Manufacturing Processes in an All-aluminum Airframe

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One often overlooked aspect to building an aircraft is the manufacturing process used to put it into production. This may be a major contributor to acquisition cost and requires a large amount of money to implement. Once all the tooling has been purchased, one of the greatest costs is labor. The experience of building an all-aluminum aircraft shows that the production process is one which may be done in many different ways. Minimizing the assembly time is important for aircraft manufacturers and one of the best ways to do that is on the assembly line itself. Specific practices in the manufacturing process can speed up production, and this paper shows some practical examples of that.

I. Introduction

Aluminum airframes have been in use since 1917 due to their light weight and strength for both skin and formers. The construction process of building a kit airplane where initial shaping of the metal is done by the manufacturer but all assembly is done by the owner is a good way to see the manufacturing process that goes into building an all-aluminum airframe and understand the benefits and drawbacks to it. The case presented here is the construction of a Zenith STOL CH 701 which was completed at the San Luis Obispo airport.

After completing the aircraft, it was interesting to look at the manufacturing process and compare it to that of Cessna's. Cessna is the leading manufacturer of aluminum aircraft for private consumers and many of its aircraft are roughly the same scale or a little larger than this project. A comparison shows the simplicity and some of the difficulties of building such an airplane as well as some of Cessna's techniques that this group used and some we might have benefitted from.

II. Production of the CH-701

The CH 701 is an all-aluminum airplane driven by a Rotax four-cylinder engine of about 100 hp. It has full-span flaperons, or a combined flap/aileron control surfaces. It also has pressure-deployed leading edge slats. This means that the slat stays retracted until the change in pressure over the top of the wing while on approach automatically deploys the slat. These characteristics combine to give the CH-701 impressive STOL capability; it has a takeoff ground roll of less than 90 feet and a landing ground roll of less than 140 feet.

Figure 1. Zenith CH-701

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Figure 2. CH701 with flaps deployed on approach

In keeping with many STOL airplanes, the CH601 has tricycle landing gear which gives it good ground clearance and allows brakes to be placed on the mains for short landings without worrying about planting the nose in the ground. It has space for a pilot and passenger to sit, though having a passenger severely impacts takeoff and range performance.

The CH 701 has a skin and internal structures layout entirely built around aluminum sheet mostly less than 0.1 inches thick folded to shape. The fasteners used are A4 and A5 rivets. The plane is mechanically actuated with cables running from the cockpit through the body to the control surfaces.

Figure 3. Yoke and rudder control linkages

The equipment used in the assembly was a mixture of hand tools and some machines such as belt sanders. All fixtures were built out of lumber and used primarily on assembly of the wings and empennage so that the skin did not warp. Holes for the placement of the rivets were often denoted on the aluminum parts with very small holes placed by the manufacture and drilled out to size by the buyer with air drills. All deburring was done by hand and parts were primed with spray cans before final assembly. Before riveting, the different parts were held together using clecos and were placed using cleco pliers by hand. The rivet guns used were likewise driven by compressed air as it was much quicker and more efficient than pulling them mechanically. There were also an assortment of wrenches and screwdrivers used for a very few things but for the most part the tooling requirements on this aircraft were very light. Some parts required trimming and this was mostly done using the belt sander. The avionics board was assembled independent of the aircraft of commercially available sensors and consists of a single board with attitude, airspeed, and fuel indicators. The intent of this design was to make it simple enough for anyone who bought it to assemble it themselves. There was a team of about a dozen people who worked on this project to some extent over the course of nine months to assemble it. Work time for the most part was limited to three hours a day, three days a week. Since not everyone could work every day, on average there were about five people present any given day. This puts the work for assembly at about 540 man-hours not including the engine rebuild, which was done by a separate team of professionals.

Figure 4. Fixture for assembling right

This airplane's simplistic design makes it a great opportunity to study the manufacturing process involved in building it and by extension general principles involved in the manufacturing of aluminum aircraft in general. Generally, aircraft are produced on an assembly line with a large amount of the operations automated, which was not how this aircraft was built. This airplane had individuals designated to build specific pieces of the airframe such as the wings, the flaperons, the fuselage, or the tail surfaces. There were four separate workstations designated for work which allowed work on four separate assemblies to be concurrent. Even though method of manufacturing was different, however, the same number and type of processes were completed on this aircraft as are done on a production line. This means that by looking at this airplane as a case study conclusions can be made about the manufacturing process in general.

The portions of the aircraft I worked on were the flaperon assemblies. These were composed of two different segments on each side, an outboard aileron and inboard flap which assists with generating lift for takeoff and landing. These are full span and are physically fastened together with a splice plate of aluminum which means that both are deflected together.

Figure 5. Work area for CH

Figure 6. Control horn (left) and splice plate (right) for attached to right flap

The flap has a longer chord length than the aileron, but the airfoil is the same. Both portions are assembled on a bench in much the same manner and then joined once installed on the trailing edge of the wing. Each flaperon has 16 ribs which are attached to a single spar in each portion. Each flaperon has two brackets which serve as hinge points for the assembly; these are also attached to the lengthwise spar. The trailing edge and then the leading edge skin are layered upon it and riveted in place.

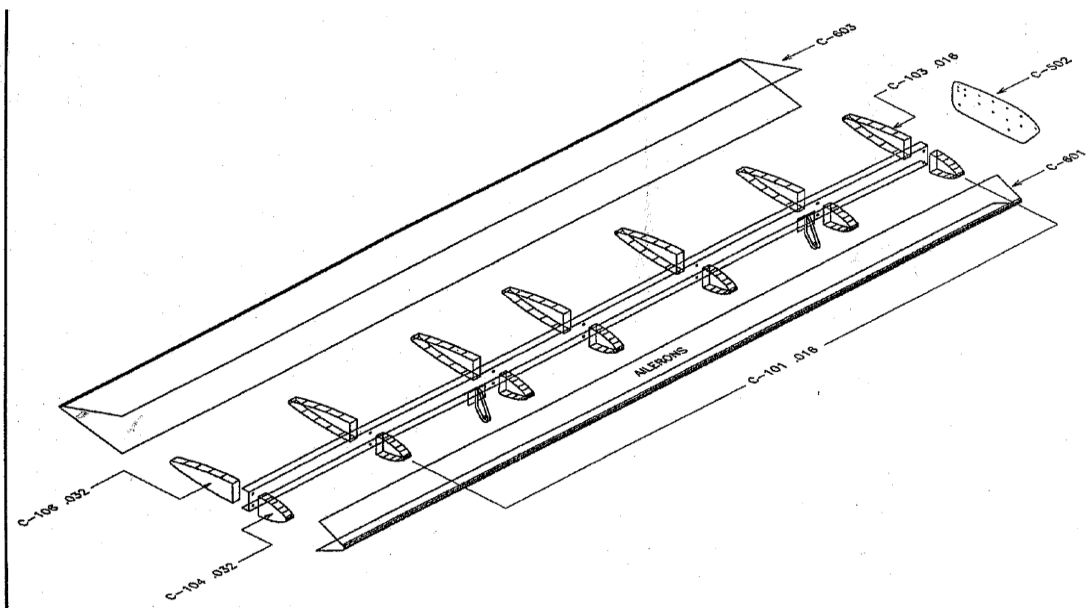

Figure 7. Left aileron

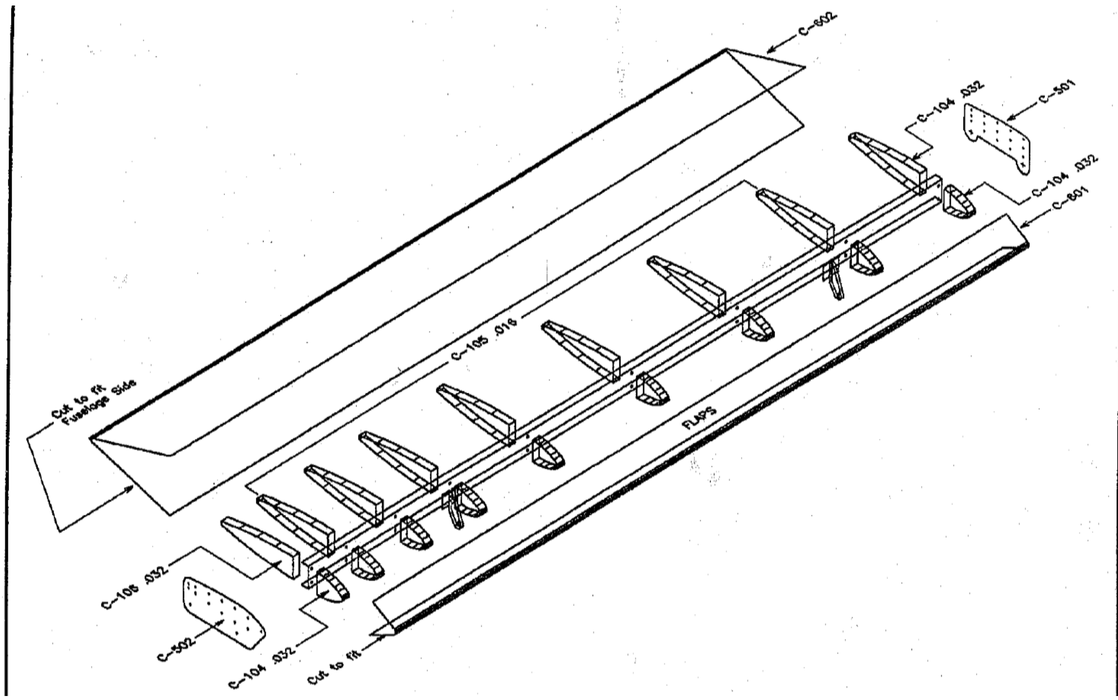

Figure 8. Left flap

Each flaperon has two rivets holding each rib in place to the spar and four holding each bracket to the spar. They use a long row of rivets through the leading edge, the trailing edge, and into the spar of 45 rivets on each side top and bottom of the aileron and 40 rivets top and bottom on the flap. Then there is a row of rivets for each rib fixing the skin to it 45 top and bottom for the flap and 35 top and bottom for the aileron. The control horn plate designated in figure 7 as C-501 has 17 rivets and the splice plate has 24 rivets. Altogether, then, each flaperon takes 419 rivets in two sizes.

Figure 9. Locating the midline of a rib

Figure 10. Fastening together structure with

This number of rivets is the final step. Before riveting, a number of different processes must take place in preparation. First the midline of each rib for the leading and trailing edges must be located so that it can be mated to the lengthwise spar and two holes are drilled out with a #40 drill bit and clecoed together. Then the hinge brackets are drilled out and fastened on. Since the standard size rivets are a little larger than these holes, each cleco is taken out one at a time and the holes are re drilled with a size #30 drill bit and refastened together. Each reassembly occurs so that the assembly can be visually confirmed to appear as it should. Each piece of the interior structure is then

disassembled a second time to be deburred and primer is sprayed on any location that metal contacts metal. After this, the interior structure is riveted together and the skin is put on. To do this, first the trailing edge skin is placed up against a fixture made of plywood and the ribs and spar are pushed fully into it so that the trailing edge of the ribs reaches all the way to the crease of the trailing edge and holes size #40 are drilled through the skin and into the midline of each rib. The skin is then clecoed on while taking care to keep the skin completely flat and no twisting or warping in its surface. The assembly is flipped and the other side is treated in the same manner, and then each side is drilled out to size #30. The skin is taken off the ribs, each hole is deburred, and primer is applied. The skin is then put back on and clecoed back together again. The process is then repeated on the leading edge skin. First, the skin is put over the ribs, the holes are drilled through at the centerline of the ribs and along the length of the spar first with a #40 drill and then with a #30, and the whole skin is deburred, primed, and clicoed together. Finally, once this is done and the flap or aileron has been inspected to ensure it is not warped, the skin is riveted to the structure. The different stages of assembly are shown in figures 12 through 15.

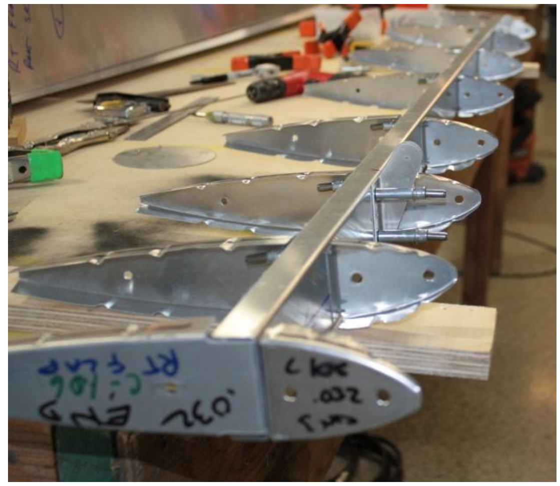

Figure 11. Clecoed flap structure

All of these steps limit the speed of achieving what is in essence a very simple objective. They were necessary for our team, however, to ensure that the aircraft was built to spec and maintain quality control. For a larger company speed and ease of assembly is key to being able to keep production high and production cost low, but quality control remains absolutely essential.

Figure 12. Right flap structure

Figure 13. Fixture for holding the trailing edge skin

Figure 14. Flap with trailing edge skin

Figure 15. Riveting the leading edge skin

III. Cessna Manufacturing

One excellent example of lean manufacturing in action is Cessna. They produce similar all-aluminum aircraft to the CH-701 but must produce many aircraft instead of the one aircraft my senior project group did. This makes streamlining the process that much more important. Cessna accomplishes this through incorporation of many lean manufacturing techniques including their equipment setup, tooling, and employee practices. A single engine Cessna such as the 172 requires about 2,000 man-hours of work [1], and a larger aluminum aircraft such as the Citation Excel which Cessna was manufacturing in three days in 2000 [2].

A good example of this is Cessna's Independence manufacturing facility in Wichita, Kansas. It was originally a fabrication site for all Cessna's propeller driven aircraft, but in 2005 it was consolidated to allow it to function as the production site for the Mustang line as well. This was mainly in response to falling demand by Cessna's buyers. Between 2008 and 2009 Cessna let 7,600 workers go, or about half its workforce, relocating some of these jobs to China or Mexico [3]. This allowed Cessna to have lower production costs but in order to keep up with its orders it instituted changes at the Independence facility. Employees were cross-trained on all the different models of aircraft. They could work on the Mustangs as well as the 172s. Cessna consolidated equipment to save as much floor space as possible. What used to require 250,000 square feet of space is now being done in 40,000 [4]. This allows greater production capacity from fewer sites for Cessna, which lowers maintenance and operation costs on the buildings themselves. Part of this is also made possible by Cessna's analysis and streamlining of the assembly process itself. Instead of installing the engine, propeller, and cowling early on as had been done in past years, Cessna began waiting until the final stages of production before doing this. It allowed greater access to the rest of the aircraft while putting in the skin, avionics, and so on, allowed a cleaner paint job, and meant that workers didn't have to take as much time and care not to damage the engine and prop while working. This technique also reduces the engine inventory that Cessna holds, which reduces their inventory costs.

Figure16. Small plane production line at Independence

Another thing Cessna does is providing quality control and testing as assemblies are put together, not waiting until the entire airplane is assembled. By doing things like doing a propellant filling of the fuel tanks as soon as the wings are done, Cessna avoids a situation where the airplane is completely assembled but needs to be taken apart and reworked to fix a few things and freezing up those assets. Once the airplane is built, it usually only takes one test flight to verify airworthiness and Cessna can sell it. The Independence facility was producing a new 172 every 4 hours in 2000 [5].

Achieving this sort of output is not easy, however, and Cessna has had to make many adjustments to do it. Some of these would not be conducive to my group's building of the CH-701. Cessna's production takes place on an assembly line, so work is not being done on multiple parts of the same airplane simultaneously. This created some issues sometimes in our work in that things like the fit of the flaps to the wing was impossible to verify while building them since the wing itself was not built yet. Also the advantage Cessna gets by cross-training employees on different airplanes would not have benefitted us. We also didn't have to worry about sleeping inventory tying up our resources like Cessna did. However, there are things Cessna enacted which would have helped our project out.

One of those advantages Cessna had to create for itself was the experience in working with sheet metal. In building control surfaces for the CH-701 it was paramount for me to make sure there was no warp along the longitudinal axis before riveting. This can be tricky, especially for someone like me without a background in it. Unfamiliarity with the equipment and process means tasks take longer. Also, the fact that no one on the project had built an aircraft like it before meant that a lot of time was taken simply making sense of the instructions. Also there were delays because Dr. Colvin couldn't be everywhere at once so if one group on the wing needed guidance they sometimes had to wait for him to get done talking with the people working on the tail. Cessna had these same problems when starting up their small plane business again in 1994. They hired many people with no background in airplane manufacturing to start it up, which meant that their output was very low the first year; only 360 airplanes were built. As the workers became more proficient, the pace picked up, and in 2000 about 900 airplanes were produced at Independence [5].

Both Cessna and our project had a great many intermediate steps before finally riveting something together. On the CH-701 any location had to get drilled out with a fine hole, then clecoed, then the cleco removed and a larger hole drilled and a different cleco placed, then the cleco removed again and the rivet put in place. Even before we touched the metal the company Dr. Colvin bought the pieces from had drilled a very small marker hole in most cases to show where the rivets would go. This is a great many steps, yet it is necessary to be able to cleco a piece in place before riveting to make sure it fits right. Cessna does the same process with their aluminum airframes [6]. This means that a lot of time is spent on intermediate steps. In order to maintain quality control this is the smart thing to do, but if there were a way to cut some of these steps out without compromising the aircraft it would certainly cut

production time. One thing I thought was that if instead of drilling every hole on a piece out to the larger size on the second pass and having to put in a whole set of the large cleco size and then take them out again while riveting we had put the rivets in immediately after drilling each hole to full size we might have saved time. In theory, since the small size clecos had lined up the pieces already the alignment doesn't change for a larger set of clecos. This does seem iffy, however, and for our project safety was a lot more important than speed.

Figure 17. Riveting process on a Cessna

Cessna has come up with other ways to speed up the process on the assembly line, however. One way they do this is by lifting the wings and tail surfaces to a vertical position with a crane while they are being worked on so that work can be done on both the upper and lower surfaces at the same time and the workers don't have to bend awkwardly over their work. Another way they have done this is by preparing the next day's work the night before so that the first shift in the morning doesn't have to go and gather everything together. Also they have attempted to reduce wasted motion by placing all the parts needed within closer reach of the workers. This is particularly applicable to the CH-701 project, where we left the work area cleaned up at night and then brought out the next work on the next day. We did leave the large pieces like the wings and the flaps on the tables overnight but always put away the spare parts and tools. On the one hand if we had set up parts in jigs and left out our work when we left we would have saved a tiny bit of time, but would have always left the place looking a mess and increased the likelihood of foreign object debris like rivets being lost inside a piece we were working on. What helped Cessna out primarily was that they had less skilled workers doing the setup at night so that the key workers could show up in the morning and get right to work, which was not the case with our situation, in which the same workers would have done the job regardless. More interesting is how Cessna organizes its parts to allow easy access. This is especially useful for small things like clecos and tools like air drills which are used often and the less time spent searching for them the better. While the workspace we had on the CH-701 project was organized very well with labels on the tool cabinets showing what was in each one as shown in figure 20 there were certain items like the drill bits which did not have a defined spot. This meant that if someone wanted a different size drill bit sometimes they had to ask other people where the set of bits was. It was a small amount of time, but would have speeded things up slightly to have had a set location. For Cessna it's a much bigger deal since they use many more types of parts and tools than we did and have a much more massive facility which would render things impossible to find if they didn't have set locations.

Figure 18. Tail surface for a Citation jet

Figure 19. Parts bins at a Cessna plant

Figure 20. Work area with labeled tool bins

Along with rapid and inexpensive production, quality assurance is key. Without it, customers will lose confidence in the product and it may cause loss of life in the case of airplanes. When building our airplane, quality assurance was done by Dr. Colvin, who checked each assembly as it was being assembled to make sure that it was being done right. He made sure of things like that no rivets were in danger of pulling out and that the skin was flat with no warping before the final riveting was done on the flaps and ailerons. Cessna has had to find the balance of achieving fast production with maintaining quality. Their reputation in the industry has been excellent, but some people have been looking at their decision to move manufacturing of the Skycatcher to China and some composite manufacturing to Mexico with unease. This was heightened in 2010 when a seven foot section of composite wing manufactured in Mexico came apart during a test flight and the FAA fined Cessna $2,425,000 for the lapse [8]. These steps were taken as a cost-cutting measure, but the results show how dangerous it can be to pursue lean, cheap manufacturing at the cost of quality.

IV. Conclusion

The Zenith CH-701 project provided an excellent chance to look at the advantages and difficulties of manufacturing an aluminum aircraft. After reviewing our construction practices on the project and comparing them to the manufacturing process used by Cessna to mass produce similar aircraft more of these advantages and difficulties are apparent. Aluminum is a simple yet dependable material to work with and requires less specialized training, but the assembly process can be drawn out because of the many steps to take before final assembly and riveting. Still, many of Cessna's lean manufacturing procedures were followed in some manner by our team and we proved an effective workforce, finishing the construction of the airframe in nine months.

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