



CREATION OF A Z 43 AEROPLANE MODEL FOR A FLIGHT SIMULATOR

Jozef Poláček

Air Transport Department
University of Žilina
Univerzitná 8215/1
010 26 Žilina
polacek28@stud.uniza.sk

Filip Škultéty

Air Transport Department
University of Žilina
Univerzitná 8215/1
010 26 Žilina
filip.skultety@uniza.sk

Abstract

This paper describes the process of developing a Zlin Z 43 aircraft for a flight simulator. Work on an aircraft simulation consists of multiple parts. The development of the flight model is the first and core part of the simulation. Work on this part consisted of an analysis of the X-Plane blade element theory-based flight model, sourcing of the data this model requires, flight testing and further editing of the data to match the known performance of the Zlin Z43. The aircraft systems are another core part of the simulation. A Mix of the simulator's default, customised and fully custom systems are used. The theory and process of creating, animating, and texturing a 3D model are described, too. Visual quality can also be important, especially for its use in virtual reality. The last part is about the user interface, user experience and how the various use cases shape their design for an aircraft simulation.

Keywords

simulator, flight model, airfoil analysis

1. Introduction

The aim is to create a simulation of the Zlín Z 43 aircraft, including a flight model, aircraft systems, visual model, and user interface for interaction with the simulation. X-Plane 11 has been chosen as the platform, as it was deemed the best fit for the project in its initial phase. The primary reason was the fact, that it was the only commercial flight simulator that allowed both professional and entertainment use in active development. During the development of the aircraft, the next major version of the simulator, X-Plane 12, has been released. Most of the work was fully compatible with the new version. However, some changes still had to be made to the flight model, systems, and visual model for both compatibility reasons, as well as to utilise some of its new features. The model of aircraft has been chosen in part because there was no existing, high-quality simulation of the type available. Neither the more modern Z 242L or Viper SD4 operated by LVVC were considered, as both are equipped with glass cockpit avionics of which no simulation exists for the X-Plane flight simulator. Creating a custom simulation of such modern avionics is beyond the scope of this project.

2. Flight model

2.1. X-Plane 12 flight model

The flight model of the X-Plane flight simulator is based on blade element theory. At the core of this flight model is a basic 3D model that is used for its calculations. This model consists of fuselage, wings, propellers/rotors, cowlings, gears, and other miscellaneous objects, all of which affect the flight model. Wings are defined by their length along the 25% chord, tip and root chords, sweep, dihedral and can be split along the chord into ten equally spaced sections – elements. Incidence can then be set for each individual element, as well as which flight controls are

present for this element. Specifications for these flight controls, such as their deflections and chord ratio as well as coefficients for flaps and slats are then defined separately. Propeller is defined by its position, cant, type, turn direction, radius and pitch range. Like a wing, a propeller blade is split into ten elements, each defined by chord lengths and its angle of incidence. This defines the geometry of wings and propeller blades, next we need the coefficients of lift, drag and moment. These are stored in airfoil files, which contain coefficients of lift, drag and moment for the whole -180 to 180 degree angle of attack range. Each airfoil can contain data for up to ten Reynolds numbers. Every wing or blade can be assigned three airfoil files which are then blended along their chord. The last two things needed for the lift, drag and moment equations is the air density, which comes from the simulator's atmosphere simulation, and the velocity. For velocity, it's not enough to simply consider the speed at which the air moves relative to the aircraft. Additional calculations are done to get the local air velocity affected by things like propwash, upwash, downwash and other interactions between the wings and bodies.

2.2. Creating the airfoils

X-Plane comes with its own program for creating the airfoil files called airfoilmaker. This program can, however only create curves for each coefficient based on entered parameters. For this project, data from airfoil analysis was directly imported into an airfoil file. For this analysis, XFOIL has been used. The biggest limitation of XFOIL for this use is its inaccuracy at higher angles of attack. It can generally predict results well within the linear range of the lift coefficient, however, it begins to overpredict the lift and underpredict drag at higher angles of attack approaching the stall (Kallstrom, 2022).

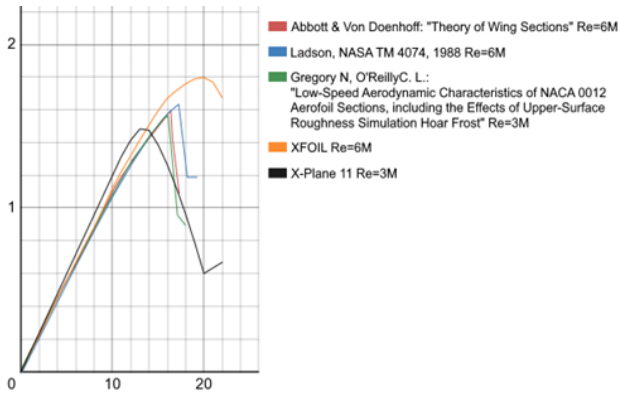


Figure 1: Comparison of the lift coefficient for NACA 0012 airfoil from experiments, XFOIL analysis and an airfoil file included with X-Plane. Source: Authors.

Figure 1. shows the overprediction of lift coefficient by XFOIL analysis in comparison to experimental data (Langley Research Center, 2023). It also shows the need to create new airfoil file, even though one for the NACA 0012 airfoil, which is used on the empennage of the Z 43, is included with the simulator. On the main wing, NACA 63-416.5 is used. Unlike for the NACA 0012, there is no experimental data available for verifying and adjusting the results of the analysis. Therefore, a different approach has been taken where the data for angles of attack approaching the stall have been gradually corrected with estimations based on known errors of XFOIL analysis and then validated and corrected further with flight tests. These corrections are shown in figure 2. where the original analysis results are shown in blue, and the correction is overlaid in red. Results are shown for ten evenly spaced Reynolds numbers between 1 and 10 million.

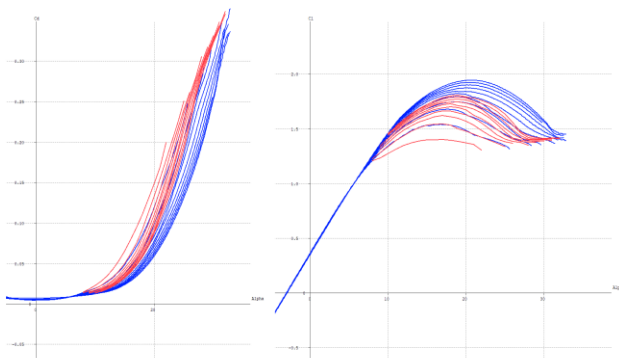


Figure 2: Visualisation of the modified drag and lift coefficients. Source: Authors.

For the stall speed flight tests a procedure described in the "Certification Specifications and Acceptable Means of Compliance for Normal, Utility, Aerobatic, and Commuter Category Aeroplanes CS-23" document was used. According to paragraph 23.201 b, the wings level stall characteristics must be demonstrated starting from a speed at least 10 knots above the stall speed, the elevator control must be pulled back so that the rate of speed reduction will not exceed 1 knot per second until a stall is produced, as shown by either:

- An uncontrollable downward pitching motion of the aeroplane; or

- A downward pitching motion of the aeroplane, which results from the activation of a device (e.g. stick pusher); or
- The control reaching the stop.

For the Z 43, wing level stall is shown by an uncontrollable downward pitching motion, as shown in figure 3. by a vertical grey line.

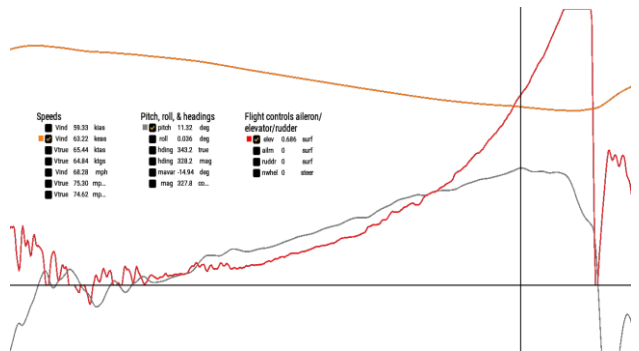


Figure 3: Wing level stall flight test data output. Source: Authors.

The graph shows a downward pitching motion which could not be stopped by increasing elevator deflection without increasing the deceleration to a value greater than 1 knot per second. When this happens the equivalent airspeed, which is practically equal to calibrated airspeed under these conditions, is 63.22 knots, while indicated airspeed is 59.33 knots. These speeds closely match the values from the flight manual as shown in figure 4.

Power setting	Configuration	CAS [km/h]	IAS [km/h]	CAS [kts]	IAS [kts]
Idle	Clean	117	110	63.17	59.39
	Take-off	110	102	59.39	55.07
	Landing	103	94	55.61	50.75
90% max. continuous	Clean	112	104	60.47	56.15
	Take-off	105	96	56.69	51.83
	Landing	95	85	51.29	45.89

Figure 4. Stall speed table. Source: EASA (2015).

With the clean configuration performance matching the real world performance, flaps can be tuned. The same procedure as before has been used. X-Plane doesn't have separate polars for airfoils with the high lift devices deployed. Instead, for flaps the increase in the coefficient of lift, drag and moment is set inside the planemaker. Planemaker estimates these values based on the flap type and the geometry of both the flap and the wing. Flight tests have shown this estimation to be accurate for the take-off configuration of 14 degrees. However, for the landing configuration of 37 degrees, the stall speed has been significantly lower in comparison to the values in the flight manual. This means, that there is no single value that can be used. Instead, these coefficients have to be driven with a plugin which can change them dynamically. After getting accurate

coefficients for both take-off and landing flap settings, a linear function has been added to smoothly interpolate between the two values. Since there is no data available to validate performance for other deflection angles and the time spent in between the 0, 14 and 37 degrees, linear interpolation has been deemed as satisfactorily accurate.

2.3. Mass and balance

The dry operating mass, DOM, as well as the dry operating index, DOI, can vary significantly between different airframes. This is due to various factory options, but more importantly, various modifications to specific aircraft that have been made. For this reason, it was decided to let the user enter these values and change the DOM and DOI of the simulated aircraft automatically to match the desired values. Initially this was done by changing the mass of the payload and moving the longitudinal centre of gravity. User could then enter the payload masses through a menu separately for front and rear seats as well as for the top and bottom baggage compartment. Payload and longitudinal centre of gravity would again be adjusted in accordance with the arms as defined in the flight manual.

However, with the release of X-Plane 12, this had to be changed to work with the new payload station system. This new system allows to creation nine payload stations, each with defined arm for all three axes. This has allowed for the vertical and lateral centre of gravity to be changed based on payload, as well as the moment of inertia. However, this change also made changing the empty centre of gravity location in a way it was done before impossible. To solve this issue and continue allowing the users to specify DOI, an extra payload station has been added. This station cannot be loaded by the user, but instead is controlled by code that adjusts the mass of the loading station in a way that results in DOI that the user has requested.

Fuel tanks have always worked in a similar way as the new payload stations do, affecting both the centre of gravity and the moments of inertia based on their location and the mass of the fuel inside them. Their arm can be changed depending on the amount of fuel in tank. However, this relationship can only be linear.

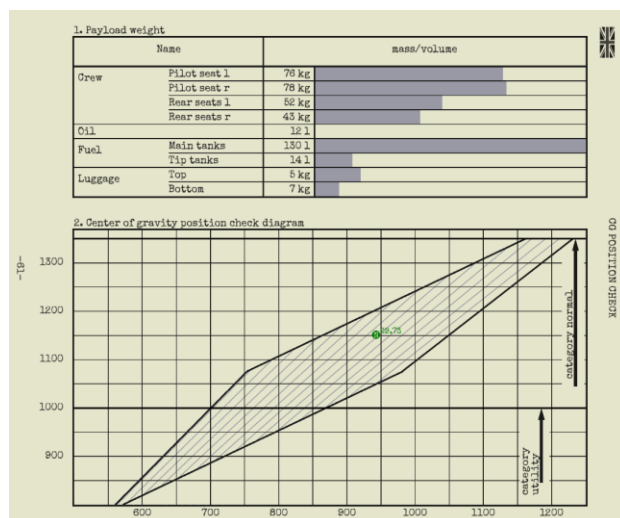


Figure 5: Mass and balance menu user interface, adapted from flight manual.

After adding payload and fuel the user is presented with centre of gravity position check diagram as shown in figure 5. This diagram shows whether the aircraft is within its centre of gravity and mass limitations as well as whether the payload is suitable for carrying out a utility category flight.

3. Aircraft systems

3.1. Simulator extensions

The X-Plane Plugin software development kit, SDK, allows developers to write additions that work inside X-Plane without modifying its code. For easier access to SDK's features for less experienced programmers, different frameworks were created. XLua has been developed internally and is used by the art team of Laminar Research. However, it only has basic functionality (Moravan, 1999). For aircraft plugins, there are two other popular Lua frameworks, SASL and Gizmo. Both are more complex than XLua and allow the developer to use almost all features of the X-Plane SDK and also offer their own digital rights management. For this project SASL has been chosen as it supports all three operating systems as the base simulator, while Gizmo lacks Linux support. SASL also doesn't require the global plugin to be installed in the simulator and is not tied to one publisher.

3.2. Electrical system

The Z 43 electrical system uses primarily direct current, with alternating current only being used to power the factory-installed attitude indicator and directional gyro. These were powered using the PAG-1FP inverter. Aircraft which had the factory gyroscopic instruments replaced with ones powered by DC have had this inverter removed. All the components are, with the exemption of the pitot heating system during its system check, connected in parallel. This has allowed for multiple simplifications in the simulation. The custom simulation can be split into two parts. The first part is the logical state of the system. This state is not calculated every frame, instead this is only done in situations where a change to its state could happen and only for the affected busses. Based on this state, the voltage, current and power is calculated for its components. These calculations must be done every frame. Even though it's not a very complex simulation, it offers multiple benefits over default electrical system implementation, such as more accurate behaviour under many different conditions. This way of simulating the system automatically results in correct behaviour of different failures, checks and of circuit breakers, fuses and even disconnected electrical connectors. The system was connected in accordance with the schematic in the Czech language version of the technical manual and has uncovered a few errors (EASA, 2015).

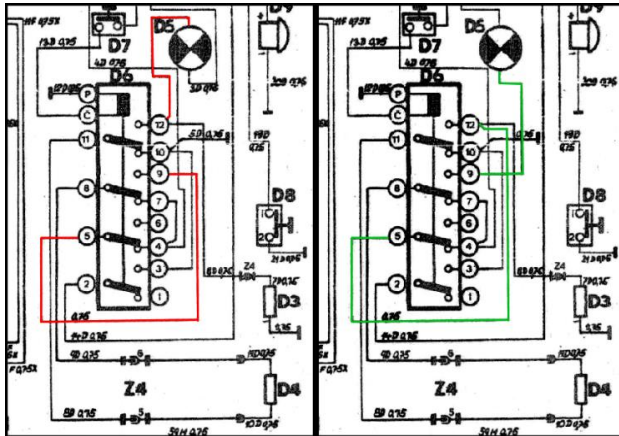


Figure 6: Erroneous schematic (left) compared with the corrected one (right).

The biggest error was wrong connection of the RP-6 relay in the pitot heat system check circuit, marked as "D6" in the schematic. After initial configuration the system was not working as intended in the simulator. After closer inspection it was clear that a circuit wired as shown in the schematic cannot result in the desired functionality. A schematic from the Z 142 technical manual was used for this system instead, as the pitot heat system is identical between these two aircraft (Moravan, 1980; 1988). Using this schematic has resulted in correct behaviour of the pitot heat check system.

3.3. Avionics

One of the primary uses the Zlin Z 43 was designed for was air navigation training. For this purpose, it could have been optionally equipped with RKL-41 automatic direction finder as well as with either LUN 3524.21, or in later models, the KY-96A VHF radio stations. Over time many aircraft were upgraded with more modern navigation and communication equipment. This means, that currently the equipment installed on these aircraft can vary from airframe to airframe quite significantly. For this reason, it was decided that instead of focusing on recreating a single, specific airframe, a way for the user to customise the panel will be added. This meant adding UI for selecting the configuration as well as creating a way to store and load saved configurations automatically, so users do not need to configure the aircraft for every flight. The simulation of the electrical circuits that power avionics also had to be made modular, to support many different configurations.

The configuration menu offers five basic presets. One based on the factory configuration and one with Bendix King avionics for radio navigation including VHF NAV, DME and ADF equipment. Other three configurations include a GPS. First of includes KLN-90B GPS. An open source simulation of this unit is used. Last two configurations offer a more modern Garmin GPS. For both, it can be either GNS430 or GTN650. First one is a basic VFR configuration with a GPS, transponder, and an audio panel, second is based on a specific airframe, currently registered as OM-LOW.



Figure 6: 3D reconstruction of a modernised Z 43 panel of OM-LOW. Source: Authors.

A basic simulation of GNS430 is included in the X-Plane flight simulator by default. It can be replaced by the Garmin trainer software with the use of third party commercial software. Third party software is also required for the GTN650, as the simulator doesn't include any simulation of this unit by default. There is no high-quality default simulation of communication and navigation radios or transponder, so a custom simulation of those devices has been developed. All features of these avionics, except for maintenance and configuration pages, have been accurately replicated. Special attention was given to the code input functions of the GTX330 transponder. This is commonly incorrectly implemented, which diminishes its use for cockpit familiarisation and in some cases can result in the user entering a wrong squawk code. Other functions including pressure altitude display, flight timer, altitude monitor, count up/down timer, temperature and density altitude display as well as options related to these functions were also modelled.

Each of these five presets can be further customised. This includes the aforementioned GPS options, as well as options for different attitude indicators, altimeter in feet or meter and more.

3.4. Configuration and system state saving

The ability to save the current state of the aircraft systems as well as its position and velocity can be very useful for both entertainment as well as professional training use cases. Therefore, a system that allows to save and load this data was created. This system works in a very similar way as the system required to save aircraft configuration. Aircraft state and position is being saved to a file in the output directory of the flight simulator. Each livery has its own state and configuration file. State files are saved every ten seconds when the simulator is running, i.e. it is not paused or in replay mode, while the configuration file is saved every time there is a change made to the aircraft configuration. If state file is not found or if its corrupted, default values are used instead. The system should be backwards compatible, so if new features are added in the future, old state files will work, with default values used for the newly added features. Configuration files have another layer, where user configurations are saved in the output folder, if this file is missing or corrupted, a livery specific file stored in the livery folder is checked. If this file is not usable either, default configuration is used. This system allows for livery specific defaults which the user can revert to at any time.

4. Visuals

As mentioned in the flight model section, every aircraft in X-Plane has a basic 3D model used for the calculation of the forces acting on the aircraft. This model can be, and in the past versions of the simulator had to be, used for the visual representation of the aircraft as well. As the capabilities of computer hardware increased, so did the expectations and requirements for visual quality. Therefore, an option to hide this basic model was added as well as the option to add more detailed 3D models. These 3D models have no effect on the flight model and the hidden model is still needed and used for its calculation. This also allows for creation of a detailed and interactive 3D model of the cockpit, which is especially important with the introduction of virtual and mixed reality based simulators. X-Plane uses its own file format for 3D models called OBJ8, not to be confused with another commonly used format for 3D models called obj. There are multiple options for 3D modelling software which can export in this format. In the past Laminar Research have used AC3D, which is a commercial, but relatively affordable option as well as easy to use. However currently Blender is being used by Laminar Research as well as by many third party developers. It is a more powerful 3D modelling software which is at the same time free and open source. Since it's used by the developers of the simulator itself, high quality export plugin for OBJ8 that is being updated with the latest features is available. These are the biggest reasons why it was chosen for this project. However, an older version of Blender, 2.79, is still being used as it was the latest version when the work on the project started and switching a major version of the modelling software for an ongoing project is not advised. For textures Adobe Substance 3D Painter was used. It is an industry standard software which allows for creation of PBR textures and export in the PBR format used by X-Plane.

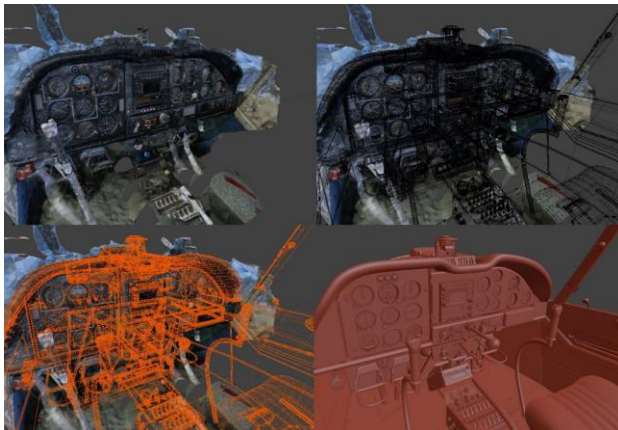


Figure 8: Process of turning a photogrammetry reconstruction into a usable 3D mesh. Source: Authors.

When creating the 3D model, technical drawings of various components were used. However, for the aircraft itself, no accurate technical drawings are publicly available. Drawing from the flight manual or one intended for scale model builders could have been used. However, usage of these kinds of references can lead to inaccuracies. To help with creation of more accurate model, aside from regular reference photos, photogrammetry was used as well. Due to limited resources the quality of the results was limited as well. Despite this it has been a great resource, especially for areas with more detail which result in

better quality reconstruction which allowed for accurate determination of panel lines, doors, rivets etc. Photogrammetry has also been used in the cockpit, although the simple shapes and the large number of components with known dimensions and accurate blueprints available made it less crucial for an accurate result. Every single gauge and piece of avionics has been exported as a separate object. Reason for this is the large amount of customisation available. If the whole gauge object is not needed in the current configuration, "object kill" feature can be used. Unlike a simple hide animation, this means the object and its assigned textures are completely unloaded from memory. However, since all manipulators and displays have to be in one object, ones associated with unused gauges and avionics have to be hidden using hide animation.

5. Conclusion

As a result of this work, a partially complete simulation of an aircraft has been created. It is possible to complete an entire flight, including startup and shutdown. Basic flight behaviour including basic aerobatic manoeuvres like spins, have been tested by pilots and instructors of the type with satisfactory results. Aircraft has also been tested in virtual reality, where all the basic interactions with manipulators were working as expected and the accuracy of the visual model, thanks to the use of photogrammetry and textures created with modern PBR workflow, was apparent. However, more work is needed to complete the textures for the exterior of the aircraft. More work is also needed for the user interface elements to be fully supported in virtual reality without the need to revert back to a 2D screen. Framework for aircraft configuration is completed along with some basic configuration options, including one of the OM-LOW aircraft operated by LVVC Žilina. However, all planned options have not been completed yet. Lastly, an update to replace the default sounds with real recordings utilising FMOD 2.02 sound engine of X-Plane 12 would bring the sound to a quality level in line with the rest of the simulation.

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