Seahawk Helicopter Simulation

Wayne Langworthy

University of New South Wales
Australian Defence Force Academy
School of Aerospace, Civil and Mechanical Engineering
Canberra ACT 2600 Australia

This thesis project is to initiate and take the first steps in development of a flight simulation black box tool for the Seahawk S70 helicopter. The simulation uses specifications based on the Seahawk and aims to mimic the Seahawk’s basic flight dynamics and parameters in hover. This simulator encompasses the Aircraft Flight Control System (AFCS) and flight control mechanism (flight controls to swash plate mechanical link) and other enhancements specific to the Seahawk. The simulation has been constructed using SIMULINK® and has been developed by modifying an existing SIMULINK® helicopter simulation program created by Dr Matt Garratt, and adding the Seahawk specific enhancements. The simulation is then compared to actual flight test data supplied by AMAFTU to validate simulation outputs.

Disclaimer

This thesis has been written in partial fulfillment of the requirements for the degree of Bachelor of Engineering (Aeronautical). It has been the direct result of a period of research and analysis by the author while a student of the University of New South Wales. Views expressed do not represent the views of the University College, the University or the Australian Defence Force Academy.

1 Aeronautical Engineering Thesis Project ZACM4049 and ZACM4050
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Glossary

AFCS  =  Aircraft Flight Control System
AMAFTU = Aircraft Maintenance and Flight Test Unit
ANTA  =  Australian National Training Authority
DSTO  =  Defence Science and Technology Organization
FFG  =  Adelaide Class Frigate
FFH  =  ANZAC Class Frigate
GENHEL = Sikorsky General Helicopter Flight Dynamics Simulation
PBA  =  Pitch Bias Actuator
PID  =  Proportional-Integral-Derivative Controller
RAN  =  Royal Australian Navy
SAS  =  Stability Augmentation System
SHOL  =  Ship Helicopter Operating Limits
TPP  =  Tip Path Plane
FPS  =  Flight Path Stabilisation
Nomenclature

\( C_d \) = Coefficient of Drag
\( C_L \) = Coefficient of Lift
\( I_b \) = Mass moment of Inertia of the blade
\( K_{\beta} \) = Rotor Hub Stiffness or Spring Constant
\( L \) = Longitudinal Moment
\( M \) = Lateral Moment
\( M_b \) = Blade Mass
\( N \) = Vertical Moment
\( N_b \) = Number of Blades
\( R \) = Main Rotor Radius
\( x_g \) = Centre of Gravity of the Blade
\( V \) = Forward Velocity
\( V_i \) = Induced Velocity
\( V_s \) = Velocity into the Rotor Orthogonal to the TPP
\( V_{tip} \) = Rotor Tip Speed (\( \Omega R \))
\( e \) = Hinge Offset (non dimensional)
\( hR \) = Distance to Centre of Gravity
\( u \) = Velocity along the X Axis
\( v \) = Velocity along the Y Axis
\( w \) = Velocity along the Z Axis

Greek Symbols

\( \alpha \) = Angle of Attack
\( \phi \) = Pitch Attack
\( \theta \) = Roll Attack
\( \psi \) = Yaw Attack
\( \mu \) = Advance Ratio
\( \gamma_{SL} \) = Lock Number at Sea-level
\( \lambda \) = Inflow Ratio
\( \sigma \) = Rotor Solidity
I. Introduction

A. Background

The Seahawk is a vital tool used by the Royal Australian Navy and the Australian Defence Force as a whole. The Seahawk’s primary role in the Australian Defence Force is to be embarked in Australian Navy FFG (Adelaide Class) and FFH (ANZAC Class) frigates. The Seahawk takes an interdictory role by providing anti-submarine warfare and anti-surface surveillance. In addition to these roles, the Seahawk also conducts secondary roles including: search & rescue, troop lift and tactical insertion, utility operations (winching and external load lift) and firebombing.¹

The Navy’s Aircraft Maintenance And Flight Test Unit (AMAFTU) is a centre of expertise for First of Class Flight Trials which involves determining the envelope in which an aircraft can safely land on a particular type of ship’s flight deck. For all aircraft there are a range of limiting conditions, including control margins, engine power, main rotor speed and pilot rating etc. Currently, AMAFTU determines that a landing condition is safe if the control position is not within 10% steady state (and not within 5% transient) of the flight control stops. Similar limits are applied to torque and main rotor speed etc.²

Often, AMAFTU is tasked to determine the effect on the current SHOL (Ship Helicopter Operating Limit) of a Seahawk engineering change, which currently cannot be quantified without flight-testing. AMAFTU requires a tool that will provide an indication of which areas of a SHOL will be affected by the engineering change. This would then allow AMAFTU to reduce the scope of flight-testing and thus reduce expenditure and resources required to conduct such flight-testing.

It should also be noted that in today’s modern tri-service environment we see the Seahawk’s cousin, the Army Blackhawk embarked in Australian Navy ships, primarily on the amphibious transport ships. This tool could also be used in narrowing the scope of flight-testing for the Blackhawk helicopter.

B. Aim

The aim of this thesis project is to initiate the development of a flight simulation black box engineering tool based on the Seahawk/Blackhawk helicopter. The simulation is to be constructed using SIMULINK® and is to enhance by using Seahawk/Blackhawk systems, specifications and properties, and the UAV helicopter time domain simulation that has been previously developed in SIMULINK® by Dr Garratt. The base simulation supplied for this thesis will be referred to as the “parent simulation” hereafter. This simulation project aims to mimic Seahawk flight in hover by using simple basic flight dynamics and parameters of the Seahawk. A further desirable aim of the project was to extend the simulations to forward flight scenarios. However, time constrains have only allowed limited development of forward flight simulations. The operation of this tool, will be initiated by inputting data into the SIMULINK® simulation via a MATLAB® set up file encoded with the designated helicopter specifications and possible engineering changes.

The ultimate goal of this work aims to target the cost and resource reduction that would be gained in shortening SHOL experiment time. First simulating the aircraft’s flight in extreme conditions and obtaining a reasonable estimation of the aircraft’s response before flight testing, will give invaluable insight into what can be expected. This knowledge would give a starting point for flight testing much closer to the boundary of the SHOL, and therefore lessen the exposure of aircrew and the aircraft to the dangers of flight testing on the edge of the aircraft’s flight envelope, additionally limiting cost and time expended on such flight testing.

One must consider SHOL testing does not just encompass only the aircraft and flight crew. It also involves the ship that is taken away from other important roles and all the associated costs with the running of the ship, such as; the ships company and the land based support personnel and resources accompanied with running the ship etc. It quickly becomes apparent that the saving in time and cost by shortening test flying is considerably large in many aspects.
C. Scope

This report looks at previous work and development conducted in the field of rotary wing simulation. It then examines several NASA reports directly related to the Seahawk/Blackhawk style of aircraft and researches the mathematical outcomes presented by these reports.

As stated earlier, the simulation endeavors to produce a simple user-friendly simulation where parameters can be input via a MATLAB® set up file that is pulled into the simulation as the simulation is executed. This simulation has been constructed and adapted for the Seahawk/Blackhawk using the parent simulation of Dr Garratt’s UAV helicopter simulation. Initially using the parent simulation, a set up file is established to input the Seahawk’s basic parameters and properties.

The specific dynamics, dimensions and parameters such as geometry, blade properties, moments of inertia, centre of gravity variation and weight etc. will be extracted from the Sikorsky Aircraft Company Report on the Seahawk SH-60B, and NASA report documentation. These values are then to be converted into units that comply with the parent simulation; at this point a basic stable hovering model is to be established. This basic stable model will be used as the platform from which Seahawk specific sub-systems enhancements are to be added.

The AFCS, propulsion and mechanical mixing box gain (mechanical link flight controls to swash-plate) subsystems will be constructed in SIMULINK® using Seahawk data. These subsystems will then be implemented into the parent simulation framework.

The simulation will also account for the vertical stabiliser aerodynamics, effect of blade twist, fuselage forces and atmospheric effects.

D. Limitations

The project has been limited to a two-semester time frame, therefore efforts have primarily concentrated on establishing a simulation for stable hovering flight.

University commitments in Canberra have impeded the anticipated free access to AMAFTU and HS 816 Seahawk Squadron at HMAS Albatross Nowra during the project period. However during university stand down periods, as much information as possible was gathered from HMAS Albatross in the time available.

The data used in efforts to validate the simulation to had to be converted to format comparable to the simulation computer program and some fidelity may have been lost in the conversion. Moreover, the validity of the data acquired on the parameters of the Seahawk to which the model is based will limit the outputs of the simulation, as no physical measurements were taken by the author.

A further challenge has been the understanding of the ‘c code’ and the inner working of the parent code simulation, however every effort has been made to understand the parent code inner working by consultations with Dr Garratt.

E. Summary

This report demonstrates the initial development from an existing UAV helicopter simulation, into a simulation that is based on the Seahawk helicopter. Seahawk parameters are employed with Seahawk specific enhancements to replicate Seahawk flight in a stable hover condition. The simulation is constructed utilising Simulink® and is first tuned to establish the stable hover situation. Once a stable hover has been established, the validity of the simulation responses are compared to actual Seahawk flight test data. The same control inputs that are used in the flight test are input into the simulation and the simulation outputs are plotted against the test data to examine the simulation’s fidelity.
A. Previous Work in the Field

Garratt’s work, ‘Biologically Inspired Vision and Control for Autonomous Flying Vehicle’, developed the parent simulation for which this thesis is developed. Therefore, it is imperative that an understanding of the parent simulation is gained. Chapter 3, ‘Helicopter Simulation and Control’ develops a time domain simulation in SIMULINK® of helicopter dynamics, sensors and controller that has been developed for a small UAV helicopter. Garratt states SIMULINK® was selected as the development environment for his simulation for convenience, as the graphical drag-and-drop building block approach speeds up development and allows the simulation to be quickly adopted to other helicopters. This is an advantage in building the Seahawk simulation, enabling time reduction by not duplicating work. Rebeschien® uses MATLAB/SIMULINK in his work with microcontrollers and he advocates this software to be a comfortable and affordable tool, further reinforcing Garratt’s choice. The graphical mask of the dynamic blocks allows the user to change inputs by double-clicking on block icons and changing variables. However, the preferred method for the majority of the variable for the Seahawk simulation will be via setup m.file in MATLAB®. Garratt claims his simulation balances fidelity against practicality. He endorses Heffley’s® rational of a minimum complexity helicopter model. Ground effect, rotor lead and lag effects and down wash with respect fuselage interaction are not factored into the simulation. The simulation employs standard aircraft body axis and inertial axis conventions. The simulation also avoids the problem of singularity at high pitch angles, by employing quaternion parameters that are related to the Euler angles. For further details refer to Garratt page 42. The parent simulation is designed primarily for the RMax and Eagle helicopters, where the variation in rotor rpm does not change by more than 1%, to that end the throttle channel has been ignored. This factor will also be ignored in the Seahawk simulation as incorporating the engine thrust factors fall outside the scope of this project. However, in future development of this project rotor thrust demands on the engines could be included to further increase the fidelity of the simulation.

Stade® conducted a thesis at UNSW ADFA in which he developed a SHOL for the Yamaha RMax helicopter to fly landing trajectories from behind a generic frigate shaped ship. He used the SIMULINK® model of the RMax simulation developed by Garratt, and data from the Defence Science and Technology Organization (DSTO) on the wind wake of the ship, to develop the SHOL for the aircraft. Stade’s work demonstrated the effectiveness of developing a SHOL by simulation and data. Whilst his work concentrated on small-scale helicopter operation, it demonstrated the significance and timesaving advantages aircraft simulation could gain. By expanding Stade’s work and incorporating a Seahawk simulation, it is possible after further refined development, a preliminary SHOL could be constructed or changes could be projected depending on changes to desired variables.

A team from the Pennsylvania State University™ conducted a study and looked at ship/helicopter dynamics with respect to the interface of a UH 60 Blackhawk helicopter operating from a landing helicopter assault class ship. The helicopter simulation was based on Sikorsky’s General Helicopter for Dynamic Simulation (GENHEL) model and uses time accurate CFD solutions for the LHA ship’s air wake. Whilst this work focuses more on pilot interaction and training, it also looks towards reducing flight test time and the cost of establishing, in their terms, safe “wind over deck” operating envelopes. It is stated that the effectiveness of such an analysis rests heavily on a high fidelity flight dynamics simulation model of the helicopter. Whilst this study did include a simple primary mechanical flight control system and an automatic fly control system, it recognized the complexity of incorporating the engine dynamics and engine fuel controller in the model and assumed the rotor RPM to remain constant.

Rodriguez® developed a software environment simulation for high-performance helicopter systems that accommodated data exchange with MATLAB. Part of the study utilized Blackhawk helicopter data in demonstrating its simulations. Rodriguez advocates that the ability to interact with simulations in real time allows the analysts to grasp the underlying relationships in analyzing and designing helicopter control systems. However, these simulations only considered longitudinal dynamics and three degrees of freedom, where the Seahawk simulation will account for all six degrees of freedom.

Ballin® has conducted several studies concerned with Sikorsky’s Black Hawk helicopters. While these studies are orientated around Sikorsky’s General Helicopter for Dynamic Simulation (GENHEL), there is an underlying rationale applied in the building of subsystems in block sets. Ballin states “The advantage of block diagram simulation is the flexibility to modify or replace any one component without modification to another component”. Of particular interest, with relation to constructing the propulsion system block set is the work conducted in the simulation of the GE T700 turboshaft engine (the engine that the Seahawk is equipped with).
The mathematical equations and block diagrams demonstrate a wealth of information as to how the engine torque produced interacts with the rotor system torque requirements. However, constructing and implementing such a block set falls outside the scope of this project given the time constraints. Yet, consideration of an enhancement of this type would provide scope for future projects in further refinement of the Seahawk simulation.

Ballin’s 1991 study was conducted on the dynamic fidelity of an operational blade element simulation model of the UH-60A Blackhawk helicopter (the cousin to the Seahawk) in hover and low speed flight regimes. He recognized the need for a predictive capability of the effects of control system and or configuration changes. His findings were that the GENHEL model utilized was adequate for hover and low speed flight regimes when compared to test flight data. He indicates particular attention should be paid to the effects of inflow (the summation of induced velocity by the rotor and the orthogonal velocity to the rotor from flight) across the operational envelope to obtain good dynamic response. Ballin is cited by Kim in his study into the validation of forward flight helicopter dynamics simulation. Kim’s selects two air speed values and compares flight test data with predicted mathematical simulation outcomes. Kim’s study considers rotor, inflow and actuator dynamics by means of blade element theory.

Ballin presents as an authority in helicopter dynamics with relation to Sikorsky Blackhawk helicopter simulation and flight data validation, however his models are heavily complex and are concerned mainly with pilot in the loop simulations. Heffley on the other hand, advocates complexity is not necessarily required to obtain high fidelity simulations. He presents the argument that complexity may limit simulations to inflexibility, especially when changes are imposed, and may restrict the clarity of the analyst. Heffley implies that making sound assumptions as to how much complexity the mathematics model evaluates will reduce the time and effort required to complete, check and debug the code. Heffley presents the notion that if an error was evident the time required to find the error is a function of the complexity of the model itself.

Heffley concedes that there is an inherent trade-off between complexity and flexibility in models of dynamic systems, such that, as more systems are added to the simulation it becomes increasingly harder to make modifications. He also states that large complex codes require large computer systems to function, however in this day and age with the power of personal computers, this is not so much the case. Yet, the underlying argument presents that it is necessary to strike a balance between complexity and the ability of the user to make parameter changes without adding complexity to the simulation design. This rational has been adopted in the parent simulation, and it is the rational that is adopted for this thesis.

The Royal Australian Navy in conjunction with DSTO conducted a study into the relationships between the simulation model of the Seahawk S-70B-2 helicopter and actual flight of the Seahawk. This simulation was developed utilising the GENHEL simulation tool. The report endeavors to observe and qualify the simulation predictions, with the statistical data produced from aircraft landing cycles on an FFG. The results of the study found that GENHEL had a greater possibility of predicting SHOLs using a pilot in the loop simulation rather than using trimmed values. This report should prove to be an excellent source of information when validating the Seahawk simulation once the simulation is developed to the stage of flying ship landing trajectories in later thesis.

Robert Toffoletto from DSTO authored a report on the post mixing unit control positions of Seahawk and Blackhawk helicopters relative to the pilot controls so as to up-date and modify the GENHEL simulation program. He noted that GENHEL calculated pilot control positions but did not calculate the post mixer control positions as a percentage of the available control movement. The report describes the development of the algorithms and how these algorithms are implemented into the GENHEL program. This report affords the reader an in-depth insight into the mechanical control and primarily the operation of the mixing unit of the Seahawk helicopter.

There is a wealth of NASA reports on the Seahawk helicopters, however more so on the similar land version the Blackhawk helicopter. These reports can be accessed using the NASA Technical Report server. Several of the reports researched are referenced within this paper and their value is apparent as the report progresses.

It becomes evident that the majority of work conducted in this field with regard to the Sikorsky Seahawk/Blackhawk helicopter, has been conducted primarily via GENHEL simulation modeling. However now that software has become more readily available and affordable, and the power of personal computers has increased exponentially over recent years, it is conceivable that simulations can be presented that are more portable and user-friendly. SIMULINK® offers a package that is both visual and user-friendly without the added expense to the user of specialized industry simulation programs. As an actual real time simulation is not essential in this case, SIMULINK® will be an adequate vehicle for this thesis simulation, whilst being an excellent operator-friendly tool that can be continuously updated with relative ease. To that end, this thesis will
adopt the same rationale that Heffley and Garratt have adopted as to assuming a minimum complexity simulation modeling.

B. Seahawk Helicopter

The Seahawk and Blackhawk helicopters have a single main rotor and a canted tail rotor. The main rotor consists of four blades that are retained by a fully articulated rotor head, and the main rotor shaft has a 3-degree forward tilt. The Tail Rotor also consists of four blades that are retained in a crossbeam arrangement with the shaft tilted 20 degrees upward. The detail of the Canted Tail Rotor will be described later in this report. The Aircraft is powered by two General Electric T-700-GE Gas Turbine engines that drive two free power turbines. The engines can provide approximately 2800 hp together at a normal continuous rating and the engines are found mounted side by side above the cabin.\(^\text{15}\) The drive chain consists of a main gearbox that is connected to the free power turbines via shafts, with interconnecting shafts to the intermediate and tail rotor gearboxes.

The flight control system is a redundant hydro-electrical-mechanical system that includes three two stage main servos, an Aircraft Flight Stabilisation System (AFCS) and a Mixing Unit. The aircraft has a triple redundant hydraulic supply and a moveable Horizontal Stabilator that rotates from a positive angle of attack of 40 degree at hover to reduce the negative pitching effects of downwash, to a possible negative 8 degree with increasing forward flight speed.\(^\text{17, 23}\) Whilst having a maximum level flight speed of around 160 knots.

C. Why Simulink\textsuperscript{®} as a Modelling Tool?

Simulink\textsuperscript{®} is a visual design tool in the overall Matlab\textsuperscript{®} computational environment that facilitates Model-Based Design. It provides a graphical modeling environment for dynamic systems development and design. Because of the visual nature of the package, constructing and developing physical systems, controllers, filters, sensors etc. is relatively effortless. This is done by dragging and dropping icons into the workspace after the user/designer has familiarized themselves with the package.\(^\text{16}\)

Moreover, Simulink\textsuperscript{®} provides an interactive graphical environment for hierarchical block set development. It has libraries of sets of blocks that can be customized to allow the design, simulation, implementation and the testing of such systems. The designer can create custom block sets from personal designs or can use inbuilt ready to use block sets if the industry package is utilized. As this simulation is being developed on a student package, the block sets are either from the parent simulation or have been customized and developed further, or have been modified from another similar project, or have been designed specifically for this project.

III. Simulation Background

A. Helicopter Axes of Flight

The helicopter is free to rotate about three body axes that are fixed to the centre of gravity. The axis system is no different to that of a fixed wing aircraft and are; the longitudinal axis also known as the rolling axis, lateral axis also known as the pitching axis and vertical axis also known as the yawing axis (observe figure 1). These axes are commonly referred to as x, y and z axes respectively. The right hand rule is applied to depict positive and negative direction and movement about an axis. To illustrate, consider the x axis to lie along a horizontal north south reference system. Where the thumb points in the northern and positive direction leaving south the negative direction, the direction the fingers can curl is considered the positive rolling direction and the
opposite the negative rolling direction. In similar fashion the $y$ axis is imagined to lie along the east west axis with east being positive, therefore a nose up pitching motion would be considered positive. The $z$ axis uses the same method where the positive is in the downward direction. (Note: Graphs presented within this report show altitude as a negative figure due to this convention). The velocity movement along the body axes is designated $u$, $v$, $w$ respectively, with pitch, roll and yaw depicted by the Euler angles $\phi$, $\theta$, and $\psi$. The pitch, roll and yaw rates are denoted by $p$, $q$ and $r$, while moments created about the same axis system are $L$, $M$, $N$.

Movement about the longitudinal axis is effected by the cyclic pitch control left or right, and movement along the longitudinal axis is conducted by a combination of forward or rearward movement of the cyclic pitch control, together with sufficient collective pitch application to prevent the helicopter losing or gaining altitude. To promote pitching movement about the lateral axis the cyclic pitching control is moved forward or rearward. While movement about the vertical axis or yaw is controlled by pushing the tail rotor control pedals left or right, increasing or decreasing tail rotor thrust by increasing or decreasing tail rotor collective pitch.

**B. Parent Simulation**

The parent simulation was supplied by Dr Garratt as stated earlier, and is the platform for which the Seahawk Simulation was constructed. The parent simulation in the form supplied is capable of simulating the two following effects; non-linear equations of motion and first order main rotor flapping (the flapping effects of the tail rotor are not accounted for). The parent simulation came equipped with an auto pilot system and a helicopter dynamics block set that is comprised of the following helicopter generic function block sets; Rigid body dynamics, Main and Tail Rotor Inflow, Power and Rotor Forces. Note the block set diagram (Figure 2) shown below. As stated previously, the simulation avoids problems of singularity at high pitch angles by using quaternion parameters that are related to the Euler angles. (For more detail on quaternion parameters see Reference 3). The parent simulation is also comprised of ‘C code’ functions imbedded in the fore mentioned block sets that accommodate the calculations required to mathematically reproduce helicopter dynamics. Whilst attempts were made to fully understand the inner working of these ‘C code’ functions, only a limited understanding was obtained, therefore any changes made to the ‘C code’ functions was done with the assistance of Dr Garratt. More detail can be obtained on the parent simulation block sets from Reference (3).

**Figure 2 Parent Simulation Helicopter Dynamics Block set before Modification**

**C. Simulation Setup File**

The setup file has been developed as the basis for which the operator of the simulation can input the designated aircraft requirements, configuration and environmental conditions. The setup file is a Matlab\textsuperscript{\textregistered} .m file that acts like a port hole into the simulation establishing data sets of aircraft parameters, weights, moments of inertia, gains conversions, wind velocities, step and pulse inputs and the like. Different setup files can be built up with saved specifics of a particular aircraft configuration, and in the future specific trajectories, as the model is more refined and forward flight is implemented. This would allow the user to create a data bank of scenarios and then make small changes to the setup file depending on the engineering or configuration change, without
continually changing a whole setup code each time. As further block sets and Seahawk enhancements are explained, examples of the information placed in the setup file and fed into the simulation will be evident. Note Appendix B for the example hover setup code.

D. Collecting and Calculating Parameters for the Simulation and the Setup File

It was necessary to source specifications and parameters of the Seahawk from various NASA and Sikorsky documents. The majority of the information with respect to Seahawk element location and configuration parameters was sourced from a Sikorsky Aircraft United Technologies Report that was supplied by AMAFTU. The parent simulation is based on metric data inputs. As all specifications and parameters are denoted for the Seahawk in imperial dimensions, conversions for all parameters and dimensions had to be ascertained. The all up weight was designated using the design gross weight and the centre of gravity was designated the aft most position with relation to the specifications which is also the position for where the inertia values are taken from. Inputs include; the effective lift curve slope widely accepted at 5.7, and the profile drag is considered to be 0.012 as defined by Heffley as a standard accepted values. The air density at this stage is considered to be at sea level. However, in proceeding simulation development, an atmospheric block set from an industry version of Simulink could be introduced that would account for the differing densities at differing altitudes and temperatures. The blade twist will be input as zero, however how blade twist is accounted for will be explained further on in this section. For further information on specify values see setup.m file Appendix B. Note conversion factors examples in (table 1) below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conversion</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>Pounds to Kilograms</td>
<td>0.4536</td>
</tr>
<tr>
<td>Distance</td>
<td>Inches to Metres</td>
<td>0.0254</td>
</tr>
<tr>
<td></td>
<td>Feet to Metres</td>
<td>0.3038</td>
</tr>
<tr>
<td>Inertia</td>
<td>Slugs-ft² to Kg-m²</td>
<td>1.355817962</td>
</tr>
</tbody>
</table>

Datums are established using conventional dimensional demarcation such as fuselage/frame stations (longitudinal), water lines (vertical) and butt lines (lateral), observe the examples in (figure 3) below. These reference dimensions are used to establish the aircraft centre of gravity location, and to establish main rotor, tail rotor and flight surfaces coordinates with regard to the centre of gravity, which in turn are used to feed into the simulation and establish moment arms with respect to the centre of gravity. This component-referencing format is established so that standardization, with respect to movement of the centre of gravity, can be input via the setup file without confusion to the user.

![Figure 3 Demonstration of Aircraft Dimension System](image)

The blade mass was established via the blade mass moment of inertia specified in the equation below, this blade mass equation was derived from the equation for $I_b$ in Prouty page 456.

$$M_b = 3\frac{I_b}{(R - eR)^2}$$  

Equation 1
The Seahawk employs an articulated rotor hub. The blade root is offset from the centre axis and attached to the offset hinge. This offset hinge allows the blade to flap up and down during flight. Rotor blade flapping, which takes place about the hinge, is the condition of dynamic equilibrium between the aerodynamic lift, the centrifugal force and the blade inertia.\(^3\) In hover, the rotor supplies lift equal and opposite to the all up weight.

In the Seahawk’s case the tail rotor supplies a portion of lift due to the 20 degree canting of the tail rotor, which will be explained later. When this equilibrium is established, a coning angle is formed where the pitch of the blades (θ) is constant at all points of a rotor revolution. This pitch is the collective pitch, the coning angle (a\(_0\)) is the angle between plane perpendicular to the rotor shaft at the rotor hub and the root of the blade to the Tip Path Plane (TPP). The angle of a revolution at any point is represented as the angle viewed from the top, anti clockwise with the starting datum at the six o’clock position, and is called the azimuth angle (ψ). When the aircraft is required to move forward, forward cyclic motion is input. The blades will flaps up at zero azimuth angle, a pitching moment is created and the TPP is tilted forward, in turn tilting the thrust vector forward. Likewise with rear and lateral movement. As this motion is periodic and related to the azimuth angle, the flapping angle can be expressed as the following:\(^3\)

\[
\beta = a_0 + a_1 \cos \psi + b_1 \sin \psi
\]

Equation 2

The longitudinal effect is denoted (a\(_1\)) and the lateral effect denoted as (b\(_1\)). This equation is composed of the coning angle constant and the first two harmonic terms from the infinite Fourier series. As the high order coefficient values die off rapidly, second order harmonic coefficient values are approximately 10 percent of the first values.\(^3\) Bramwell\(^19\) interprets these higher terms as a ‘crinkling’ of the rotor cone and suggests that even though the term can be calculated, they are negligible and can be ignored. These flapping effects also feed into the longitudinal and lateral moments, as will be shown.

The distance from the centre rotor shaft to the hinge is called the hinge offset (e). The offset relates directly to the control sensitivity, where the larger the offset the higher the degree of sensitivity.\(^20\) The offset accentuates the forces and moments that accelerate the aircraft in pitch and roll. This implies that \(d\beta/dt\) is increased, (note figure 4). Where the TTP tilts and the blade flaps, the centrifugal force lines acting through each blade’s own centre of gravity are no longer coincident and create a couple.\(^20\) This is demonstrated in (figure 5) on the next page. Therefore, it is necessary to derive equations for the longitudinal moment (\(L\)) and lateral moment (\(M\)) about the rotor head that include the offset contribution.

---

Figure 4 Flapping at Constant Feathering Angle (Cooke)
Bramwell\textsuperscript{19} derives equations for $L$ and $M$ per blade, where second order integral terms are neglected as they are found to be very much smaller and assume small angle theory. These equations are reproduced below.

\begin{align*}
L &= \bar{Y}hR + \frac{1}{2} M_b \epsilon \Omega^2 R^2 b_1 & \text{Equation 3} \\
M &= -\bar{X}hR + \frac{1}{2} M_b \epsilon \Omega^2 R^2 a_1 & \text{Equation 4} \\
\epsilon &= \frac{(1 - e)}{2} & \text{Equation 5}
\end{align*}

The first part of the equations is the moment produced due to the respective forces and moment arms with respect to the aircraft centre of gravity, while the second part of the equations is the additional moment due to the offset. Cooke\textsuperscript{20} derives rotor hub moments including hinge offset and arrives at a similar solution. The only difference is the offset term is $e(1-e)$ instead of $e$. Evaluating the difference between the two the results is negligible; for example in the case of the Seahawk:

\[ e = 0.0466 \quad \text{and} \quad e(1-e) = 0.0444 \]

Heffley’s code\textsuperscript{5} uses equations for $L$ and $M$ that are in essence, the same as above. However, Heffley incorporates the cross coupling affect due to the offset. The cross coupling effect is where a small portion of roll will be encountered for an input of pitch and visa versa. Yet Heffley suggests when considering rotor hub moment equations, the approach at first is to assume the moments are decoupled, and then systematically add terms to best suit a simulation match. Therefore at this stage of simulation development, the rotor cross coupling will be ignored.

The rotor spring constant $K_g$ is established from the additional portion of the moment equation due to the offset because it is dependent on the offset of the rotor blades. Where as the parent simulation rotor spring constant was defined for a semi rigid rotor hub and the value was obtained via testing. To define the spring constant or rotor hub stiffness all blades are taken into account and in the case of the Seahawk, there are four blades. Heffley’s code\textsuperscript{5} defines the spring constant due to the flapping to be:
However, by using the Bramwell\textsuperscript{19} moments equations (equation 3) or (equation 4), $K_b$ can be extracted from the additional moment due to offset portion of the equations. Such that the rotor spring constant would be:

$$K_b = \frac{b}{2} (1.5 \times I_b \times e \times \Omega^2)$$

\textbf{Equation 6}

When calculating $K_b$ using Seahawk specifications for the two different methods there is approximately a 5\% difference in the results. At this stage, $K_b$ will be established via (equation 7) for the setup file.

$$K_b = \frac{b}{2} M_e x \epsilon \Omega^2 R^2$$

\textbf{Equation 7}

Garratt\textsuperscript{3} and Prouty\textsuperscript{18} both explain Dihedral Effect in similar fashion. Garratt likens the dihedral effect experienced by a fixed wing aircraft has the same stabilizing effect for a helicopter.\textsuperscript{3,18} When a gust of wind is encountered, the blade advancing towards the wind gust will experience an increase in lift and the blade retreating from the wind gust will experience the opposite. The 90\textdegree phase lag will see the TPP tilt away from the oncoming gust and cause the aircraft to roll in the same direction as the TPP has been tilted.

The parent code makes use of an equation for TPP dihedral effect from Heffley’s code and states that because the thrust coefficient between hover and forward flight is only slight, calculating the thrust coefficient for steady hover and using the same results throughout the simulation is sound. Heffley and Garratt also extract the values for $a_1$ and $b_1$ via the equation for dihedral effect shown below. The dihedral effect is part of the setup file input into the parent code and will remain the same for the Seahawk enhanced setup file. See set up code Appendix B.

$$\frac{db}{dv} = \frac{da}{du} = \frac{2}{\Omega R} \left( \frac{8 C_T}{a \sigma} + \sqrt{\frac{C_T}{2}} \right)$$

\textbf{Equation 8}

The Lock Number ($\gamma$) is also a parameter entered in to the set up code. The Lock Number is the ratio of the aerodynamic force compared to the inertia forces of the blade and its value is effected by the air density therefore is effected by altitude, note (equation 9) below.\textsuperscript{21} The Lock Number plays a role in the increase in rotor dampening and a decrease in phase lag with altitude. However, the change in Lock Number within the altitude region that is being considered at this point is negligible, therefore the value for the Lock Number will be fixed to the value at sea level. ($\gamma_{SL} = 8.2867$)

$$\gamma = \frac{\rho a c R^4}{I_b}$$

\textbf{Equation 9}

As previously mentioned, it is necessary to account for the blade twist of the main and tail rotors, and the Seahawk has in both cases a twist of -18\textdegree. The parent code simulation accounts only for a blade without twist. However the blade twist is accommodated via the method explained below. Blade twist is introduced in an effort to obtain a constant induced velocity ($V_i$) across the blade disc. It is possible to obtain the thrust required to be produced by the rotor and the blade collective angle require by blade element theory. Where an integration would be carried out across the blade radius to account for the blade twist angle at each point on the radius. Alternately, Seddon\textsuperscript{22} suggests a less complicated method with comparable results. The equation below that returns the coefficient of thrust for a rotor blade with no twist can be used for a blade with linear twist provided the twist angle at ¼ radius is used in place of $\theta_o$.

$$C_T = \frac{1}{2} \sigma a \left[ \frac{1}{3} \theta_o \left( 1 + \frac{3 \mu^2}{2} \right) - \frac{1}{2} \lambda \right]$$

\textbf{Equation 10}

where

$$\sigma = \frac{N_b c}{\pi R}, \quad \lambda = \frac{V_a + V_i}{\Omega R}, \quad \mu = \frac{V}{\Omega R}$$
IV. Seahawk Specific Enhancements

E. Automatic Flight Control System (AFCS)\textsuperscript{23}

The Seahawk’s AFCS is an electro-hydro mechanical servo system employed to introduce improved control and stability characteristics and reduce pilot workload. The AFCS incorporates the inner loop, outer loop and the variable horizontal stabilator control. The inner loop is the Stability Augmentation System (SAS). This system uses rate damping to improve dynamic stability and will be discussed in more detail in a later section. The outer loop system known as the Flight Path Stabilisation (FPS), acts as the helicopter’s autopilot. This FPS serves as the long-term memory and operates with 100% authority over the flight controls, at a limited rate, to maintain the pilots selected flight regime, such as heading hold and altitude hold. However, the parent simulation already has an outer loop system established that effectively provides a similar service. Therefore, for the purposes of keeping the simulation less complicated and focusing on the other components of the Seahawk enhancements, the parent code outer loop system will be utilised for this thesis. The Horizontal Stabilator System aids in the reduction of pitch trim attitude changes as a result of airspeed, collective and side slip coupling and promotes dynamic stability. The Stabilator will also be discussed in more detail later in the report.

i. Stability Augmentation System (SAS)\textsuperscript{15,17,23}

As stated previously, the inner loop of the AFCS is the Stability Augmentation System and employs rate damping to improve dynamic stability. The Seahawk SAS system is based on the system developed for U-60A Blackhawk. This system is a fast response system with ±5% authority. The actuating servos are placed in series with the flight controls, and thus operate without movement to the cockpit controls. The SAS is a duel system comprising of two channels, one being an analog amplifier (SAS 1) and the other a digital computer (SAS 2). The Simulation pitch channel block set below will be use to assist in illustrating the operation of the system.

![Figure 6 Stability Augmentation System Pitch Channel Block set (Produced using Reference 15)](image-url)

The helicopter motion is sensed through rate gyroscopes; in this case the pitch rate gyro. This signal is then passed through a conditioning filter before being shaped by a washout circuit, if required, to provide a wash out rate. The washout circuit automatically reduces the effective washout system washout time constant, as a function of attitude error. Then the signal is passed thought the 2:1 redundancy gain switch. The redundancy gain switch is not required for the simulation, however for completeness, a gain of one has been put in place. To illustrate the switch’s operation, when both channels are working normally the gain at each channel is 1. If one of the two channels were to malfunction, be it the analog or digital channel, the gain in the opposite channel would go to 2, thus compensating for the defective channel that would go to a gain of zero. In the case of the

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digital channel, the signal passes through a zero order hold to account for computer update delays, and as mentioned previously, both sides have ±5% authority. The output signal is a sum of both (SAS 1) and (SAS 2) and is a percentage of the servo movement. The yaw SAS system also has a component to aid in turn coordination that also utilizes lateral acceleration sensing. Please find in Appendix C a lay out of all three SAS component block sets constructed from information source from Reference 15.

ii. Pitch Bias Actuator

The Pitch Bias Actuator (PBR) is a variable length motor driven control rod that is located in the mixing unit.24 This variable length control rod lies in series with the pitch controls. It changes the relationship between the longitudinal cyclic control and swashplate tilt, and its length is a function of three inputs: pitch attitude, pitch rate and airspeed.25 The primary function of the PBR is to increase the static longitudinal stability of the helicopter by only affecting the pitch channel input to the mixing unit. Note where the PBA feeds into the pitch channel in the Mixing Unit schematic (figure 8) and the block set diagram (figure 15). Also find in Appendix C a lay out of the PBA block set constructed from information source from Reference 15.

F. Canted Tail

The Canted tail rotor is a standard tail rotor where the rotor shaft has been angled upward from the vertical as demonstrated in (figure 7). This is a common feature with Sikorsky Seahawk and Blackhawk helicopters. The advantage of the canted tail rotor is that not only does it conduct the normal function of directional control and anti-torque reaction, it also provides small degree of lift force at the tail and thus aids at hover in conditions of AFT centre of gravity.

The Seahawk and Blackhawk 20 degree canted tail rotor can provide 2.5% of the total lifting force at hover.26 The distance aft from the center of gravity of the tail rotor creates a moment that causes the nose to pitch down with increased thrust. This aspect of the Seahawk has been considered in the simulation, and has been accounted for via the Forces and Moment block set within the section of the Helicopter Dynamics block set of the simulation, and is discussed later in the report.

G. Stabilator

Whilst the rotatable Horizontal Stabiliser or Stabilator is an integral component of the Seahawk dynamic stabilisation system, it will not be included in this thesis version of the Seahawk simulation. The Seahawk Stabilator, as mentioned previously, rotates from approximately 40 degrees trailing edge down at hover, to negative 8 degrees trailing edge up in forward flight. The 40 degrees trailing edge down is to minimise the effects of the Stabilator with respect to main rotor downwash at hover. Therefore, because the scope of this thesis is mainly concerned with stable hover, and considering the extensive time and research required to correctly mathematically attain the downwash implications over a moving Horizontal Stabiliser, this simulation will not incorporate the moving Stabilator. However, during research into the SAS, information on how the Stabilator operates has been compiled. This information will become useful in future forward flight development of this simulation is conducted.
H. Mechanical Mixing Unit

The mixing box alleviates much of the cross coupling that naturally occurs in helicopters. The component also partially compensates for the adverse effects of the twenty degree canted tail rotor that is specific to Seahawk and Blackhawk helicopters. The canted tail rotor adds additional coupling between the lateral and longitudinal motion.

The control inputs to the control surfaces are passed through a Mechanical mixing Unit. The schematic of the mixing unit in figure 8 depicts how the control inputs are fed into the unit and are cross-fed to combine with the other controls.

The Mixing Unit combines and couples the four channels (yaw, roll, pitch and collective) by receiving control inputs for the various channels and then provides proportional outputs to the aircraft’s two rotors. Whilst the mixing unit is employed to decouple the effects of the cantered rotor, the mechanical and fixed gain nature of the unit comes with minor adverse effects of it’s own. These effects were noted in implementation of the mixing box into the simulation, and considerable time adjusting and tuning the outer loop system was required.

The logic behind the mixing unit is as follows:

- Collective increases are fed through to increase the tail rotor pitch to account for the extra torque generated.
- Collective is also fed through to the lateral pitch control to counter the side force created by the increase in thrust at the tail rotor from the torque compensation and because of the rolling moment created by the tail rotor, due to its position well above the helicopters centre of gravity.
- The third collective increase effect is to generate a nose down pitching moment from the increase in downwash over the tail section of the fuselage (however the downwash over the tail boom section is not factored into the current simulation) and to counter the main rotor’s tendency to flap back at forward speed when collective is added.
- Finally, when an increase in tail rotor thrust is experienced from directional pedal inputs, a nose down pitching moment is experienced as a result of the canted tail rotor. Therefore, an opposing gain is fed from the yaw channel to the longitudinal channel to compensate for this cross coupling.

It must also be noted that the setup of the mixing unit is designed for a ‘typical’ flight condition of the aircraft, and other flight conditions at which the aircraft operates, will not be optimal for the specific designed mixing unit gains of the aircraft. This situation was experienced with the simulation when experimental flight-testing of forward flight was tried. When going from a stable hover to a slow forward flight situation with no mixing box in the loop, flight could be achieved with still a converging aircraft stability response and minimal PID gain adjustments were required. However when hover was established with the mixing box engaged and then moving to forward flight the opposite was encountered, very quickly a divergent stability situation developed and considerable time tuning the PID gains was necessary. This will be discussed further in the conclusion.
V. New and Modified Parent Simulation Block sets

A. Helicopter Dynamics Block set

As mentioned earlier, the Helicopter Dynamics block set was already part of the parent simulation as shown in (figure 6), however to simulate Seahawk dynamics it was necessary to make modifications. To begin with, the parent simulation’s rotor moved in a clockwise direction while the Seahawk’s rotor rotates in a counter-clockwise fashion. Therefore a change had to made with relation to the torque direction. This was taken care of by placing a negative one gain block in the torque fed line to the forces and moments block set. This reversed the direction of the torque to clockwise and thus simulated anti-clockwise main rotor rotation.

Figure 9 Modified Helicopter Dynamics Block Set

There are three new block sets within the Helicopter Dynamics block set: the Wind Gust Simulation Model; the Fuselage Drag Model and the Vertical Tail Fin Model. The existing Forces and Moments Block Set was modified to cater for the output of these enhancements.

iii. Wind and Gust Model

The Wind and Gust Model (orange in figure 9) is used to simulate a gust of wind, a head or crosswind, or a combination of any or all of these conditions. The wind and gust model accesses the orthogonal velocities of the aircraft and by adding a ramp inputs at a desired time and gradient to any or all of the three velocities $u$, $v$ and $w$, the desire external environmental condition can be created. The required inputs are entered via the setup code and by simply using trigonometry and time co-ordination, any wind or gust vector in the required direction can be simulated. In the same fashion, a turbulence model could be incorporated, the RMAX simulation has a turbulence model than could be adapted easily to the Seahawk simulation.
iv. Fuselage Drag Model

The Fuselage Drag Model (green in figure 9) accounts for the drag encountered due to the flat plate projected area opposing movement in the direction being traveled or experienced, known as parasite drag. Prouty\(^1\) defines parasite drag in simple terms, where the flat plate area is the drag divided by the dynamic pressure. Therefore when arranged in terms of drag, the parasite drag due to the fuselage can be calculated via the drag equation shown below.

\[
Drag = \frac{1}{2} \rho v^2 AC_d
\]

Equation 11

Where the area \((A)\) is the flat plate area and with a drag coefficient \((C_d)\) of 1, and thus making the drag calculation quite straightforward. However, the flat plate area is an estimate at this point and could be tightened up further by physical aircraft measurements. The velocity must be correctly equated directionally for the fuselage parasite drag calculation to hold fidelity, especially when dealing with the vertical velocity as the rotor-induced velocity also plays a part. (Note Block set diagram below).

![Fuselage Drag Model Diagram](image)

Figure 11  Fuselage Drag Model

v. Vertical Tail Fin Reaction Model

The Tail Fin Model (purple in figure 9) incorporates the weather cocking operation of the Vertical Stabiliser in conjunction with the Vertical Stabiliser’s distance from the centre of gravity. The Vertical Stabiliser creates a sideway force in the same manner in which a wing generates lift force. The sideway force at the Vertical Stabiliser \((Y_{Tail})\) is calculated via the equations shown below that are fed through the simulation by a Matlab\textsuperscript{®} m.file.

\[
Y_{Tail} = \frac{1}{2} \rho V_{Tail}^2 V_{stab \ area} C_L
\]

Equation 12

The velocity the tail encounters \((V_{Tail})\) is calculated via trigonometry using the velocities of the tail in the \(x\) and \(y\) directions. It should be noted that the velocity of the tail in the \(y\) direction is also a product of the yaw rate \((r)\) and the distance from the centre of gravity. This is included in the calculation of the tail velocity in the \(y\) direction at follows. (Note block set diagram below)

\[
V_{yTail} = v - r \times V_{stab X}
\]

Equation 13

![Vertical Stabiliser Model Diagram](image)

Figure 12  Vertical Stabiliser Model
vi. Forces and Moments Model

The Forces and Moments Block set (yellow in figure 9) as mentioned previously was an existing parent simulation block set. This part of the simulation considers and culminates, as the title suggests, the forces and moments generated by the helicopter into the six degrees of freedom. This block set takes in the rotor forces and rotor moments calculated from the rotor sub-code embedded in the helicopter dynamics via the method shown in the (equations 3 and 4) from the rotor flapping. It also takes in forces and moment generated from the main rotor thrust and torque, tail rotor thrust, tail fin and the fuselage drag. All these input are then multiplied by respective distance arms from the centre of gravity if required, and then summed into their respective degrees of freedom.

It is in this block set where the 20 degree canted tail rotor and the 3 degree forward tilted main rotor mast can be taken into account. This is accomplished by using basic trigonometry to distribute the appropriate force in the correct axis direction. (Note the green gain blocks in figure 13 below). Then using these forces multiplied by their respective distances from the centre of gravity (C of G), via the moment arm input from the setup code, their contributing moment are accredited. (eg. Main_Z being the distance of the main rotor to the C of G in the Z axis direction, Note the blue blocks figure 13 below). However, it is necessary to assure the moments are being added in the correct sense as in the correct direction, to accommodate this, a position or negative moment arm is applied depending on which direction is required. The output from the block set is then loop fed back to the rigid body dynamics imbedded sub-code. For further detail on the Helicopter Dynamics Block Set, refer to Reference 3.

Figure 13  Forces and Moments Block Set

B. Controller Model

The Controller Model houses the outer and inner loop systems. The outer loop system is an existing system from the parent model that consists of the heading and altitude hold by means of an error feed back. The SAS and the PBA are both controlled from within the inner loop system and operate as discussed in the previous section Seahawk Specific Enhancements. The gains and transfer functions used within the Seahawk inner loop
system were sourced from Reference 15. This is an area where adjustments could be made if required by a control engineer to enhance aircraft stability or to compliment any engineering changes to the mechanical flight control system. The Controller is a large block set and can be viewed in it entirety in Appendix C. For further information on the operation of the outer loop, refer to Reference 3.

Figure 14 Controller SAS Inner Loop

C. Mixing Box

The Mixing Box (or Mixing Unit) as discussed previously adds proportioned gains from the collective to the other three channels, while the yaw channels adds a correction gain to the longitudinal channel, all in an effort to reduce adverse cross coupling effects. By observing the structure and gains of the Mixing Box block set diagram (figure 15) and the Mixing Unit gains (table 2) it can be seen how the gains are fed to the other channels and to what magnitude. As stated in the controller section, it is envisioned once the simulation is refined, this is also one of the areas of the simulation to which engineering changes and adjustments could be made. By making adjustments to a cross-feed gain or a conversion gain, and thus for instance, simulate a bellcrank length change or a flight control lever change. Therefore, obtaining first by simulation a reasonable indication of how the aircraft might respond or handle before a piloted flight test. It can also be observed in (figure 15) as described previously that the PBA length is added to the longitudinal pitch channel.

Table 2 Mixing Unit Gains

<table>
<thead>
<tr>
<th>Channel</th>
<th>Conversion Gains [Deg/Inch] (flight control movement)</th>
<th>Cross Feed</th>
<th>Gain [Deg/Inch]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal (Pitch)</td>
<td>-2.83</td>
<td>Collective to Longitudinal</td>
<td>0.464</td>
</tr>
<tr>
<td>Lateral (Roll)</td>
<td>1.60</td>
<td>Collective to Lateral</td>
<td>-0.256</td>
</tr>
<tr>
<td>Yaw</td>
<td>-5.539</td>
<td>Collective to Yaw</td>
<td>1.60</td>
</tr>
<tr>
<td>Collective</td>
<td>1.60</td>
<td>Yaw to Lateral</td>
<td>1.63</td>
</tr>
</tbody>
</table>
D. Primary Servo Model

The Primary Servo Model allows trimming of the simulation where constants are input via the setup code. These trim constants are obtained by running the simulation and adjusting the constant to where flight control stabilises. These constants could also be utilised if a flight control bias is required. The primary servo actuation reaction is replicated by a second order system transfer function, that simulates the action of primary servo jacks on the main rotor, and the collective servo movement on the tail rotor. These functions were sourced from Reference 15. Observe figure 16.

E. Analytic Stick Inputs Model

This block set is used to input experimental flight control movement. The block set simply utilises a combined summation of step inputs at required time intervals, to obtain desired analytic conditions, such as a continued step or pulse. These inputs are converted from stick movements in inches to flight surface angular movement in degrees. See Appendices B and C for more.

Figure 16 Primary Servo and Trim Bias
VI. Results

When the simulation reached completion for the scope of this thesis, the simulation was tested in hover at an altitude of 6 metres. The plots in (figure 17) below show that the simulation mostly settles down to a stable status at approximately the 30 seconds point, with the exception of the X axis velocity that settles completely at approximately the 90 seconds point. Yet, this velocity is very small at the 30 seconds point therefore the aircraft simulation can be considered stable in hover. It should be noted that the roll settles at -2.2 degrees, demonstrating the compensation for the sideways thrust and positive rolling moment generated by the tail rotor, called the translating effect. Moreover, it can be seen that there is a positive pitch settling of 5 degrees that would be accounting for the negative pitch moment caused by the vertical thrust from the canted tail rotor. These conditions demonstrate the simulation is working correctly and the outputs are feasible.

![Figure 17 Hover with No Inputs](image)

The next step is to observe the simulations reaction to wind gusts. The wind gust chosen to demonstrate has an in coming direction of 235 degrees where the forward X axis is considered zero degrees. The gust begins at 30 seconds into the simulation to allow the simulation to steady. The gust is allowed to build up to 5 m/s (approximately 10 knots) at the 35 second point and then die off to zero at the 40 seconds point. This can be observed in (figure 18) below. The plots demonstrates the simulation can handle a wind gust disturbance and recovers to a stable hover approximately 10 seconds after the gust has past with the exception of the pitch that takes about 5 more seconds to recover. Simulations were run with wind gusts from different directions, with similar results.

The response of the SAS can be observed in (figure 19), showing that the system is working in response to the gust and the correctional outputs marry up to that of (figure 18). However, the challenge is to now compare the simulation to actual flight data to evaluate the fidelity of the simulation in its current version status.
Figure 18 Hover with a 10kt Wind Gust at 235°

Figure 19 SAS Response to 10kt Wind Gust at 235°
Data was sourced from AMAFTU so a comparison could be conducted. The data was from flight testing carried out by AMAFTU on the S70B Seahawk on 05 December 1994. The flight test was conducted with a cross wind of 15kts at 280° and the data acquired was for hover. Inputs were placed into the setup code of the simulation to match the conditions of the flight test. The respective pitch, roll and yaw rate data was extracted from the flight test data from varied pilot control stick movements, such as; 1” forward and 1” back cyclic step, 1” left and 1” right cyclic step, and finally 0.5” left and right pedal step. The comparisons are presented in (figures 20, 21, 22 and 23) below. The primary channel of movement in each case was selected for comparison to ascertain how close the simulation could emulate Seahawk flight dynamics.

The case shown in (figure 20) is a one-inch aft cyclic step movement of the controls, comparing pitch rate. The plot shows that the responds are of reasonably similar magnitude and response time. The same can be said about the forward cyclic movement step in (figure 21). It must be kept in mind that the aircraft is accounting for small turbulence that the simulation does not have to deal with, which would account for the small rate movements lending up to and after the step inputs of the flight test data plots in both cases.

When comparing left and right cyclic step inputs (figures 22 and 23 respectively), the initial response of both plots differ up to 20% with the roll rate reached, more so with the left cyclic input which could be attributed to the 15knot wind coming from the left side. The gradient of the initial response to the step input in both cases are of the same magnitude. However the response after the step differ considerably. It is more than possible, at least highly probable this is attributed to the lateral position hold in the open loop of the simulation, as the system error from the step input is trying to be over come by the position hold auto pilot. Where as the aircraft is piloted without position hold engaged. Further investigation will be required into these responses as
similar type responses were encountered in testing the yaw rate with 0.5-inch pedal step inputs. However, the initial simulation response gradients were of the same magnitude as the piloted test data, as with all the previous comparisons. For more see Appendix D.

Forward flight simulations were attempted at several fight velocities, however the dynamics block set develops an error when more than 10 knots forward velocity is input. Yet the 10 knot simulations did look promising. After a considerable amount of time was spent at several different times to correct the issues, forward flight tests were abandoned. Simulating forward flight will have to be further investigated in future thesis reports.

VII. Methodology and Thesis process

At the start of the project research was commenced to firstly look into what work had been achieved in this field. It became apparent that a lot of work had and is still being done into small UAV simulations. Yet the majority of work with regard to the Seahawk and Blackhawk was with ‘pilot in the loop’ flight simulation, and not specifically from an engineering or maintenance aspect.

Once Dr Garratt passed on his cut down version of the RMax simulation (parent simulation), I set about to gain an understanding of how the simulation worked. From that point I began researching the specific Seahawk parameters from Sikorsky and NASA sources and reports. I discovered that the Seahawk was developed from the Blackhawk, making the parameters very much the same. Except for a few obvious but small differences between the aircraft, the documentation and information was very similar, thus allowing information to be used and cross-checked from a wider source base.

Adjustments had to be made to the parent simulation, such as for example the direction of the rotor and the associated reconfigurements, as discussed. Therefore several tuition sessions with Dr Garratt were required to grasp an understanding of the inner working of the parent simulation code. However once the adjustments were made it was then time to put the basic aircraft parameters into the parent simulation (via a continually developing setup code) such as all up weight, centre of gravity with the accompanying moments of inertia and specific component locations such as main rotor, tail rotor etc, using the method described in the setup code section. After which, considerable time was spent adjusting the outer and inner loop integral PID gains to obtain some form of stable hover before attempting to introduce Seahawk specific configuration enhancements.

A period of research was taken to source the inner working of the Seahawk AFCS. On completion of that period I took the decision to utilise the parent simulation outer loop auto pilot, and concentrate on constructing and implementing the inner loop Seahawk SAS. During this period it had become apparent the AFCS is enormously complicated and fully understanding this system is a thesis in itself. Several NASA research reports were used to reproduce the SAS, the SAS servos and the PBA. The transfer functions, gains and conversions from these documents were an excellent source of information in the development of these systems. (Reference is made to these documents within this report). As the SAS is a rate damping system to implement the system the dampening rate gains were gradually reduced to zero whilst tuning the rest of the system, a task that took considerable time to accomplish, more than I had envisioned. It was, at this point I realised that constructing and implementing an engine torque model would not been possible within the time frame of this thesis. However a considerable amount of information was compiled towards constructing this system which can be used in future work.

From this point it was time to commence the task of constructing the mixing unit mechanical linkage block set and research into the function of this unit. Again, NASA and Sikorsky documentation were a excellent source of information, along with my previous experience as a helicopter maintainer. After a period of research and construction, the mixing unit was implemented into the simulation. A whole new period of simulation gain adjustments were necessary, as the simulation now had to compensate for the cross coupling effects of the unit. However once the system was tuned through extensive trial an error, the simulation converged to a steady hover much more quickly than previously. The stability was also increased when the PBA was later introduced to the mixing unit pitch channel.

It was at this time I realized that implementing the horizontal stabiliser and the extensive research required to account for the downwash effects over a moveable stabiliser was going to take more time that the thesis time frame would allow. In short, I was running out of time, it was suggested to me earlier it was better to concentrate on a small portions of the simulation and get it right, rather that taking on too much and doing it poorly. The SAS and setup code are equipped with the necessary outputs for the stabilator’s operational triggers, and with the data compiled, it’s implementation could be dealt with in future thesis assignments.
The simulation then needed a means by which it could be tested against actual flight data. Therefore a wind-gust model and analytical control inputs model were developed and implemented. From this point flight test comparison were conducted.

VIII. Recommendations

The Seahawk simulation in its current state does demonstrate stable hover, with reasonable indications the simulation can mimic Seahawk flight in the pitch channel. Further investigation into the other channels will need to be conducted to determine how best to tune the model to bring the model in line with Seahawk flight data. It was suggested mid way through the thesis by LCMR Dawes, an undergraduate thesis could be conducted just trying to simulate one channel and get it right. Therefore, it is recommended using the simulation in its current status, that each channel be investigated separately to then determine what adjustments need to be carried out, to more closely replicate Seahawk dynamic flight responses. This would encompass (but not be limited to) further research in to the gains within the simulation AFCS and the implementation of the Seahawk outer loop Flight Path Stabilisation System (FPS).

Forward flight simulation were attempted, with errors developing it the dynamics bloke set, it is recommended that the dynamics block set imbedded code be investigated in consultation with Dr Garratt. It may be possible by using the built in aerodynamic toolbox of the industry version of Simulink®, that adapting the built in dynamics block set to the simulation could overcome the error problem quickest.

It is recommended that the downwash effects over the fuselage be investigated, as to how the downwash effects the pitching moment reaction with relation to the drag over the tail boom. Further, future simulation development would need to incorporate the moving horizontal stabiliser. Not only with respect to its movement operation and control from the AFCS, but the downwash effects especially at the different angles of attack.

It was intended that physical measurements would be taken of the flight control linkages and bell cranks, so a database could be established and gain ratios could be assigned to the individual item. Therefore, if an engineering change to the mechanical fight control system were to be made, a simple gain change could be made within the simulation and flight responses could be ascertained. It is recommended this data base be established in the future.

It is also recommended that research be conducted on developing an engine torque model using Simulink® that could replicate engine power output under the most demands of the rotors. This would be especially useful simulating take off and landing trajectories when the engines are under heavy loading. This model could be developed as a stand alone thesis and on completion be implemented into the Seahawk Simulation.

IX. Conclusion

In conclusion the goals of the thesis were met. The simulation in its current status produces a graphical depiction of a stable hover situation with Seahawk parameters imbedded in the simulation. The Seahawk enhancements compliment the simulation and aid in producing simulated flight responses similar to that of the Seahawk. Yet further work on the simulation is required to increase the fidelity of the simulation and to move towards forward flight reigns. This thesis is the first building block towards a fully operational, reliable black box simulation engineering tool, that will reduce flight test time and associated resources, and the continued safe operation of the Seahawk in RAN.
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References

1 S-70B-2 Seahawk Royal Australian Navy (RAN), Online accessed 13 April 2008.
2 LEUT Steven Arney, RAN, Senior Flight test Engineer AMAFTU personal communication, 27 September 2007.
3 Garratt, M. "Biologically Inspired Vision and Control for Autonomous Flying Vehicle", UNSW@ADFA Canberra ACT 2007.
17 Sikorsky Aircraft United Technologies, Document no. SER-520005, August 1979
23 United Technologies Sikorsky Aircraft Document NO. SER 520211
26 “Rotary Flight Systems and Maintenance”, Australian National Training Authority 1997