Air Cargo Challenge 2013

Project Report

Team no. 27
AkaModell Stuttgart

University of Stuttgart
Germany
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1 Introduction

1.1 AkaModell Stuttgart

AkaModell Stuttgart e.V. is an association of students at the University of Stuttgart. Our aim is to pursue the fascinating sport of R/C aero-modelling on an academic level. Since many of our members are graduating in aerospace engineering, it is more than just a hobby to us. It is a way of applying the rather theoretical knowledge from our studies to the real world. Designing and building aeroplanes is worthless without flying them. To make the flying even more fun, AkaModell members are travelling together several times a year. We are usually camping on an airfield or even going to the Alps to test our newest glider designs.

AkaModell Stuttgart e.V. was founded in 1978, thus being the oldest club of its kind in Germany. With even more than three decades of experience in designing and building model aeroplanes, we can rely on a vast base of knowledge when new challenges emerge, just like the Air Cargo Challenge. After a massive drawback in 1999 when our old workshop burnt down, our members managed to re-establish our workshop at a new site. It is located on the university campus, right between the research institutes and equipped with all the machinery needed. Our 3D CNC mill enables us to build our CAD designed aeroplanes more precisely and faster than before.

1.2 University of Stuttgart

Located in the state capital of Baden-Württemberg, the University of Stuttgart is situated in one of Europe’s strongest economic regions. It is a research university with a strong focus on engineering and natural sciences. Approximately 20,000 students are enrolled here, about 1,700 of them graduate each year. The University of Stuttgart is a member of TU9, the association of the German Institutes of Technology. The university consists of ten faculties, one of which is the faculty for Aerospace Engineering and Geodesy. The 13 institutes of this department cover a broad range of research and educational topics. Their spectrum extends the “classical” aerospace focus to topics such as wind energy, satellite navigation or remote sensing.

1.3 Team Members

AkaModell Stuttgart's ACC 2013 team consists of students. Three of our team members were participants in ACC 2009, too, when AKAModell won the competition. They were also part of the organization team when ACC was hosted in Stuttgart in 2011. The remaining team members are all model pilots with a good base of experience in building and flying. All team members are introduced in the following.
Ruben Bühler – team leader  
Age: 26
Course of studies: electrical engineering & information tech.
Reputation: Ruben has been flying model airplanes for 12 years now. He is member of the Akamodell since 2007. He was member of the winner team of ACC 09 and also of the organisation team of ACC 2011. In his studies he deals with electronics for aerospace applications.

Christian Molter  
Age: 31
Course of studies: aerospace engineering
Reputation: For his diploma thesis Christian built a radio controlled VTOL aircraft with tilting prop rotors. These rotors have adaptive rotor blades, which can be twisted during operation to optimise the thrust depending on the air speed of the plane. Christian is now a research assistant and Ph.D. candidate at the chair of wind energy at the University of Stuttgart. His topic are airborne measurements with UAVs near wind turbines.

Jonas Illg – pilot  
Age: 26
Course of studies: aerospace engineering
Reputation: Jonas has been flying model airplanes for 13 years now. He is a member of AkaModell since 2009. He was member of the winner team of ACC 09 and also of the organisation team of ACC 2011. He is a Ph.D. student at the Institute for Aerodynamics and Gas Dynamics and deals with aeroacoustics of airfoil sections in turbulent flow conditions.

Michael Abel  
Age: 32
Course of studies: electrical engineering & information tech.
Reputation: Michael started flying model airplanes about 18 years ago. He is an AkaModell member since 2005 and took part in ACC 2007 and 2009. In the year 2011 he was a member of the ACC organisation team. Michael is currently doing his Ph.D. at the Institute for Control Engineering of Machine Tools and Manufacturing Units.
**Bo Armbruster**  
Age: 23  
Course of studies: aerospace engineering  
Reputation: Bo has been flying model airplanes since he was eleven years old. He is an expert in brushless motors. When he was 13 years old, Bo built his first CD-ROM motor and in the meantime he develops and builds them all by himself. Bo has been studying for two years so far and is a member of AkaModell from the beginning of his study onwards.

**Christian Hille**  
Age: 23  
Course of studies: aerospace engineering  
Reputation: Christian has been building RC Vehicles (cars, boats, airplanes) for 13 years. He is a member of Akamodell since autumn 2009. He is working on his Bachelor thesis at the moment.

## 2 Project Management

During the Air Cargo Challenge project there are many deadlines a team has to meet. Thus, proper time planning and resource planning is one of the keys to success in the competition. We utilise three pillars of project management as indicated in figure 1.

![Three pillars of project management](image)

*Fig. 1: Three pillars of project management.*
2.1 1st Pillar: Team meetings

We organise team meetings every second week. During these meetings, we develop our goals and do the necessary planning. We discuss the progress of our individual work and coordinate the next steps to avoid doubled work and mistakes. In addition, a team meeting is an excellent place to exchange experience between team members.

2.2 2nd Pillar: Time management

During the last Air Cargo Challenges we learned a lot about time management. Especially during ACC 2009 we had been behind the schedule resulting in an extraordinary high workload six weeks before the competition. To avoid this, we gave time management a higher priority this time.

In figure 2 one can see a sketch of our time line. We tried to adapt the plan to the workload students have during the semester. At the University of Stuttgart, exams are in the semester break (February till April). During this period of time we mainly focused on sponsoring and design. In May, when the summer term began, we started the building process, where we need most manpower to get the plane completed.

Fig. 2: Time line for the preparation of the competition.

Fig. 3: Critical path of the project.

Our time schedule is straightened for the critical path, pictured in figure 3, of our time line. On this path, most work has to be done. The punctual supply of all important materials is necessary, otherwise the processes will stop and the delay will increase. Especially to get the tooling material
was an important milestone, since building the moulds without this material is impossible. But also all other parts of the plane like fuselage parts, the landing gear or the rest of the wing have to be manufactured in time. Therefore, we try to use synergy effects between the processing steps. For example, all wing moulds have to be painted before laminating. The main task is preparing and cleaning. Accordingly, painting all moulds together saves a lot of work.

2.3 3rd Pillar: Human Resources

The Goliath Heron project is very challenging for us and results in a large amount of working hours. AkaModell's ACC 2013 team consists of students working on their studies and have their private life as well. For sure, every member of the team is individual in this context. To balance the differences we always try to have different packages of work. For example building the moulds is a lot of sanding work. A single person can finish a mould, and this work can be interrupted at any time. On the other side, laminating the shells of the wing must be done by three people at the same time without interruptions. Only with a good management of the different work packages and the personal issues of our team members it is possible to get this project to success.

2.4 Sponsors and Supporters

Without the help of our sponsors and supporters we would not be able to manage this project. Especially, the transfer to Portugal and the application fee is a big financial issue. But also RC components and material for the build up of the plane increase the costs. As we already have a little history in ACC participation some sponsors keep supporting us. In addition, we have managed to win further supporting organisations.

2.4.1 Sponsors

DMFV

The DMFV was founded in 11/3/1972 and is the biggest model airplane association in Germany with about 63,000 members. Its objectives are preservation and and support of the aeromodelling sport, especially by supporting young modellers and model flight clubs in Germany. Beyond that, they also offer insurances for members and clubs and do a lot of lobbying work.

R&G

Serving the composite industry is R&G’s business for more than 30 years. They provide a complete range of resins, fibre reinforcements and all auxiliary material necessary for composite construction. R&G’s offer is well balanced for industrial applications and hobbyists alike, having a great reputation in the field of modelling, especially at aeroplane model construction.
Oxeon

Oxeon develops, produces and markets patented Spread Tow carbon reinforcements for achieving superior surface smoothness, significant weight savings, improved mechanical properties and new design possibilities. TeXtreme® is used by manufacturers of advanced aerospace, racing, sports, automotive and industrial products – all having extreme demands on material performance.

Kontronik

Since 1994, Kontronik produces processor operated speed controllers in its own facilities. Already in 1997 the portfolio was extended by self-made powerful motors. Kontronik combines innovative development, high quality production and customer oriented service in its headquarters in Rottenburg-Hailfingen, Germany. Therefore, all Kontronik products are exclusively produced in Germany.

Bertrandt

The Bertrandt Group has been providing development solutions for the international automotive and aviation industries in Europe, China and the USA for more than 35 years. A total of more than 10,000 employees at 45 locations guarantee extensive know-how, sustainable project solutions and a high level of customer orientation. Its main customers include major manufacturers and numerous system suppliers.

2.4.2 Supporters

Institute of Aerodynamics and Gas Dynamics of the University of Stuttgart

The IAG has a long reputation in the field of theoretical and practical research, amongst others in the field of low Reynolds number aerodynamics. We are grateful for the opportunity to use the facilities like wind tunnels for airfoil and propeller testing.
3 Airplane Specification and Mission Requirements

The first step was to analyse the specifications resulting from the regulations. Additionally, we derived a list of requirements for best results in the competition flights based on experience.

3.1 Airplane Specification Sheet

- Maximum of payload
- No rotary wing, not lighter-than-air
- No external assisted take-off power (e.g. rocket boosters)
- Motor: ModelMotors AXI Gold 2826/10; max. current $I = 40$ A
- One LiPo Battery, 3 cells, capacity > 2500 mAh
- Usage of commercial propellers (without variable pitch)
- No rotation speed change between motor and propeller
- Given cargo bay dimensions and payload support
- Prescribed transportation box dimensions (1000×400×400 mm$^3$)
- Maximum take-off distance: 60 m
- Maximum runway length for the initial touch down at landing: 120 m
- Passing structure validation test, plane supported at the wing tips while fully loaded

3.2 Mission Requirements

- Passing of several test and competition flights
- Payload compounding as fast as possible
- Good handling (flight stability, manoeuvrability, predictable stall behaviour)
- Adequate solid construction

4 Propulsion System

Amongst others, the choice of the propeller is essential in order to enable our plane to carry as much payload as possible. One of our aims is to achieve the highest possible thrust. Based on our experience from ACC 2009, we have already drawn up a pre-selection of propellers. As the propulsion system is relatively independent of the exact airplane design, we chose this topic as starting point for the project. To find the best suited propeller for this application, we built a propeller test bench as displayed in figure 4. The test bench consists of a motor fitting the ACC regulations, energy supply, radio control, a load cell for thrust measurements and an Eagle Tree logger system which measures rpm, voltage and current.
We used the same standard RC equipment to command the electronic speed controller we intend to use for our plane, too. Furthermore, the test bench was designed aerodynamically to reduce interfering forces on the load cell to achieve results as accurately as possible. The measuring system automatically saves the arithmetic average of all measurement results obtained during a period of time.

To simplify the selection of propellers for a detailed measurement, the static thrust values of all propellers were compared. Afterwards, we measured the preselected propellers with a constant airspeed to reduce the amount of possible propellers again. For these measurements, we chose airspeeds of 3, 6, 9 and 12 m/s. The measurement results are shown in Fig. 9. Finally, eleven non-folding propellers and ten CAMcarbon folding propellers, shown in figure 5, with six different centre pieces each, were analysed in nearly 200 measurements.
Additionally, we tested all folding propellers as one bladed propellers due to a theoretically higher efficiency, which is why we designed the adjustable counter balance pictured in figure 6. Instead of the second blade, we assembled the counter balance, so that we were able to equilibrate the propeller. The measurement results showed that the one bladed propeller has got huge potential, since it achieved nearly the same results as our best propeller. However, we decided against the one bladed propeller due to safety issues and vibrations.

To equalize the effect of small deviations of voltage \( U \), current \( I \) and air density \( \rho \) on thrust \( T \) among particular measurements, our team member Jonas derived a correction equation (1) based on propeller theory. The exponents of the equation were fine-tuned to account for non-linear losses of the electrical system by means of statistical analysis.

\[
T_2 = T_1 \left( \frac{\rho_2}{\rho_1} \right)^{\frac{U_2 I_2}{U_1 I_1}}^{\frac{2}{3}}
\]

(1)

Fig. 7: Correction equation (continuous line) compared to thrust values measured at different voltages.
Fig. 8: Correction equation (continuous line) compared to thrust values measured at different currents.

Figures 7 and 8 illustrate the correction equation and measured values that are well matched. The corrected measurement results were plotted depending on airspeed as pictured in figure 9.

Fig. 9: Measured values of thrust over airspeed for some selected propellers.
The major aspect for the choice of the propeller is thrust in the period of acceleration and take-off, followed by maximum climbing performance. Finally, we decided to use the three propellers listed in the following table.

### Propellers chosen for flight competition

<table>
<thead>
<tr>
<th>No.</th>
<th>Propeller type</th>
<th>Manufacturer</th>
<th>Max. RPM measured</th>
<th>RPM limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15×4 electro</td>
<td>APC</td>
<td>7000</td>
<td>9667 [1]</td>
</tr>
<tr>
<td>2</td>
<td>16×6 folding</td>
<td>aero-naut</td>
<td>8000</td>
<td>9000 [2]</td>
</tr>
<tr>
<td>3</td>
<td>14×7 electro</td>
<td>APC</td>
<td>7300</td>
<td>10357 [1]</td>
</tr>
</tbody>
</table>

5 Aircraft Design

5.1 General Configuration and Lessons Learned

In 2007 and 2009, AkaModell competed at the Air Cargo Challenge very successfully. The basic configuration of our plane, as it is pictured in figure 10, turned out to be effective and reliable. More experimental configurations were less convincing at the competitions in 2009 and 2011. There are only minor details offering potential for optimisation at our 2009 airplane “Heavy Heron”. Keeping these details in mind, a design according to the 2013 regulations based on the successful 2009 design seems to be the most promising approach. As the requirements suggest a considerably larger aircraft compared to 2009, we decided to name it “Goliath Heron”.

![Fig. 10: Evolution of airplane geometries from 2007 by 2009 to 2013 (ACC Akut, Heavy Heron and Goliath Heron).](image)

5.2 Aerodynamic Design

5.2.1 Airfoil Selection

At the beginning of the design process, the main wing Airfoil has to be selected, as it decides on the aerodynamic design of the whole configuration. The maximum lift coefficient $c_{l,\text{max}}$ is the most significant parameter for maximum take-off weight at a specified wing area. The critical Reynolds number $Re_{\text{crit}}$ limits the minimum chord length and consequently the aspect ratio $\Lambda$ of the wing. Along with the aspect ratio, the airfoil drag coefficient $c_d$ determines the maximum climbing angle and rate of climb of the configuration at maximum payload. Hence, the airfoil must be chosen carefully at the very beginning of the design process.
At the Air Cargo Challenge, two airfoils have been used successfully since AkaModell participated for the first time in 2007: the S1223 designed by Michael Selig [3] (plus more or less promising derivatives) and, in 2009, AkaModell's two element airfoil ACC09-SK33.

Multiple element airfoils were first mentioned by Lachmann [4] and Handley Page [5] in 1921 as a means to improve maximum lift compared to conventional airfoils. Nowadays, multiple element airfoils are used commonly in commercial and military aviation to reduce take-off and landing runway length. However, at Reynolds numbers relevant for model airplanes, few research has been conducted up to now.

The development of the two element airfoil was the topic of the diploma thesis of our ACC 2009 team member André Zöbisch [6]. Preliminary design was performed using the inverse design routines of MSES [7]. Flow around airfoils in the relevant range of Reynolds numbers (125,000 to 250,000) is governed by laminar separation bubbles, which can only be modelled by approximation. Separation bubbles on main element and flap constitute a highly non-linear system leading to exponentially growing modelling errors. Thus fine tuning of slot width, flap angle and overlap had to be done by means of wind tunnel measurements. Separation bubble location can be clearly identified on the photography in figure 11.

![Image of ACC09-SK33 airfoil](image.jpg)
Fig. 11: Flow visualisation on the suction surface of ACC09-SK33 airfoil with lamp black and petroleum coating [6]. \( \text{Re}=250000, \alpha=12^\circ \).

Since polars for both airfoils have been measured at the model wind tunnel of the Institute for Aerodynamics and Gas Dynamics (IAG), the resulting data set is more reliable than calculated polars. The ACC09-SK33 provides nearly 50% more lift than the S1223 at the same free stream conditions, whereas the drag coefficients of both airfoils are of the same order of magnitude. Drag polars are diagrammed for both airfoils in figure 12 and figure 13, respectively. Since deviations of the contour of both the main element and the flap have a strong impact on the flow through the gap, which is crucial for high lift performance, a wing with the ACC09-SK33 airfoil needs to be built as accurately as possible. Ribbed wing constructions do not provide the required accuracy. Of course, the maximum lift coefficient of the S1223 airfoil will also be reduced by expanding separation...
bubbles induced by skin sagging. The separate flap of the ACC09-SK33 allows a straightforward chord wise splitting of the wing, which could be beneficial regarding the constraint of the limited transportation box size. On the other hand, the required chord length is only two third of the chord length of a S1223 wing for the same lift. So a chord wise splitting might be unnecessary. The most important drawback of a wing equipped with the two element airfoil is higher weight compared to a single element airfoil wing. Coupling links between the elements, the fact that the overall length of seams is higher and the required accuracy are taking their toll. Further analyses have to show whether the higher maximum lift will overbalance the higher weight of a wing with the ACC09-SK33 airfoil.

Fig. 12: Measured polars of S1223 airfoil at various Reynolds numbers [6].

Fig. 13: Measured polars of ACC09-SK33 airfoil in the relevant range of Reynolds numbers [6].

5.2.2 Wing Geometry

As pointed out in section 3, the transportation box size is one limiting constraint for the wing geometry. The span width of one wing section is limited to the inner length of the transportation box. Assuming one centimetre thickness of the box walls, the maximum segment span width is 98 cm. Hence, the maximum chord width of a S1223 wing is 38 cm, whereas the option of a detachable flap pushes the limit for a wing with the ACC09-SK33 airfoil to about 54 cm. The maximum feasible number of sections is not as obvious as it seems, because it depends on the chord width and the dimensions of fuselage and empennage, which in turn depend on wing geometry. Based on experience, a wing divided into five sections was selected as starting point for an iterative study. Especially if moulds for the wings have to be built, building five individual sections exceeds our team's capacity. Therefore, an additional constraint was introduced, requiring the inner three sections being rectangular, hence these three sections can be built in the same mould. The taper ratio of the outer sections (left and right) has to be selected in a way that provides gentle stall behaviour, accounting the tip Reynolds number, but without exposing excessive wetted area. A sweep angle unequal to zero is not considered, as sweep increases torsional loads and reduces maximum lift.

In 2009, ACC regulations prescribed a limited projected area. Winglets were a suitable means to augment lift and to reduce induced drag for a given wing area. Induced drag \( C_{D,i} \) is calculated with equation (2), where \( C_L \) is the lift coefficient of the wing, \( \Lambda \) is the aspect ratio, \( c_{mean} \) is the mean wing chord and \( b \) is the wing span. The Oswald factor \( e \) equals one for a planar, untwisted elliptical wing.
With winglets, an Oswald factor greater than unity can be achieved.

\[ C_{D,1} = \frac{C_L^2}{\pi \Lambda e} = \frac{C_L^2 c_{mean}}{\pi b e} \quad (2) \]

\[ b_{eff} = b e \quad (3) \]

Wing area is not limited by the 2013 regulations, but increased wing span has a strong impact on structural weight of the wing, especially when the required ability to withstand the stability test is considered. In this case, winglets can be used to increase the effective wing span \( b_{eff} \) according to equation (3) with the same geometrical wing span in order to save structural weight without drawbacks in induced drag. Two element airfoils are not suitable for the winglet, since the flow field around the winglet is three-dimensional and the slot requires mainly two-dimensional flow. The lift loading at the winglet root is rather high, so the S1223 was chosen as winglet root airfoil. The required root chord is determined by the maximum lift coefficient of the root airfoil. At the tip, the lift loading is less pronounced. Here, a modified S1210 airfoil is sufficient. To prevent the winglets from producing negative lift when the wing is bending in flight, the winglets are slightly leant outboards. During the stability test, the wing will bend, too, hence the winglets will not protrude the wing contour.

Consequently, the multi-degree-of-freedom problem of optimizing the wing geometry has been reduced to a system with the three independent variables root chord, wing span and winglet height. For the optimisation process, the aerodynamic coefficients, except airfoil lift and drag coefficients, are simulated with the vortex-lattice code AVL 3.32 [8]. In Figure 14, the geometry modelled in AVL is shown. Lift and drag coefficients of the airfoils were taken from measurements. The empty weight of the aircraft is estimated based on geometry and on the weight of test pieces manufactured from the corresponding materials. For details, see section 6.

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**Fig. 14:** Final configuration modelled in AVL.
From given aerodynamic coefficients, given take-off weight \( m \) (empty weight estimated according to section 5.7 plus payload), estimated rolling friction coefficient and measured thrust values the required take-off rolling distance can be determined. This was done using a spreadsheet by explicit time integration and a look up table for drag \( D \) and thrust \( T \) values at the velocity \( v \) corresponding to each time step \( n \) (4). Acceleration \( a \) is assumed being constant during each increment \( \Delta t \) (5), as well as velocity. The distance \( s \) covered is accumulated (6).

\[
v_n = v_{n-1} + a(v_{n-1}) \cdot \Delta t \quad (4)
\]

\[
a(v) = \frac{(T(v) - D(v))}{m} \quad (5)
\]

\[
s_n = s_{n-1} + v_{n-1} \cdot \Delta t \quad (6)
\]

With these tools, the optimal wing geometry for maximum payload can be found iteratively by varying the independent variables. However, it turned out that for a configuration optimized for maximum payload, the maximum rate of climb would be very low or even negative. Hence, a trade-off between maximum rate of climb and maximum payload has to be found. The required rate of climb was set to 0.5 m/s. Actually, this value is very low, since average thermal conditions can produce a downwash of far more than 1 m/s. In difficult weather conditions, the rate of climb can be augmented by choosing less payload, whereas in good conditions the maximum possible payload can be lifted.

These considerations lead to a smaller wing chord compared to a design optimised for maximum payload, reducing parasite drag during climb. The result of the optimisation process is a wing with 4.5 m span, still requiring five span-wise segments, and 0.35 m root chord with the ACC09-SK33 airfoil. A wing of the same span equipped with the S1223 airfoil and the maximum chord of 0.38 m to fit into the transportation box will perform inferior. The winglet height was set to 0.45 m, reducing induced drag at maximum lift by more than 20 %, compared to a planar, untwisted elliptical wing. Even when the additional parasite drag of the winglet is considered, an overall drag reduction at maximum climb conditions of up to 10 % is achieved. The winglets were shifted backwards to decouple the adverse pressure gradients of wing and winglet boundary layers and thus to reduce the risk of massive flow separation at the intersection. The distributions of lift and lift coefficient are shown in figure 15 for the wing, as calculated by AVL, and in figure 16 for the winglet, respectively.

As soon as the wing geometry was determined, paper stencils were used to check the remaining space in the transportation box. It was detected that there is enough space left for the remaining aircraft components.
5.2.3 Ground Effect Influence

During take-off and landing, the aircraft operates in proximity of the ground. There are two critical parameters influenced by ground effect. First, induced drag of a three-dimensional wing is reduced considerably in proximity of the ground. The graph in figure 17 illustrates the decrease in induced drag depending on the ratio of wing span to ground clearance. The graph was obtained using the slender wing theory described in Gersten [9].

![Fig. 15: Distributions of lift (C_l/c_{ref}, continuous line) and lift coefficient (C_l, dashed line) in spanwise direction (y) at maximum lift.](image)

![Fig. 16: Distributions of lift (C_l/c_{ref}, continuous line) and lift coefficient (C_l, dashed line) perpendicular to the wing planform (z) at maximum lift.](image)

![Fig. 17: Effect of ground clearance (h) in relation to wing span (b) on induced drag (C_D,i), according to Gersten [9].](image)

The second, adverse, effect is, that the maximum lift coefficient C_{l,max} of a two-dimensional airfoil is reduced in proximity of the ground. As pointed out by Recant in [10], the reduction is the more pronounced, the higher C_{l,max} for a particular airfoil in free stream conditions is, and the closer the airfoil is located to the ground. In figure 18, the correlation is shown for a fixed distance to the ground. For the ACC09-SK33 airfoil and the realised ground distance, one can extrapolate values...
from the graphs given in [10]. The resulting reduction of $C_{l, \text{max}}$ is about 15 %, which corresponds to MSES [7] simulations. However, the advantages of the two element airfoil compared to the S1223 airfoil are still considerable.

Both effects affect the rolling distance required for lifting a particular payload quantity in opposite sense. A relatively high aspect ratio wing is beneficial, since the favourable effect scales with wing span and the adverse effect scales with wing chord. Furthermore, increased ground clearance increases maximum lift at take-off, whereas induced drag is influenced less pronounced. Ground effect also alters the local upstream flow angle at the horizontal tail plane, which causes trim settings being dependent on ground clearance. The higher the horizontal tail plane is mounted, the less trim settings will be affected. All these facts have been considered during the design process.

\[ \text{Fig. 18: Effect of free-air maximum lift coefficient on decrease in maximum lift due to ground effect at 0.7 chord below wing, from [10].} \]

### 5.3 Stability and Control

Static and dynamic stability are both required for controlled flight. Especially handling characteristics of the airplane require accurately tailored design of stability and control surfaces. Good handling characteristics are essential, since the flight envelope of the heavy loaded plane is narrow and leaving this envelope will result in a crash with high probability. So the airplane must follow all pilot commands exactly and has to neutralise disturbances automatically. As the wing geometry is definite as a result of an optimisation process, longitudinal stability can only be controlled by sizing of tail planes, corresponding lever arms and the position of the centre of gravity $X_{\text{CG}}$.

The airfoil ACC09-SK33 requires a relatively large horizontal stabiliser, due to its large moment coefficient $c_m$. A drawback of large horizontal stabilisers is, that they require an aft position of the centre of gravity to achieve the desired static margin $ST$, normally implying a broad band width of lift coefficients at the horizontal stabilizer. The static margin is a measure for static stability. It is calculated in equation 7, where $X_N$ is the location of the neutral point and $c_{\text{mean}}$ is the mean aerodynamic chord. Convenient values for the static margin are between 8 and 12 %, according to experience.

\[ ST = \frac{X_N - X_{\text{CG}}}{c_{\text{mean}}} \quad (7) \]

Usually, large downforce is produced by the tail at high lift coefficients of the wing, thus reducing payload lift capability. However, a low position of the centre of gravity relative to the lifting
surfaces counteracts this issue as the centre of gravity is shifted forwards with increasing angle of
attack. This is, among structural stability, the reason why the cargo bay is located as low as possible.
An almost constant, positive horizontal tail plane lift coefficient could be achieved for all angles of
attack within the flight envelope. The only problem remaining is, that this lift coefficient must be
reached in spite of large negative elevator deflections. For this reason, the airfoil HT14 by Mark
Drela with hinge line at 60 % chord was selected for the elevator, complying this demand
successfully. The positive lifting force of the tail even improves climbing performance, since the
additional lift affects rate of climb more than the additional drag due to the large elevator.

Dynamic stability was achieved by adjusting the ratio of lever length and tail area. The eigenvalues
corresponding to flight dynamics modes like phugoid, short-period and dutch roll are plotted in
figure 19. All eigenvalues are located on the left half-plane, indicating a damped behaviour. The
frequencies of the modes, indicated by the imaginary part, are sufficiently spread to prohibit
coupling of two modes.

The flaps of the outmost wing sections are used as ailerons. Since the flaps are set to a position
generating maximum lift, positive deflections would cause stall. Reducing lift on one side by
negative deflection is the only means. For efficient heading corrections, the use of rudder
deflections is preferable to aileron deflections as lift is retained. A dihedral angle of three degrees
between each wing section will provide adequate rudder effectiveness. Stability and control
behaviour were analysed using AVL, since analytical solutions considering the actual lift
distribution and effects of downwash behind the wing are hard to obtain. However, one must be
aware that in all these calculations linear lift curves are assumed with a slope of 2π. This will not be
the case in reality. So the stability calculations contain a large amount of uncertainty and final
positioning of center of gravity and tail plane sizes will have to be tweaked in practical flight tests.

\begin{table}[h]
\centering
\begin{tabular}{cccccccccc}
\hline
\$\alpha$ & $\delta$ & $C_L$ & $C_{\text{ail}}$ & bank & $V$ & $\rho$ & $R_{\text{arm}}$ & $X_{\text{cg}}$ & $Z_{\text{cg}}$ & mass \\
\hline
1 & -14.16 & 0.0 & 2.960 & 6.000e-2 & 0.0 & 7.566 & 1.225 & 0.0 & 6.180 & -0.1300 & 15.00 \\
2 & 3.964 & 0.0 & 2.000 & 6.000e-2 & 0.0 & 8.116 & 1.225 & 0.0 & 6.180 & -0.1300 & 15.00 \\
3 & -0.1342 & 0.0 & 1.600 & 6.000e-2 & 0.0 & 10.19 & 1.225 & 0.0 & 6.180 & -0.1300 & 15.00 \\
\hline
\end{tabular}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure19}
\caption{Eigenvalues in the complex plane as a result of an AVL analysis of Akamodell's ACC 2013 design at three
different trimmed velocities.}
\end{figure}
5.4 Design of selected components

5.4.1 Fuselage Design

The fuselage accommodates the RC equipment and the propulsion system. One challenge was to design the fuselage in two parts since it is not possible to fit the long fuselage into the transportation box in one piece. We divided the fuselage right after the wing. To put the two pieces together we integrated a hexagonal, tapered connection into the fuselage. Hence, a self-retaining, non-twistable connection is guaranteed.

5.4.2 Landing Gear

Based on our experience from ACC 2007/2009, we improved the established design. The cargo bay together with the payload is located at the centre of the main gear. The main gear is made of carbon fibre reinforced plastic. Since the usual tubes generate much higher aerodynamic drag, we decided on a symmetrical drop-shaped profile to reduce these forces. We maintained the tapered wheels and the tricycle concept with a controllable front wheel, which provides a straight take off run. The only thing we changed in comparison to ACC 2009, is an enlargement of the wheel diameter in order to minimize the rolling resistance and the ground effect.

5.4.3 Integration of the Cargo Bay

Since one aspect of the regulations is to load the plane fast, we decided to use our concept of 2009, which is to push the payload into the cargo bay from behind. The payload plates are going to be piled up as a package, which is pushed into the cargo bay at once. It is necessary to lock the package with a small bolt in order to keep it in the right place. To hold the steel plates together, we designed a quick lock system. The system, as shown in the drawings, consists of a connecting plate with two oval holes, above which two R-pins are glued.

5.5 Structural Design

The bending load of an airplane wing is nearly carried solely by the wing spar. For calculation purposes it is sufficient to take only the wing spar into consideration. The wing’s root bending moment resulting from the lift can be calculated by integrating the lift distribution along the wing span. The lift distribution of our airplane is shown in figure 15 in section 5.2.2. For man-carrying airplanes an elliptical lift distribution is often assumed to simplify calculations. Since the present lift distribution is far away from being elliptical, we assumed a constant lift coefficient $c_l(y)$ for the load calculation, which adds an extra safety margin together with the actual local wing chord $c(y)$.

Two load cases are considered. For the first case, a load factor of $n = 4.5$ at a maximum take-off weight of 17 kg is assumed in flight to account for emergency manoeuvres and gust loads. The second case is the structural validation test at the competition, when the plane has to withstand the load from being supported at the wing tips being fully loaded. A concentrated load of 200 N acting at the centre of the wing is assumed for this load case, including a safety margin.

Integration of the lift along the wing span $b$ using equation (8) results in the normal force $F_N(y)$ on the wing spar shear web for the flight case. For the structural validation test case, each half wing has to bear a constant normal force of half the concentrated load. Integration of the normal force along the wing span using equation (9) results in the spar bending moment. For an exact calculation the weight of the wing itself has to be taken into account before integration. This is not necessary in this.
case because the weight of the wing is negligible compared to the total weight.

\[ F_N(y) = \int_{y=\frac{b}{2}}^{0} n \cdot c_{l,\text{max}}(y) \frac{\rho}{2} \frac{v^2}{\min} \cdot c(y) \, dy \quad (8) \]

\[ M_b(y) = \int_{y=\frac{b}{2}}^{0} F_N(y) \, dy \quad (9) \]

In figure 20, the resulting normal forces and bending moments along the wing span \( b \) are diagrammed.

**Fig. 20:** Normal forces \( F_N \) and bending moments \( M_b \) on the wing in flight and at structural validation test.

For structural dimensioning, the maximum values of both load cases at the corresponding span wise position is relevant. With the known bending moment along the wing span the wing spar stress can be calculated according to equation (10).

\[ \sigma_{\text{max}}(y) = M_b(y) \frac{z_{\text{max}}(y)}{I_x(y)} \quad (10) \]

Therefore the moment of inertia of area \( I_x(y) \) has to be determined. The moment of inertia depends on vertical distance, width and cross section of the spar flanges. The maximum distance of the spar flanges to the neutral axis is described by \( z_{\text{max}} \). By rearranging the equation and inserting the maximum stress of the used carbon fibre, the necessary cross section area can be calculated.

The wing torsional stiffness shall be as high as possible. Otherwise a torsional wing deformation could occur during flight and decrease the outer wing sections angle of attack and thereby its lift. Additionally, wing flutter could become an issue.

The aim is to build a wing as stiff as possible at a very low weight. To achieve this, we use high modulus carbon spread tow fabric. For estimation of the resulting stiffness and to provide a comparison of different carbon fibre lay-ups the D-box can be simplified as a closed shell. For closed, thin shells the polar moment of inertia can be calculated with the Bredt-Batho equation (11).
\[ I_T = \frac{(2 \cdot A_M)^2 \cdot t}{U} \]  

(11)

\( A_M \) is the enclosed area of the shell, \( t \) is the thickness of the shell and \( U \) the circumference. The torsional stiffness \( k_t \) of the wing can now be calculated with equation 12, where \( G \) is the shear modulus and \( b \) the wing span.

\[ k_t = \frac{G \cdot I_T}{b/2} \]  

(12)

It is obvious that the wing’s torsional stiffness for a given cross section size depends solely on the shear modulus and the thickness of the shell. A thicker shell means more carbon tissue layers and thus more weight. Accordingly, we increased the shear modulus by using high modulus spread tow tissue. The mechanical properties of the different fibre types used are compiled in the following table.

<table>
<thead>
<tr>
<th>Fibre properties [11]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
</tr>
<tr>
<td>E-glass</td>
</tr>
<tr>
<td>Young's Modulus [GPa]</td>
</tr>
<tr>
<td>E-glass</td>
</tr>
<tr>
<td>Elongation at break</td>
</tr>
<tr>
<td>Used fabrics</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

It should also be mentioned that the shear modulus of the carbon layer cannot easily be extracted from material tables because the carbon layer is used in a 45° orientation. So for an exact calculation classical laminate theory (CLT) has to be applied.

### 5.6 RC Equipment

The RC components must be chosen wisely, since the weight to performance relation is significant. The following text describes the components used and why we chose it for the Air Cargo Challenge 2013.

#### 5.6.1 Current Limiter

It is prescribed by the Regulations that the current of the electric motor has to be limited to 40 A. So we decided to use our own micro controller based limiter designed for ACC 2009. The limiter measures current via a Hall effect transducer and generates a PWM signal for the motor controller.
(ESC). The PWM signal is computed by a control algorithm in a way that the measured current is just below 40 A at full throttle. In figure 21, a block diagram of the mode of operation is shown. Since the penalty for exceeding the current limit is drastic, some tweaking of the algorithm has to be done to ensure that the current specification is kept exactly.

![Block diagram of the current limiter mode of operation.](image)

**Fig. 21:** Block diagram of the current limiter mode of operation.

### 5.6.2 Battery

Input power is linearly dependent on input voltage and current. Since current is prescribed to 40 A and the number of cells to three, the only parameter to optimize is battery voltage at operational current. Our experience, as well as test reports in magazines show that SLS APL lithium polymer batteries keep high voltage while loaded. There are different batteries available from this series suiting the regulations. Further tests have to be conducted to determine the best combination of current rating, capacity and weight.

### 5.6.3 ESC (Electronic Speed Controller)

In consideration of the fact that we are sponsored by Kontronik and the very good experiences with Kontronik speed controllers, we compared the performance of a Koby 55 LV and a Jive 80+ LV controller, as well as a Jeti Advance 70 Pro 6-12 Nixx / 2-4 Lixx, at competition conditions. There is no detectable difference in efficiency for both Kontronik controllers, however, the Koby controller is lighter by 32 g. The efficiency of the Jeti Advance controller is lower. Therefore we decided to apply the Koby controller at the competition.

### 5.6.4 Servos

Usually, for a model airplane of the size and weight of our design, big and heavy servos are used. However, flight velocity and thus control surface loads of our competition airplane will be low. Since five servos are necessary for our airplane, servo weight is considerable. When the law of lever is considered and maximum travel of the servos is applied, lighter servos can be used. The Dymond D60 is a robust and strong servo at a weight of only 9 g. A further advantage is that the operating voltage range permits two cell lithium polymer receiver batteries without voltage converter. We decided to use this servo type for all control surfaces and the steerable front wheel.

### 5.6.5 RX battery

A separate RX battery is not required according to the regulations. The selected ESC provides a power source output for receiver and servos. However, the power consumption of these components would reduce the power available for the motor, as the current draw of the ESC is limited to 40 A. Considering that we intend to use Dymond D60 servos and most receivers are authorised for a
voltage of 7.4 V, a lightweight two cell lithium polymer battery without voltage converter will be used.

5.6.6 Radio System

Radio systems in 2.4 GHz technology have proven good reliability. For this reason, we prefer to use this transmission frequency. However, the short 2.4 GHz antennas are prone to shielding by carbon fibre parts or the metal payload. If this problem is insoluble, we will switch to 35 MHz technology.

5.7 Weight Estimation

For finding the optimum plane geometry a reliable weight calculation is necessary. The complete wing and the fuselage will be built from fiber composites. For this reason we did several test pieces to estimate the exact weight of our laminates. All test pieces were built on a glass plate with one layer of carbon reinforced plastic, a layer of sandwich material and a layer of glass reinforced plastic. This sandwich structure was vacuumed. Based on the area weight of the test pieces and on our experience it was possible to calculate the estimated weights of the aircraft components, which are listed in the following table.

<table>
<thead>
<tr>
<th>Estimated component weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing</td>
</tr>
<tr>
<td>Laminates</td>
</tr>
<tr>
<td>Thickened epoxy for glueing</td>
</tr>
<tr>
<td>Foam core</td>
</tr>
<tr>
<td>Painting</td>
</tr>
<tr>
<td>Winglets</td>
</tr>
<tr>
<td>Joiners, servos and cables</td>
</tr>
<tr>
<td>Total wing mass</td>
</tr>
<tr>
<td>Cargo bay</td>
</tr>
<tr>
<td>Landing gear</td>
</tr>
<tr>
<td>Fuselage</td>
</tr>
<tr>
<td>Empennage</td>
</tr>
<tr>
<td>Battery, motor, RC components</td>
</tr>
<tr>
<td>Total plane mass</td>
</tr>
</tbody>
</table>

6 Manufacturing Techniques

6.1 Wing

As we are going to use the ACC09-SK33 airfoil (see section 5.2.1), building the wing from composite materials and using moulds is mandatory. A traditional construction technique with cross-beam and ribs would result in a favourable weight for the competition. But the contour
accuracy is not adequate for our slotted flaps, which are very sensitive to changes in the geometrical shape.

The moulds were all CNC milled at the AkaModell out of Sika Block™ tooling boards. For most of the moulds SikaBlock M700™ is used for financial reasons. Wing moulds of this type are pictured in figure 22. This material needs to be sealed after milling. For the inner wing moulds SikaBlock M940 is used, which can be polished to shiny gloss without any special treatment after milling.

**Fig. 22**: Moulds after milling and sanding.

The M700 moulds were sealed with a 2-component acrylic filler produced by Sikkens. This filler has ideal sanding and polishing characteristics.

The lay-up of the sandwich wing shells is illustrated in figure 23. The section in front of the wing spar together with the rear end of the wing spar shear web forms a closed carbon fibre shell – a so-called D-box. This D-box is responsible for the absorption of the torsional loads and delivers nearly the complete torsional stiffness of the wing.

**Fig. 23**: Lay-up of the wing shells.
The wing spar consists of the upper and lower flange and a shear web. The flanges are supposed to sustain only to tension and compression loads, while the shear web is supposed to stand the shear load. In section 5.5, structural dimensioning is described in detail.

The winglets will be built out of a foam core, covered with glass tissue without any additional moulds. This worked just fine for the ACC 2009 aircraft.

For joining the five wing sections, carbon fibre joiners with a foam core will be laminated in milled moulds.

### 6.2 Fuselage and Landing Gear

The fuselage will be built from composite material, too. For the landing gear a carbon fibre spar is supposed to be used. This spar will be exchangeable for the case it breaks during a tough landing. The wheels will be manufactured from carbon fibre tissue with a foam core in milled moulds.

For the Cargo Bay the moulds built for the ACC 2009 aircraft can be reused. Because of the higher payload expected it had to be enlarged. A simple fix was to just cut the mould in two halves, re-glue it with an additional wooden piece in the middle and fill the gap with putty.

### 6.3 Stabilizers

The horizontal and vertical stabilizer will be built as a conventional wooden design with beams and ribs, covered with iron-on film, because this is the lightest possible solution.

### 7 Take-Off and Flight Performance

With the given regulations there are two critical circumstances for lifting a maximum of payload. On one hand take-off runway length is critical, but on the other hand there must be enough excess power for climbing during flight.

#### 7.1 Take-Off

For calculation of the required take-off rolling distance following conditions have to be considered:

- The plane must take off after 60 m of runway. Our calculations are performed with 5 m backup. Accordingly, after 55 m the speed of our plane must be higher than $v_{\text{min}}$. For our plane $v_{\text{min}}$ is about 8 m/s, according to equation (13).

\[
 v_{\text{min}} = \sqrt{\frac{mg}{\frac{C_L \cdot A \cdot \rho}{2}}} \tag{13}
\]

- Decreasing thrust of the propulsion setup with higher velocity.
- Increasing aerodynamic drag of wing, fuselage, winglets and tail with higher velocity.
- Decreasing roll resistance when loading on the wheels is reduced by lift when velocity increases.
7 Take-Off and Flight Performance

7.2 Flight

During flight, thrust must be higher than the sum of aerodynamic drag occurring to achieve climbing of the plane. As announced in section 5.2, we set the minimum rate of climb required to 0.5 m/s. In figure 26 the occurring forces during flight and in figure 27 the rate of climb over speed is presented.

7.3 Payload over Air Density

As demanded in the regulations the linear function for calculation of payload $m_{\text{payload}}$ [kg] over air density $\rho$ in [kg/m$^3$] is given with equation (14). The required graph is given in figure 28.

$$m_{\text{payload}}(\rho) = 2.7 + 9 \cdot \rho$$  \hfill (14)
8 Conclusion and Outlook

The delivery of this report is an important milestone. From now on we can focus all manpower on the building phase that has already started. The moulds for the wing are ready for use and the first parts of the wing are in construction, as pictured in figure 29. The moulds for the fuselage will be milled and prepared for building as soon as possible.

For our team the participation at ACC is already a success. All team members have gained a lot of experience in a wide technical field like aerodynamics and fiber composite construction, but also in so called soft skills and project management abilities are widely improved.

The whole team is looking forward to the competition in August and we give our best to be competitive in time.

Fig. 28: Payload over air density graph.

Fig. 29: The first laminated parts for the centre wing section.
9 References


10 Appendix

Professor in charge statement
Registration form
3-view drawing
Isometric perspective view
Cargo bay
Integration of cargo bay