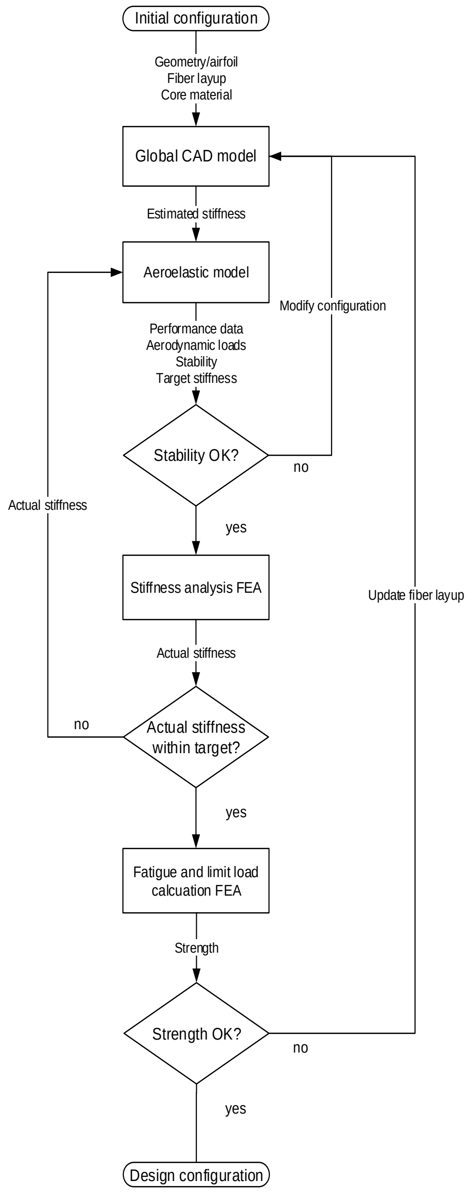

Figure 2 Rotor blade design process

2.2. Stability analyses

The stability of the blade is calculated by an in-house developed aero-elastic analyses tool. A program written in Python has a Ritz-Hamilton elastic model and a quasi steady aerodynamic model. With this model, a Campbell diagram is made, to investigate the possible resonance of the blades with the system frequencies. A typical Campbell diagram can be seen in *Figure 3*.

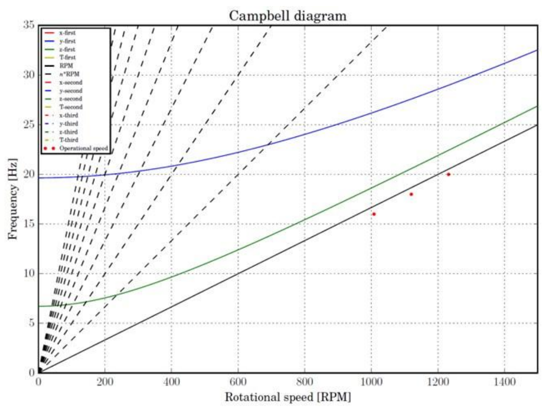

Figure 3 Campbell diagram

2.3. Ultimate load case

The ultimate load case is mostly used during preliminary design. It is defined as the maximum centrifugal force multiplied by a factor of 5. This load case ensures a robust root strength to make sure a catastrophic failure can never occur. It also takes into account some reserve factors with regards to limit loads and fatigue loads. Reserve factors are used to take into account uncertainties regarding loads, material variation manufacturing flaws and strength degradation effects due to hot wet environment fatigue and impact damage. To validate this strength, this load case is generally tested statically on a test bench.

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2.4. Limit load case

The limit load case is defined as follows: The loads generated by the maximum collective pitch angle are limited by the engine power. The rotor blade should be able to withstand these loads without degradation of stiffness or strength. With this load case it is checked if the bending loads are sufficiently carried by the blade.

2.5. Fatigue load case

The fatigue load case is defined as follows: The loads generated by the cyclic loads which are generated during cruise flight. The rotor blade should be able to withstand these loads without degradation of stiffness or strength taking into account strength reductions due to fatigue damage. The calculations of the cruise flight conditions are more complex than the limit load case, because they contain load contributions resulting from forward flight. Because of this complexity, the AE software developed by KVE is currently not capable to calculate this load case. If budget allows, these calculations are normally subcontracted to the Netherlands Aerospace Centre (NLR), which uses Flightlab software to perform these calculations.

3. ROTOR BLADE DESIGN

The rotor blades designed by KVE have typically the following components: (Figure 4)

1. Bushing: For load introduction, made of hardened steel for larger blades and brass for lighter blades.
2. Main girder: Primary load carrying item, carries centrifugal force and bending stresses. Mostly made of glass fibre which is wrapped around the wedge and bushing. The reason for using glass is that glass increases the tensile strength but does not make the rotor blade too stiff in bending thereby reducing the vibration loads on the rotor system. For smaller rotor blades up to 1 meter, carbon fibre is chosen more often.
3. Skin: Primary load carrying item, carries shear stresses from torsion. Made of ±45 oriented carbon fibres.
4. Wedge: For guiding the glass fibers of the main girder to the bushing, made of glass fibre.
5. Balancing weight: For centre of gravity (CoG) balancing, made of casted lead.
6. Foam core: For local compressive skin stiffness and bucking stability, also needed for RTM manufacturing process.
7. Leading edge weight: Used for balancing the CoG more towards the leading edge.

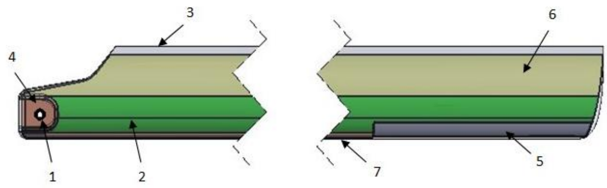

Figure 4 Rotor blade components

4. RTM PROCESS

For 20 year, KVE has design and build high-end products with the RTM process. From the first rotor blade development, KVE has selected this process because of the following advantages: improved fibre lay-up and process speed.

4.1. RTM blade structure

Traditionally, a UAV rotor blade is manufactured with the wet lay-up technique, or the prepreg trapped foam core technique. Both have the same drawbacks compared to KVE's RTM rotor blades. This can best be explained with *Figure 5*. With the conventional methods, small blades are manufactured by the lay-up of the top and bottom mould and closing the moulds with a trapped foam core. During cure, the composite plies are pressed together with vertical force, resulting from the external mould closing force and the internal core compressive force. With this process, the plies at the trailing and leading edge are discontinues and since the very front of the leading edge is vertical, just at the mould closing pressure the leading edge there is a lack of consolidation pressure. Due to the lack of this pressure, many voids can stay entrapped in the laminate. These voids can cause stress concentrations.

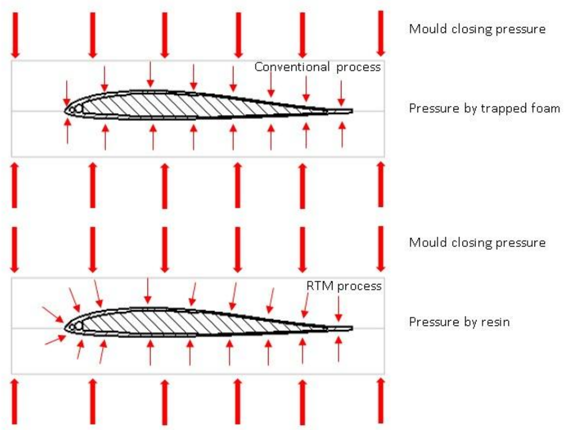

Figure 5 Pressure differences between conventional process and RTM process

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With the RTM process used by KVE, the plies are wrapped around the foam core, and the preform is applied in the bottom mould. After closing the mould, liquid resin is injected at 3 bar and cured afterwards. This way, the plies are continues around the leading edge and trailing edge and the complete laminate, including the leading edge, is cured under 3 bars of hydrostatic pressure, which minimizes void content.

4.2. Process steps

The process steps of the production of RTM rotor blade are as follows:

1. Subcomponent manufacturing; Bushings, wedge, foam core, balancing weights are manufactured. Foam cores and wedges are machined from raw material. The balancing weights are casted into a mould.
2. Ply cutting of dry materials; depending on the required quantities. Carbon and glass plies are cut by CNC and kits are made.
3. Preforming and weighing. The foam core, wedge and balance weight are bonded together and wrapped by a main girder and carbon skin. After finishing, the prefrom is weighted.
4. Mould application and closing; The preform is applied into the mould and the mould is closed.
5. Injection and cure; At small series, typically the mould has to heat up before injection. At larger series, the mould is at a temperature of 50 degrees continuously. This temperature reduces the viscosity of the injection resin and shortens the cure time. Typically, the window of injection is around 10 minutes. After that, the resin thickens and cures within 1 hour to obtain sufficient strength before release.
6. Release; when opening the mould, the product is released. For larger series, ejection pins automatically eject the product from the mould.
7. Finishing; normally the RTM rotor blades are manufactured net shaped; only limited finishing is needed. Generally, the connection hole is trimmed and bushings are bonded.
8. Freestanding post-cure; typically the glass transition temperature (Tg) of the resin after cure is around 60^{o}C. The post-cure up to 120^{o}C, enhances the temperature resistance and maximizes the toughness of the resin.
9. End control and balancing; optionally, rotor blades are painted before balancing. Using an in-house developed CoG and weight measuring tool, blades are balanced in sets and inspected. If necessary leading edge protection is applied.

Process steps 1 to 3 and 7 to 9 can be done large series without the need for curing equipment. Process steps 4 to 6 can typically be done in 2 hours, so for larger series, the mould is used around 2 hours per blade. The hand-layup process and the prepreg autoclave process require the use of the mould during lay-up so the manufacturing rates are typically lower.

5. TESTING

KVE has developed in-house tools to perform extensive testing on rotor blades. For the full rotor testing, KVE has developed a whirl tower equipped with a 100HP electric motor with variable rotation speeds (Figure 8). This whirl tower is instrumented with weighing gauges to measure the lift generated by the rotor blades. Currently, KVE is developing instrumentation to measure also pitch link forces. Typically, during prototyping, based on the CoG measurements and stiffness measurements, small adjustments of the balance weights and main girder stiffness are made to improve the match with the calculation models.

The following testing is performed to validate the design, before new rotor blades are delivered for flight testing.

1. Dimensional measurements; Typically, a surface scan of the first prototype blades is made to measure profile deviations such as thickness variations and angle variations. If necessary, modifications to the tooling are done to compensate for these deviations.
2. Weight and centre of gravity; KVE has developed tooling to measure the location of the CoG based on the weight measurements of three weighing gauges. With a calculation program, the CoG can be calculated with an accuracy of 0.1mm.
3. Stiffness; To validate the stiffness of the blade, a setup is made to measure flap and lag bending stiffness and torsion stiffness at two locations. Typically these locations are at 40% r/R and 80% r/R. These values are compared with the calculated stiffness of the FE model. This comparison indicated the accuracy of the FE and AE calculations.
4. Eigenfrequency; After mass, CoG and stiffness requirements have been met, the natural frequencies are measured to validate the mass- stiffness interaction and the stiffness and mass model of the AE calculations. This measurement is a good indication of the structural stability of the rotor blade.

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5. Pull out testing on test bench; the ultimate strength of the root of the blade is tested by a pull out test performed on a test bench. Before testing, effort must be put into the preparation of the load introduction of the rotor blade. If the load is not smoothly introduced, the chance of failure at load introduction is significant.
6. Combined loading testing on test bench (Figure 7); to test the limit load on the root of the rotor blade, the blade is tested in the test bench, similar to the pull out test. In addition, an extra force is applied to simulate bending forces. This force is calculated by FE simulations.
7. Spinning at 125% of maximum revolutions per minute (RPM); At the test bench testing, the root strength is already validated. To test the structural robustness of rest of the blade, especially the balance weight adhesion, the rotor blade is tested at 125% of the maximum possible rotation speed. Before and after the test the CoG is measured, to confirm that the balance weight has not deformed or moved.
8. Extra whirl tower testing. Depending on the requests from the customer additional testing can be done on the whirl tower. Performance measurements such as lift and drag can be measured. Also, when a swash plate is mounted, a cyclic pitch can be set for rotor blade fatigue testing.

Figure 6 Stiffness testing setup

Figure 7 Combined loading setup on test bench

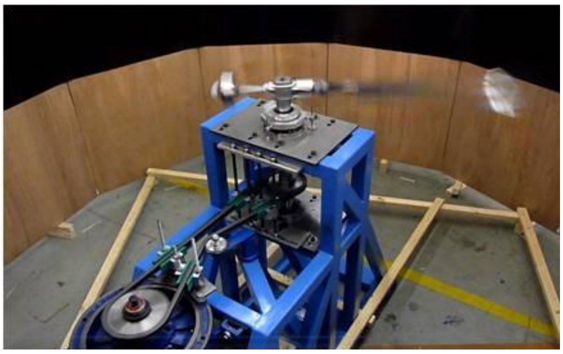

Figure 8 Whirltower

6. CONCLUSIONS

This paper has explained KVE's development steps for a new UAV rotor blade. The design approach is used to make limited but robust calculations for stability analyses and limit and ultimate strength. The RTM process used provided a structural more sound leading and trailing edge and higher process speeds that conventional processes. In house developed testing tooling such as a whirltower, provides a validation of prototypes before delivery for flight testing. Because all of these processes are done in house, from design to tooling machining to testing, lead times of blade developments at typically from 4 to twelve months, depending on budget, rotor blade dimensions and complexity.

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