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A basic flight simulation tool for rigid airships

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Summary

The National Aerospace Laboratory NLR is developing a basic flight simulation tool of a rigid airship. This tool will allow simulation of a generic large rigid airship and it will support the fundamentals of Flight Mechanics and Stability and Control. The tool will run in a PC-based environment using MATLAB/Simulink. The basic simulation will support six degrees of freedom and will cover the complete flight envelope. A modular approach is used for the design, which gives the possibility for an easy upgrade when new or modified data is available.



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1 Introduction

The National Aerospace Laboratory NLR operates at its Amsterdam establishment a versatile flight simulation facility for research in various areas. This is a high-quality modular research and development facility, capable of simulating both fixed-wing and rotary-wing aircraft. It is used in military and civil research programmes for national and international customers. NLR's research flight simulation facility consists of a set of advanced hardware and software components, structured in a modular fashion to allow virtually any vehicle to be simulated. The simulator equipment consists of many modules, such as cockpits, visual, motion and computer systems, and a large set of simulation software modules and tools. The simulator's modular and versatile set-up enables efficient interchange of aircraft models, equipment, etc.

NLR currently operates the following simulation facilities:

- § the National Simulation Facility (NSF), primarily assigned to military simulation projects (F-16MLU, helicopter etc.) mounted on a six degrees-of-freedom (6-dof) motion platform.
- § the Research Flight Simulator (RFS) with a generic transport aircraft cockpit for civil simulation projects mounted on a six degrees-of-freedom (6-dof) motion system.
- § two fixed-base Pilot Stations (currently F-16 and helicopter, see Figure 1).
- § AIRSIM, a civil aircraft desktop research flight simulator.
- § AVIATOR, a fighter aircraft desktop flight simulator.

All these simulators are based on the same modular flight simulation software. This opens up possibilities to develop models in an easily accessible desktop environment and to integrate these models easily in fixed base pilot stations or high-fidelity moving-base flight simulators.

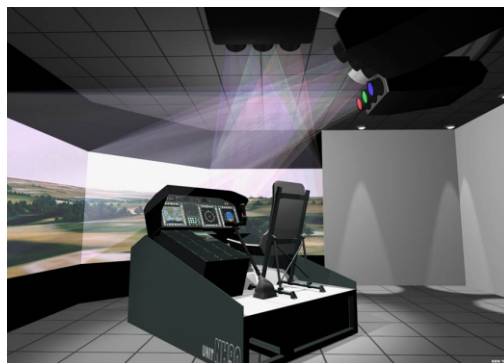


Figure 1 NLR Fixed-base pilot station



In September 1999 the NLR Flight Simulation department started a project with Rigid Airship Design (RAD) to develop a Basic Flight Simulation Tool. This tool will allow simulation of a generic large rigid airship. The tool will be developed using MATLAB/Simulink and will run in a PC-based desktop environment. This basic tool will support the fundamentals of Flight Mechanics and Stability and Control and will provide the user with response analysis of control-surface, engine and trim commands. Also the reaction on changing winds may be investigated.

The basic simulation will support full six degrees of freedom equations of motion. Models for the aerodynamics, buoyancy, mass and inertia including virtual mass, and engines are implemented in the airship simulation tool. A modular approach is used for the design and development of the simulation tool, which gives the possibility for an easy upgrade and incorporation of new or modified models and data. This is an extremely useful property in the design process of an airship, because it allows synchronous maturation of airship design and the simulation tool. This opens up simulation possibilities in every stage of the design process.

Although the basic simulation tool will be built with MATLAB/Simulink on PCs, the potential to exchange models with more sophisticated simulators is available. NLR has tools to integrate these MATLAB/Simulink models in a real-time simulation environment, which is required for studies with a pilot-in-the-loop. Studies in the fields of flight handling and human factors are obvious. Growth potential towards an engineering simulator is foreseen to test all (avionics) equipment on board. Eventually a training simulator may be derived from this tool.

2 Development philosophy

A simulation tool can support various phases in the development of a rigid airship. Initially the basic simulation tool will support RAD in understanding the dynamic behaviour of the rigid airship while adapting the configuration. In future stages of the rigid airship development an engineering simulator will be required to test avionics equipment on board and pilot handling before the maiden flight and to analyse the flight tests. When the airship is used in an operational environment also a training simulator will be needed. To ease the development of all these simulation tools and to assure consistency between these tools, use of the same airship model would be a large advantage. Therefore it is necessary that the basic simulation tool will be able to grow with the progress of the airship development.

During the development process more and more data will become available. For example the aerodynamic model, first the aerodynamic data is gathered with handbook methods, later data from windtunnel measurements will become available and in the final development stage data

from real flight tests can be used. This will lead to more sophisticated aerodynamic models during the progress of the airship development. To take advantage of these high-fidelity models the simulation tool must have the capability to exchange models. To achieve this capability a modular approach will be used for the simulation tool.

The basic simulation tool will be built with MATLAB/Simulink in order to provide a PC-based desktop environment. MATLAB is a technical computing environment that combines numeric computation, advanced graphics and visualisation, and a high-level programming language. MATLAB includes numerous preprogrammed functions for data analysis and visualisation, modelling, simulation, prototyping, application development and GUI design. Simulink has been built on top of MATLAB and enables developers to build graphical block diagrams, simulate dynamic systems and evaluate system performance. NLR has developed MOSAIC [tenDam99], a tool to import externally developed models into MATLAB/Simulink and to export the models for use in the real-time simulation (RTS) environment at NLR [Brouwer96]. This allows an upgrade of the basic simulation tool to a real-time simulator.

In Figure 2 the basic simulation tool is integrated in the NLR Real-Time simulation environment.

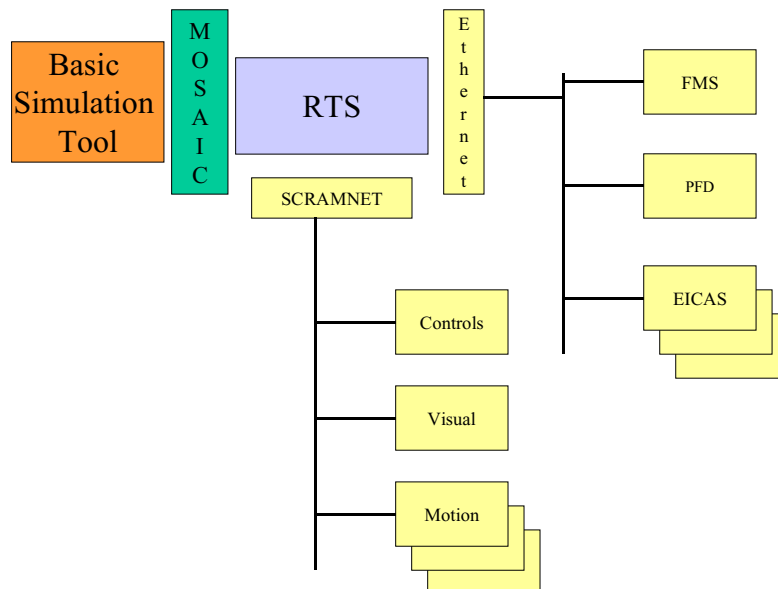


Figure 2 NLR Real-Time Simulation Environment with Basic Simulation Tool



3 Architecture of the simulation tool

In the previous paragraph the reasons for using a modular approach were discussed. In this paragraph the general structure of the simulation model will be outlined and an overview of the implementation of this model in Simulink will be given.

In Figure 3 the modular structure of the basic flight simulation tool is given. This diagram shows the sequence of operations which will be used for off-line simulation of aircraft. This is a generic sequence and it is valid for all kind of aircraft or airships. For online piloted flight simulation it is necessary to include additional modules to determine indications of cockpit instruments, visual system projection, deflections of the actuators of the motion system, etc. However the model structure of the simulator will be the same.

Before starting the simulations, the data of the airship will be loaded and a trim routine will be used to calculate steady-state values for the state and input variables for a flight condition specified by the user. Now the actual simulation can start. A number of subroutines, such as the aerodynamic, buoyancy and propulsion modules, have to be called to calculate the time derivatives. These time derivatives of the state equations will be integrated numerically with integration routines included within the simulation program. After the simulation the data will be processed and will be presented in a number of figures.

The global structure of the airship simulation tool is shown in Figure 4 in Simulink block diagram format. The structure of the airship model is based on the simulation model of the amphibious aircraft Canadair CL-415 [Lemmers96]. Several blocks can be determined in the airship model: controls, atmosphere, mass and inertia, forces and moments, and the equations of motion. The overall structure is clearly visible in this figure. The state derivatives are functions of external forces and moments and the mass and inertia properties of the airship. Other blocks are *atmosphere*, which contains calculation of atmospheric variables like pressure, air temperature, etc., and *engine controls* in which the control settings of the engines can be adapted. The external forces and moments can be divided into different categories (see Figure 5): aerodynamics, propulsion, buoyancy, gravity and virtual mass. These models will be discussed in the next chapter.

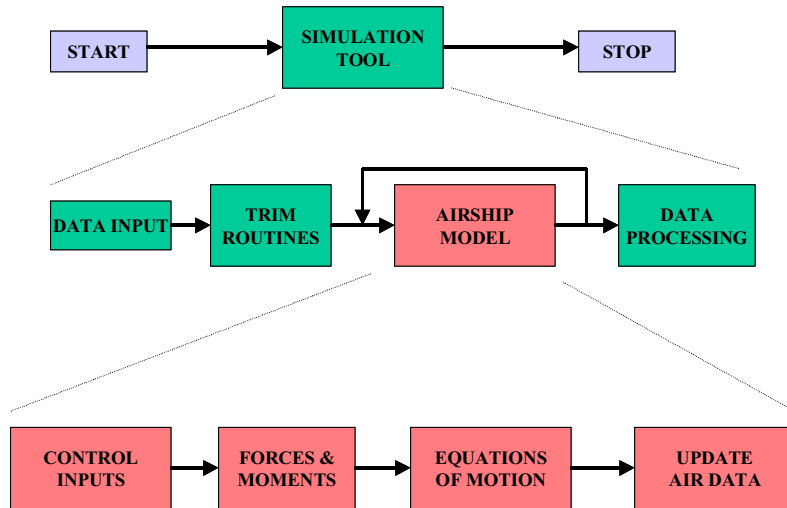


Figure 3 Structure diagram of basic simulation tool

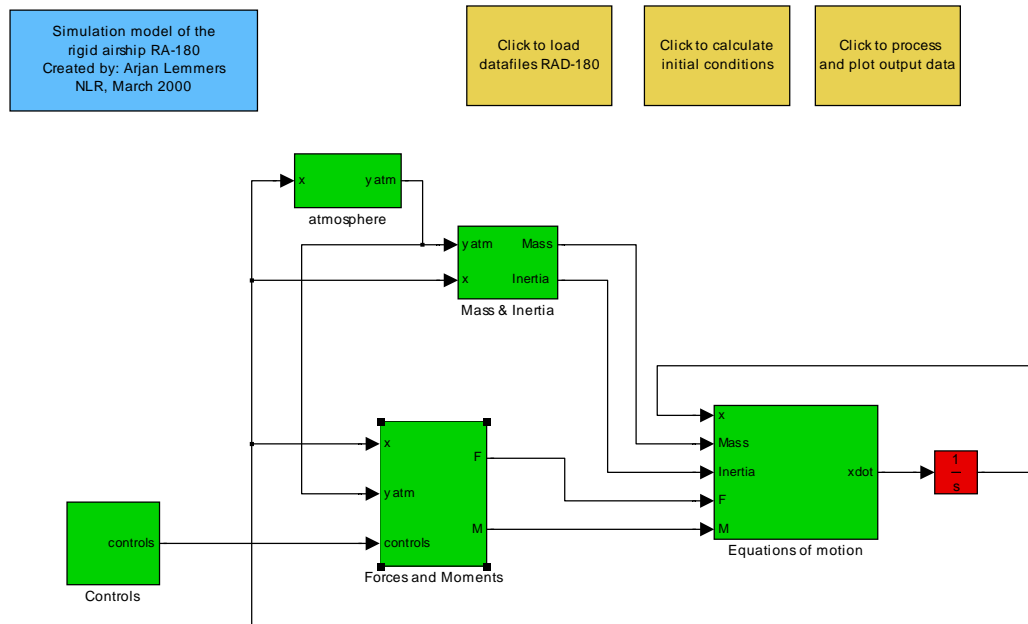


Figure 4 Global structure airship simulation tool in Simulink block diagram format

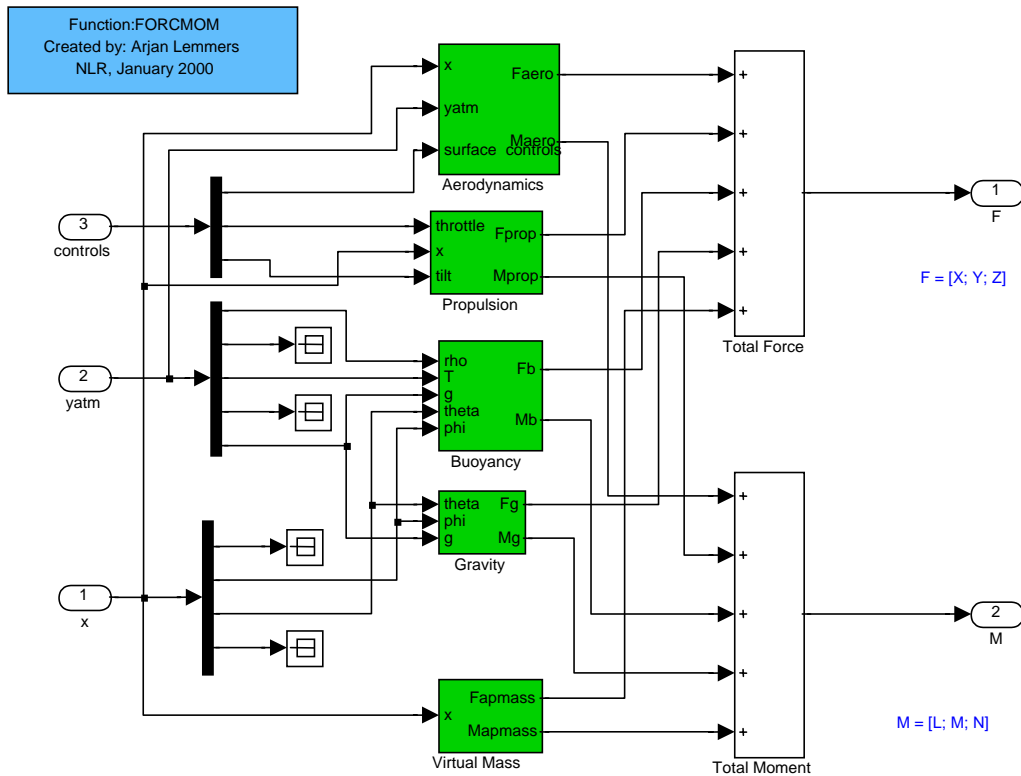


Figure 5 Structure diagram Forces and Moments Simulink block

4 Components of the simulation tool

Below the components of the simulation tool are being discussed. The design of all those components is such that a complete flight can be simulated, from lift-off, through cruise towards a landing. However, specific flight conditions can be chosen as well.

4.1 Buoyancy and static lift

Buoyancy gives the airship its right of existence. As with ships for water -or better submarines- Archimedes' law is applicable to airships as well. The weight of the displaced air volume yields to the upward force.



$$B = V \cdot \rho_{air} \cdot g \quad [1]$$

where,

B is the buoyancy force [N],

V the volume of the airship [m³],

ρ_{air} the density of the air [kg/m³] and

g the Earth gravity constant [m/s²].

However, internally the airship contains helium and partly air as shown in Figure 6, which has a weight of its own:

$$W_{gas} = \{V_{He} \cdot \rho_{He} - (V - V_{He}) \cdot \rho_{air}\} \cdot g \quad [2]$$

where,

W_{gas} weight of the internal gasses [N],

V_{He} volume of the helium [m³] and

ρ_{He} density of the helium [kg/m³].

The difference between buoyancy and weight of the internal gasses is the static lift:

$$\begin{aligned} L &= B - W_{gas} \quad or \\ L &= V_{He} \cdot (\rho_{air} - \rho_{He}) \cdot g \end{aligned} \quad [3]$$

where,

L is the static lift [N].

When the static lift is greater than the total weight of the construction and all the goods and persons onboard, the airship will lift-off.

These are the basic formulas for the simulation tool. In the following sections these formulas are described in more detail.

The construction of a rigid airship is divided in a number of compartments. Each compartment will contain a helium bag. Typically for a rigid airship is that the pressure at the bottom of the helium bag is in equilibrium with the outside air. In order to cope with different pressures (and thus different densities of the helium) the bags do not contaminate the compartments at all



times. At low altitudes the lower part of each compartment will be filled with air, which will be ventilated with the surrounding as the volume of the helium bag is varying, see Figure 6.

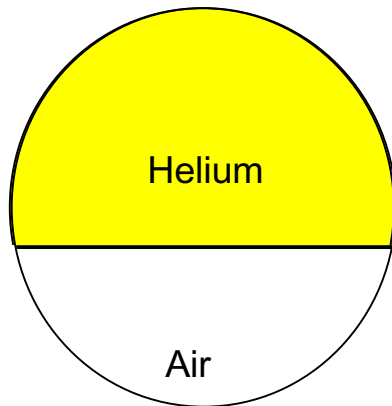


Figure 6 Helium bag in compartments

Within the simulation tool the density within the bags does not just vary due to different (pressure) altitudes, but also other effects may be investigated:

- § Different purity of the helium
- § Different fullness factors per bag
- § Different superheat per bag.

When the helium is polluted with other gasses, the purity becomes less than 100% and therefore the density within the bag increases, yielding to less static lift than according to equation [3]

Due to leakage, the fullness factor of each bag will reduce with time, and thus the volume of the bag. By decreasing the fullness factor relatively rapid the loss of a bag in a compartment can be simulated.

Superheat, certainly when the sun heats just a part of the airship, may destabilise the flight. Due to the higher temperature the volume of the bags increase according to the first gas-law:

$$V = \frac{R \cdot T}{P} \quad [4]$$

where,

R is the gas constant [K/(N.m)],

T the temperature [K] and

P the pressure [Pa].

The static lift equation [3] may become different for a set of compartments, which may induce a pitching moment.



4.2 Aerodynamics

Due to its large size and relative low speed, the aerodynamics of an airship are characterised by high Reynolds-numbers and a profound boundary layer. However, for the simulation tool any aerodynamic function may be implemented. Compared with fixed wing aircraft, the structure of the aerodynamic calculations is adapted for the axial-symmetric body of an airship. Table-lookup function blocks enable easy modification of the aerodynamics when more data becomes available. Initially data from literature and theoretical aerodynamics must be used, replaced by windtunnel data in a later stage and eventually updated by flight test results.

4.3 Virtual mass

Virtual mass is the phenomenon that the surrounding air will interact with the airship. In fact the air stream velocities around the airship due to its movement have a direct relation with the airship speed, see Figure 7.

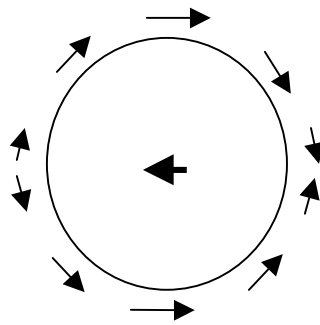


Figure 7 Virtual Mass

Each body encounters a virtual mass when moving through a gas or fluid. For gas (i.e. air) it is mostly negligible, but for an airship that has the same mass as the air it displaces, the virtual mass is of the same magnitude as the mass of the airship itself [Lamb].

In contrary to [Khoury99], [Lamb] and many others, the basic simulation tool herein does not include the virtual mass within the inertia of the airship. Instead the virtual mass is incorporated in external forces and moments when the airship accelerates.

4.4 Propulsion

The model for the engines is kept very simple for the moment, as the choice for a specific engine will be done at a later stage of the airship design. Multiple engines (i.e. 6) can be handled by the simulation tool. Those engines may be tilted by 90° for hovering purposes.



4.5 Mass properties

Weight is the counterpart of buoyancy. The total weight of an airship is the sum of:

- § the frame and all systems (i.e. the engines),
- § the fuel in the fuel tanks,
- § the water in the ballast tanks,
- § the payload,
- § the internal gas

The weight of frame and systems can be seen as constant for this simulation program, while the fuel-weight will reduce due to fuel consumption. Furthermore the centre of gravity may be controlled by rearranging the water over the ballast tanks. Within this simulation program the payload is regarded as an invariable entity. Finally the weight of the internal gas, already mentioned by equation [2] is a variable as the part filled with air is ventilated according the volume of the helium bags.

By taking into account the co-ordinates of all these weight contributions the centre of gravity can be computed. For each weight contribution also the moments of inertia are being determined many times during the simulation in order to cope with all changes during the simulation (i.e. loss of a helium bag). Note that for the determination of these moments of inertia the “effect of the raw egg” must be taken into account. In other words: the fluid within the egg won’t rotate with the shell. Therefore the moments of inertia of a raw egg are smaller than of a hard-boiled egg. The gasses in the compartments, the fuel and water in their respective tanks won’t rotate either. Finally the moments of inertia are converted for the centre of volume, which is used as the origin for the equations of motion instead of the centre of gravity (see Figure 8).

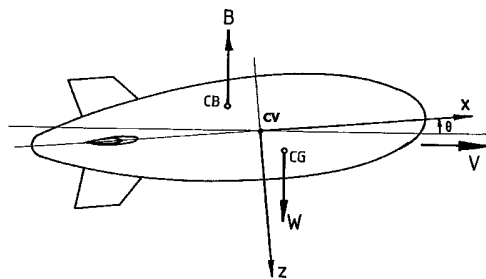


Figure 8 Body axes reference frame



4.6 Equations of motion

The airship dynamics can be expressed as a set of differential equations. These equations express the motions of the airship in terms of external forces and moments. The development of the equations of motion can follow the standard aircraft practice. The major differences with an aircraft model are due to the effect that the airship is buoyant and displaces a large volume. Therefore the familiar aircraft equations of motion are extended with buoyancy and virtual mass forces. However the virtual mass contribution can also be included in the mass properties of the airship as is described in [Khoury99]. An other difference is that the airship equations of motion are developed with respect to a body axes reference frame with the origin at the centre of volume (see Figure 8) instead of the centre of gravity. The centre of volume has been chosen because this centre is assumed to be constant during the flight unlike the centre of gravity. This leads to additional mass and inertia terms in the equations of motion.

5 Applications

As already indicated in the introduction, this basic simulation tool has a growth potential:

- § The MATLAB/Simulink version as is, has applications in the support of the airship design.
- § When downloading the models into a research flight simulator pilot-in-the-loop handling and other Human Factors can be investigated.
- § Another focus on simulated testing is with an engineering simulator allowing hardware-in-the-loop such as avionics and actuators.
- § Eventually a training simulator may be derived from this tool.

The basic simulation tool finds its applications in the design stage of a rigid airship. The effects of different configurations (i.e. three or four fins, engine positions, stretching the body, etc.) can be visualised for normal operations as well as for degraded modes (i.e. loss of a helium bag, engine failure) or adverse weather conditions. Requirements such as the size of the control surfaces can be investigated.

Furthermore the basic tool can be used to design the -digital- flight control laws and to perform analytical tests well in advance of either pilot or hardware-in-the-loop tests.



6 Conclusions

A basic flight simulation tool is developed that allows the simulation of a generic large rigid airship. It supports the fundamentals of Flight Mechanics and Stability and Control and provides the user with response analysis of control-surface, engine and trim commands or changing winds. The basic simulation supports the whole flight envelope and full six degrees of freedom of motion. It finds its applications in the design stage of a rigid airship. The effects of different configurations can be visualised and requirements such as the size of control surfaces can be investigated.

The modular approach makes it easy to upgrade the tool by incorporation of new or modified data and models. This opens up simulation possibilities in every stage of the design process. The basic tool has the potential to exchange models with more sophisticated simulators and can be integrated in a real-time simulation environment. This real-time environment gives possibilities for pilot-in-the-loop handling and other Human Factor studies. Eventually an engineering simulator for testing avionics systems or a training simulator may be derived from this tool.



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