Transition Analysis on a Tilt Rotor UAV – Static and Dynamic Analysis

J2 UNIVERSAL TOOL-KIT, AIRCRAFT MODELLING AND PERFORMANCE PREDICTION SOFTWARE

Key Aspects

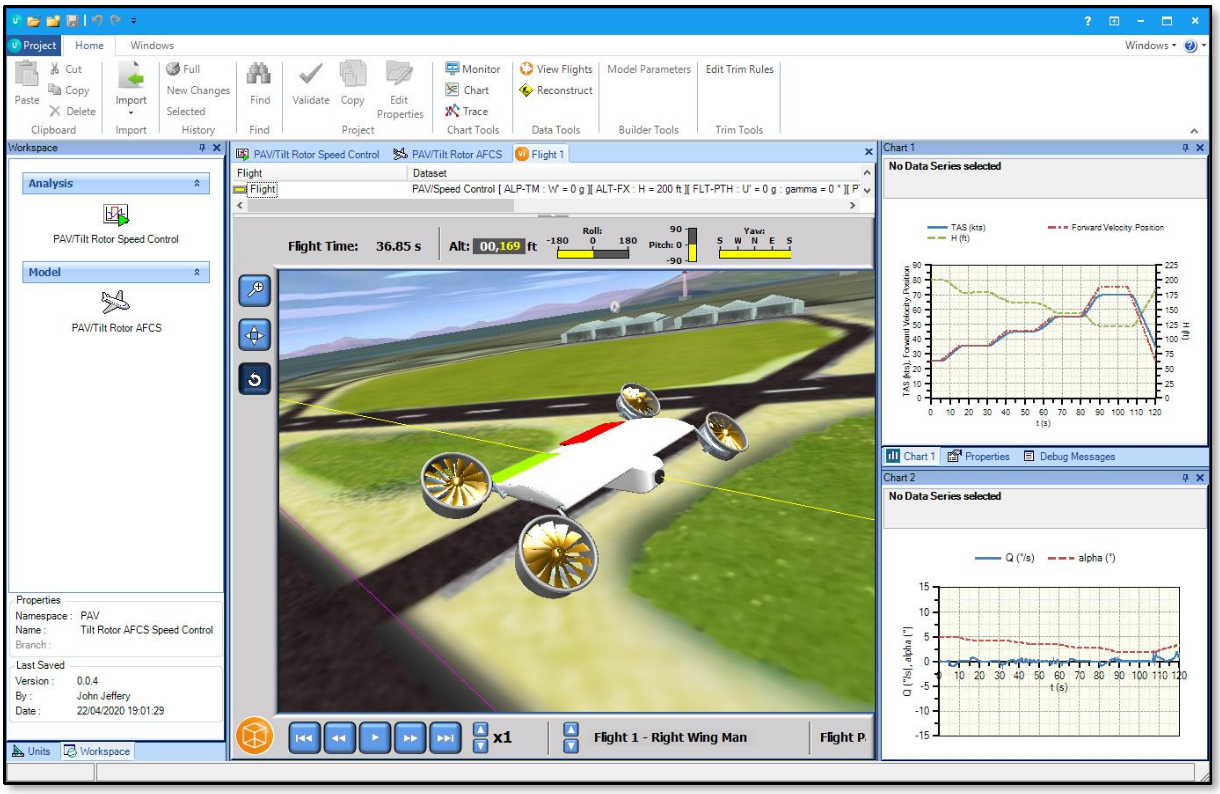
AIRCRAFT DYNAMICS
Predicting Performance

ABSTRACT

When considering PAV's and eVTOL aircraft, there is a critical phase in the flight path as the aircraft transitions between hover/vertical flight and forwards flight. Whether this transition is through the tilting of the complete aircraft and the balancing of the thrust as in a multi-rotor vehicle, or the change in orientation of the engines and the balancing of thrust as in a tilt rotor, it is important to have an understanding of the aircraft behaviour and the blending/balancing of the thrust and orientation in order to evaluate and further develop the Automatic Flight Control System (AFCS).

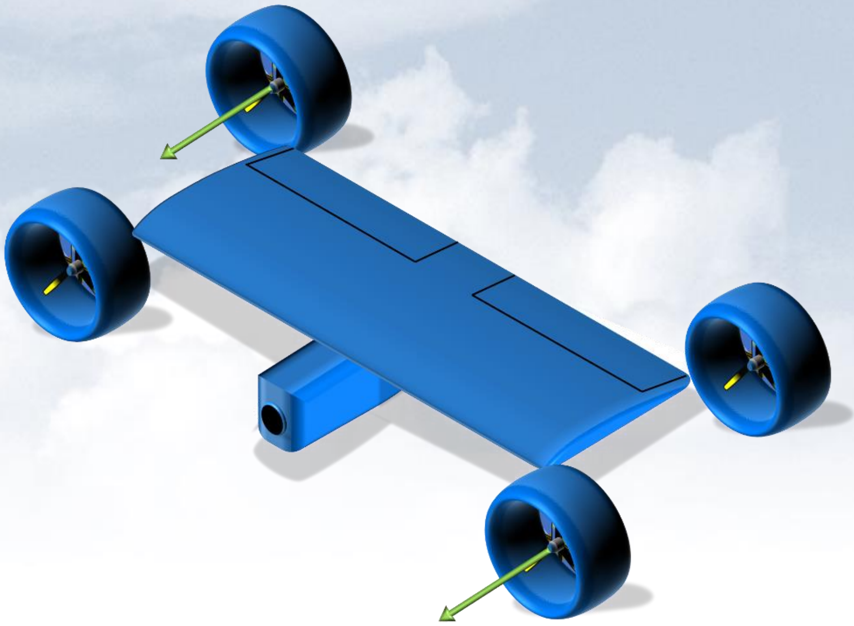
This paper continues the work from the previous, Model Build, paper in providing an outline of work that has been carried out using the **j2 Universal Tool-Kit** to assess the behaviour of a Tilt Rotor UAV complete with variations in engine thrust location and centre of gravity. Further papers will go on to discuss the approach to static and dynamic analysis performed to support and enhance the Automatic Flight Control System development.

This work was originally performed for a customer on their own vehicle but has been reproduced here using an example aircraft. The data and model information shown are representative as is the work process used in order to present the capability of applying the **j2 Universal Tool-Kit** to analysing and solving such challenges.



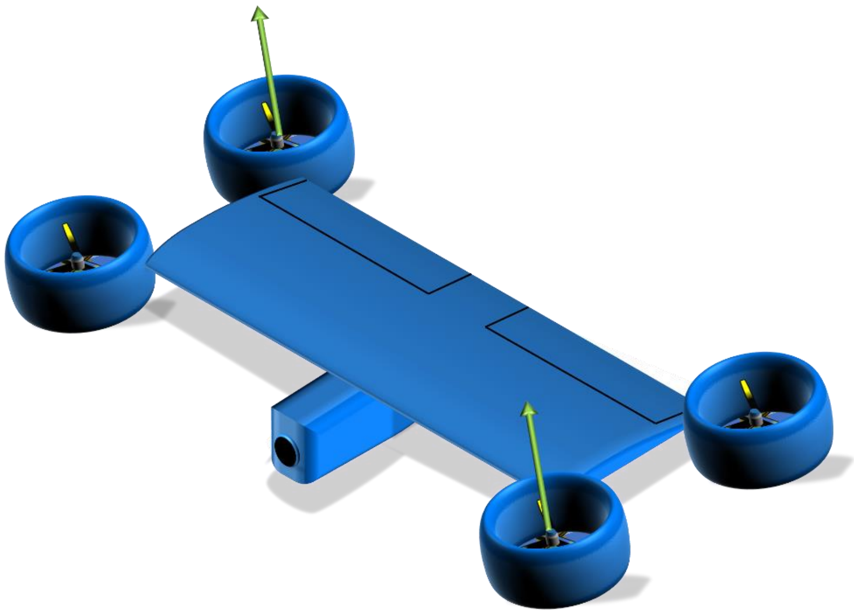
The Aircraft

The aircraft under test is a Tilt-Rotor UAV that has a rectangular wing with a fuselage underneath. 4 ducted propellers are attached via linkages located at each corner. The linkages allow the engines to not only change orientation but also to move their locations.



Tilt Rotor Configuration Forward Flight

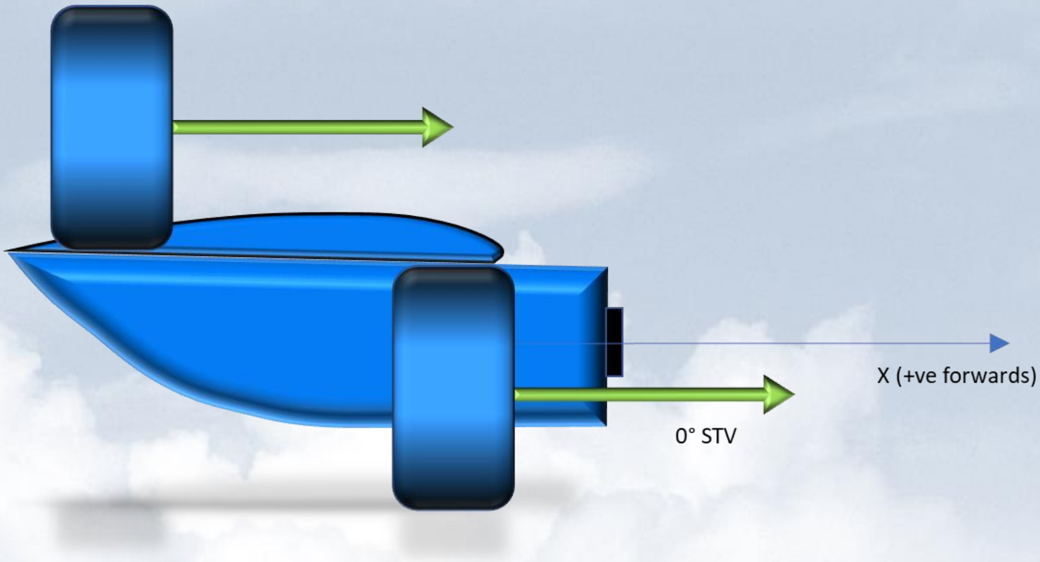
The benefits of the change in engine location is that it enables thrust differential to be used to assist stability e.g. in forward flight the engines thrust lines are located above and below the CG.



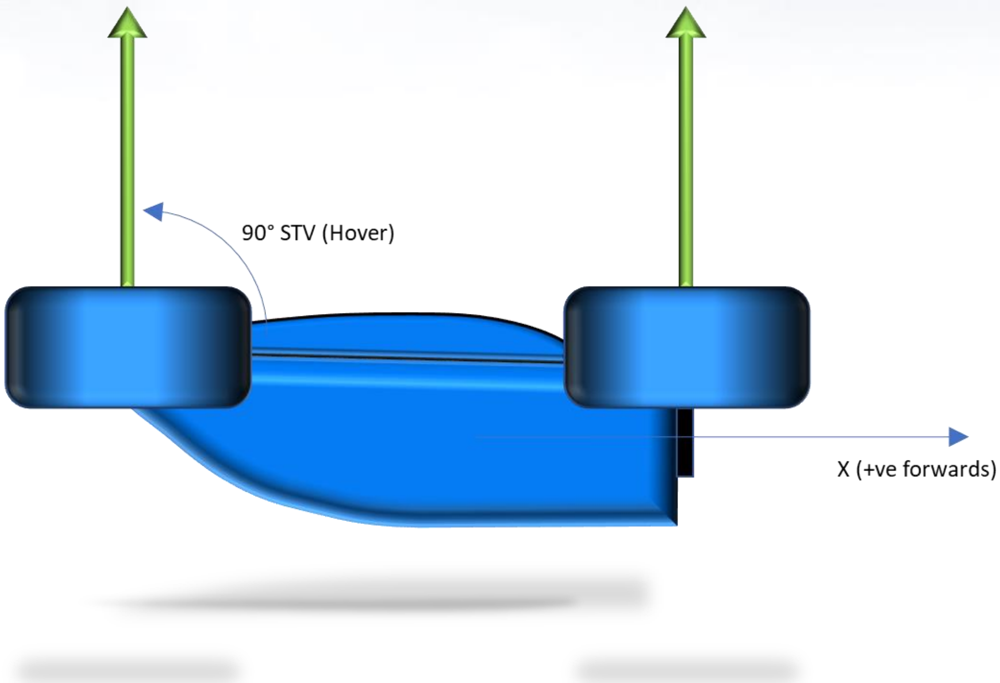
Tilt Rotor Configuration Hover

In hover, the engine thrust lines are separated further forward and aft of the cg giving a larger moment arm and a more stable platform.

The Thrust Vector (STV) angle can range from -15° through to 105°. This increased range of movement allows for further manoeuvrability.

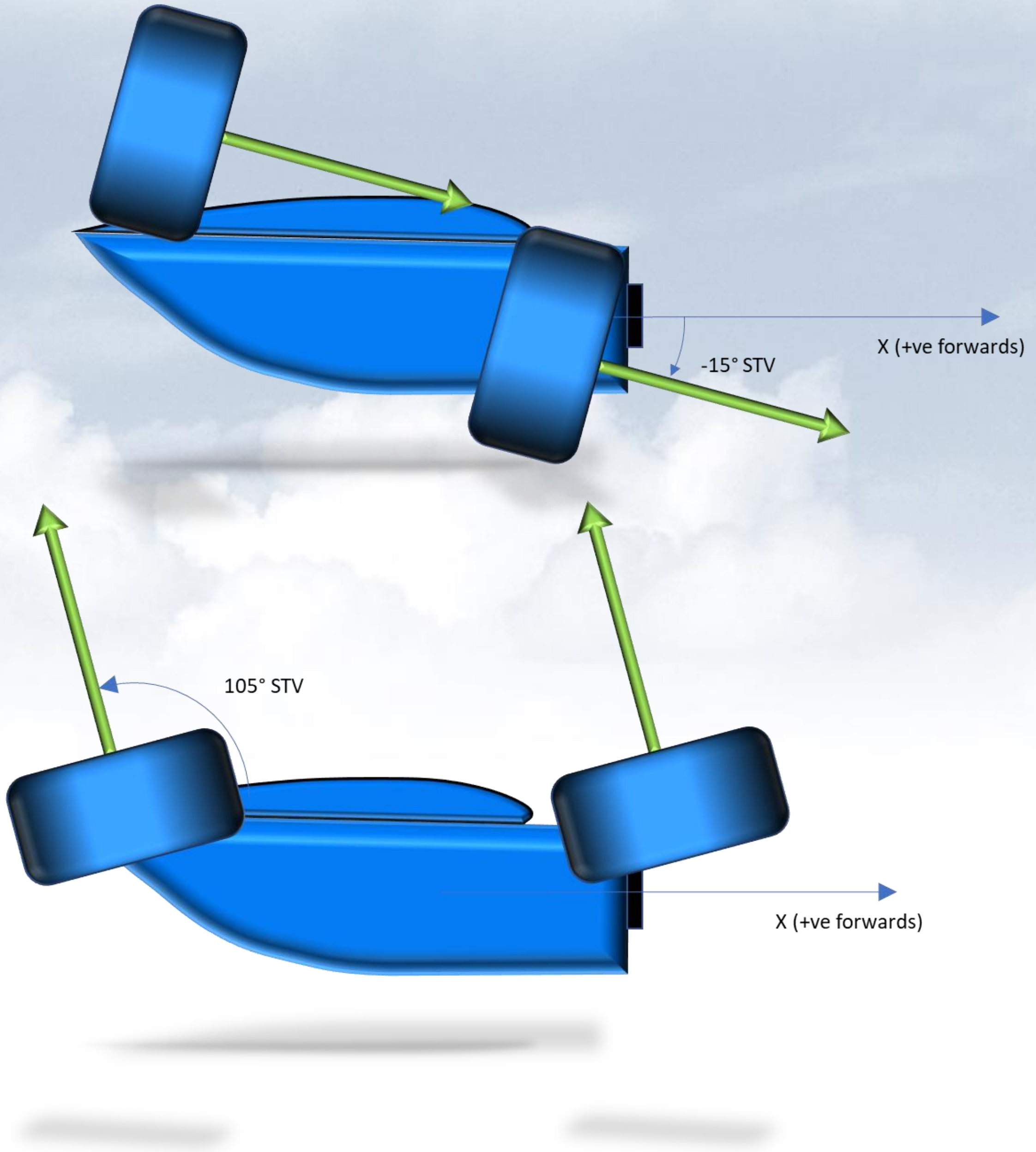


Thrust Lines for Forward Flight

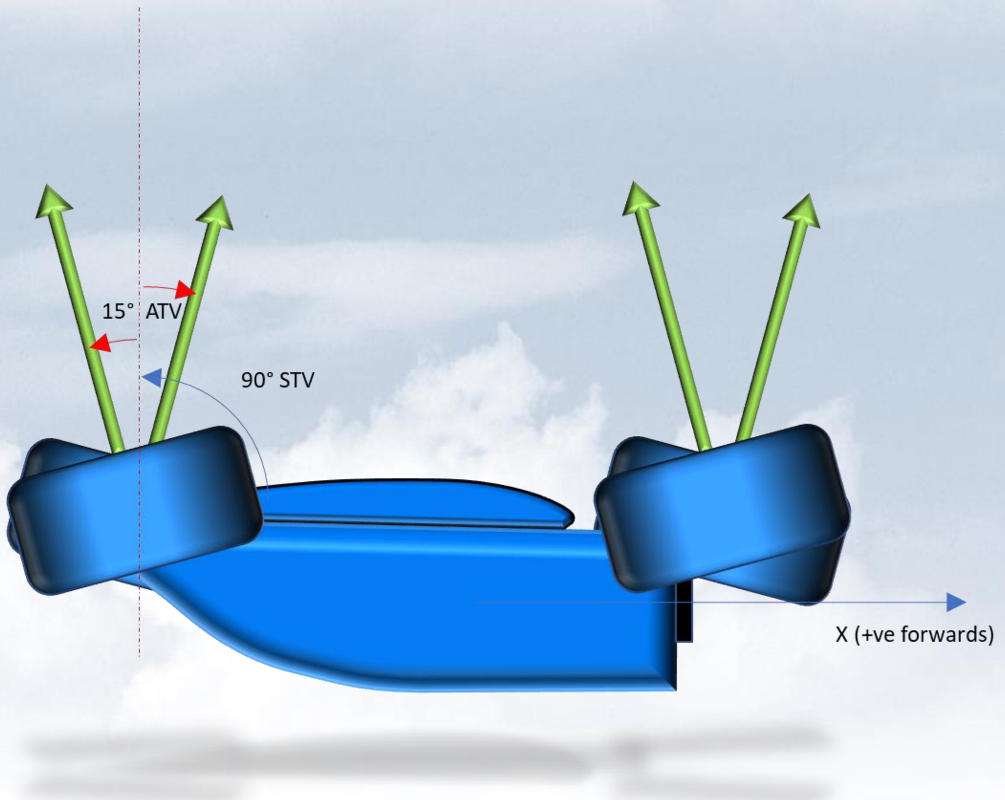


Thrust Lines in Hover

Changing the Symmetric Thrust Vector (STV) manoeuvres all 4 engines at once. The Asymmetric Thrust Vectoring (ATV) manoeuvres the left and right engines alternatively.



Additional Range of Movement



Yawing the Aircraft in Hover through Asymmetric Thrust Vectoring

Finally, in addition to the vectoring, a thrust differential can be applied longitudinally and laterally to provide pitch control and roll control in low speed flight.

During conventional flight, roll and pitch control is provided through flaperons at the trailing edge of the wing. These can also be moved symmetrically if further lift is required.

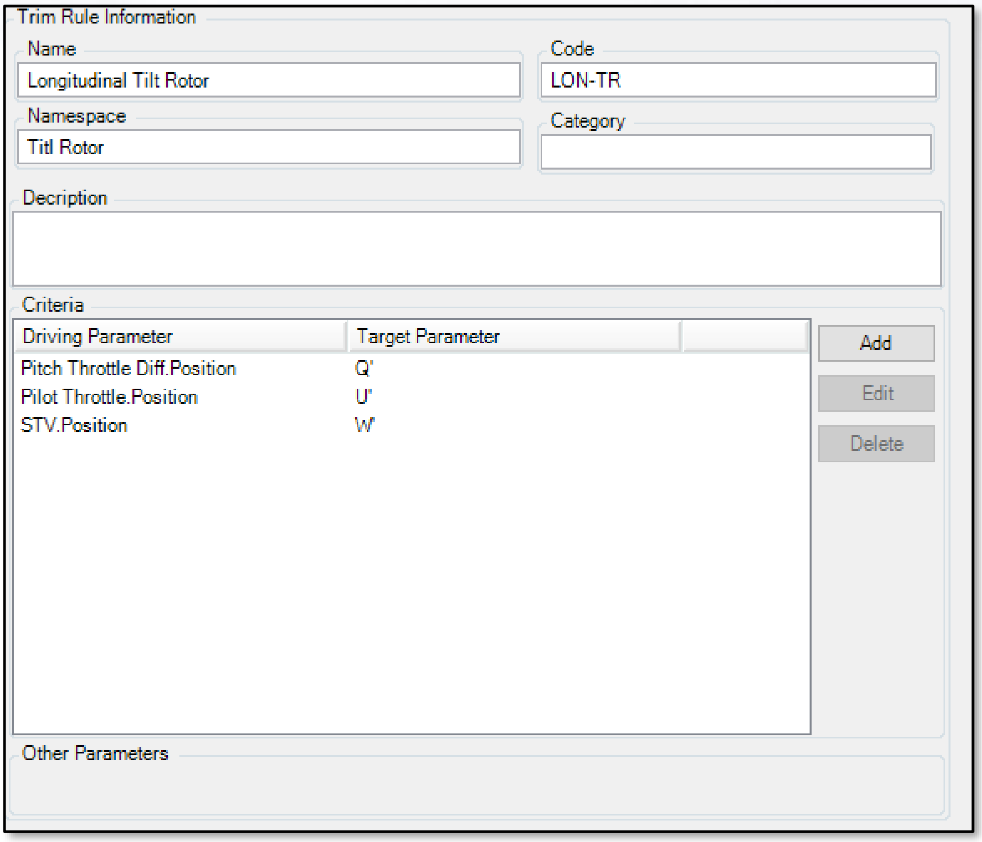
As you can see, the controls challenge is that the control of the aircraft utilises multiple variables that are required to be merged and blended to provide suitable aircraft control.

BASELINE TESTING

The first stage of testing is to look at the Baseline model. At this point there is no controls logic included and everything is driven manually. The test cases considered were to set the aircraft at a variety of airspeeds and angles of attack at a target altitude (200ft) and to establish the Pilot Throttle settings, STV angle, and Pitch Differential Throttle required for the aircraft to trim.

The condition that is being investigated is a non-conventional approach to trimming and as such it would not be possible with many conventional aircraft design products. Another alternative would be to code a system that can take the different types of inputs and using some form of solver to establish the values needed to trim the aircraft. Whilst solvers and systems exist to speed up this process, there is still a significant amount of development required. All of this is already built into the j2 Universal Tool-Kit through the j2 Freedom plug-in, so there is no need to write any code.

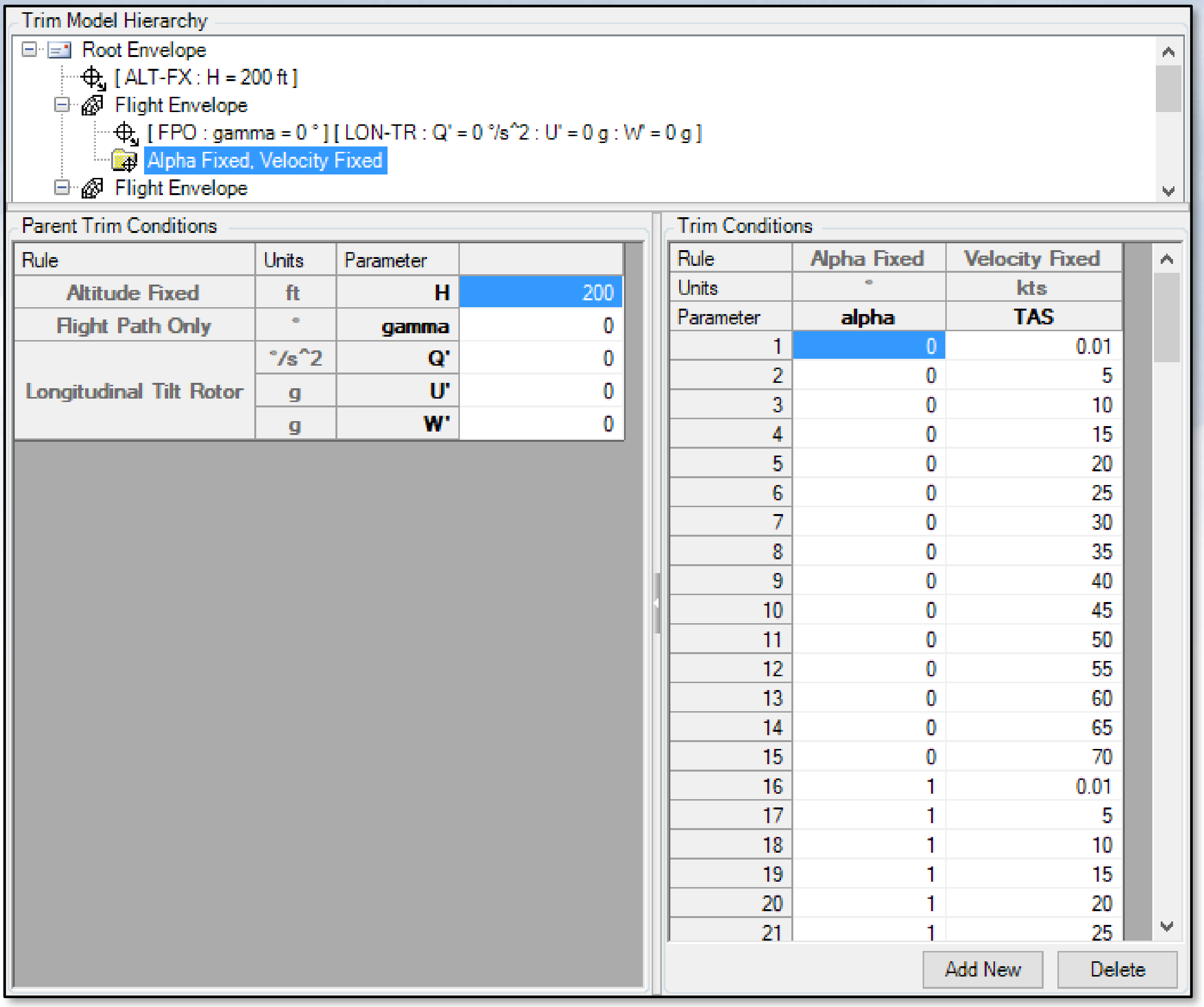
For generating initial conditions, j2 Freedom uniquely uses a system of Trim Rules. Each Trim Rule contains a set of Driving Parameters and pairs those to a set of Target Parameters, where the change in the driving will have an effect on the target values. The Trim Rules are created through the GUI by selecting Driving and Target parameters from a list of those available and relevant on the model.



Creating Trim Rules

By stacking multiple rules together, a Test Point is created, and by inputting ranges of values, multiple test cases are created automatically covering all combinations of the values entered.

For the baseline case, the trim rules used defined the altitude (200ft), the flight path angle (0°), thus ensuring the pitch angle changed with angle of attack and modifying the tilt rotor controls to set the target linear and angular accelerations (Q'=0°/s^2, U'=W'=0m/s^2). A range of angles of attack from 0 to 10° and a range of airspeeds from 0.01 to 70kts were entered. A complete set of all 165 combinations was created automatically.

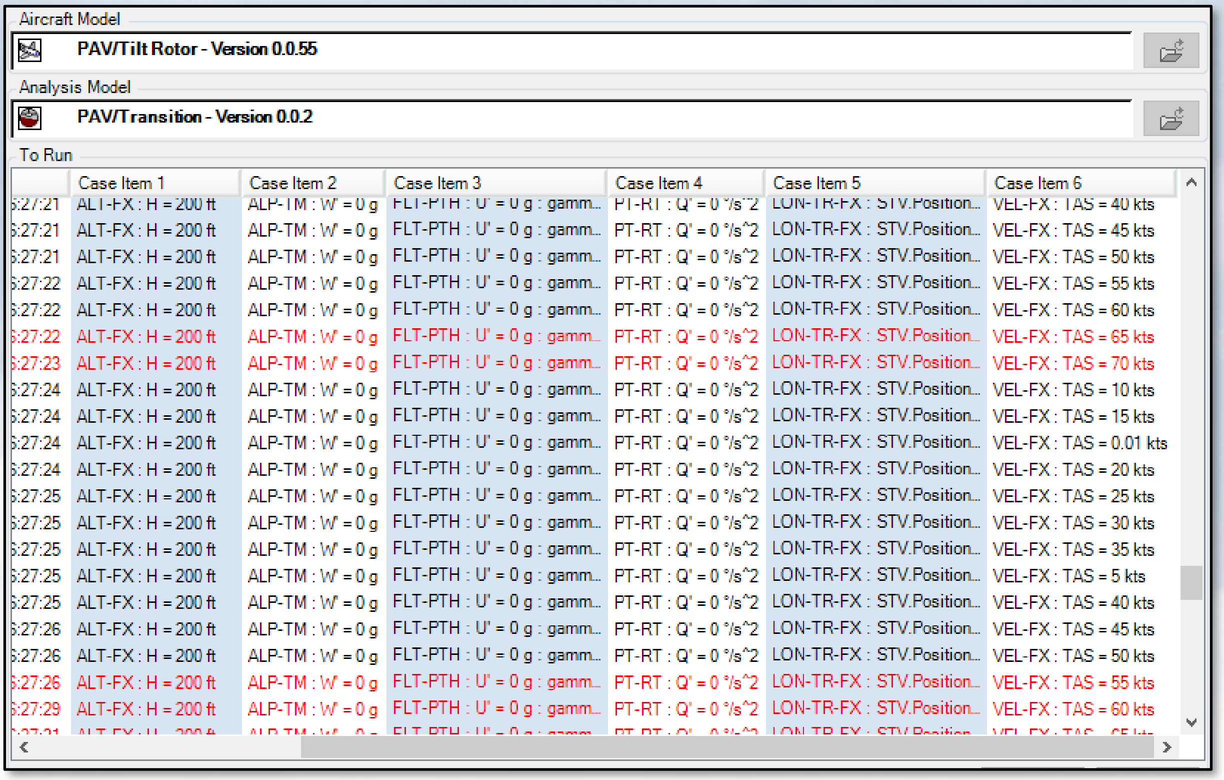


Rule	Units	Parameter	
Altitude Fixed	ft	H	200
Flight Path Only	°	gamma	0
Longitudinal Tilt Rotor	°/s^2	Q'	0
	g	U'	0
	g	W'	0

Rule	Alpha Fixed	Velocity Fixed
Units	°	kts
Parameter	alpha	TAS
1	0	0.01
2	0	5
3	0	10
4	0	15
5	0	20
6	0	25
7	0	30
8	0	35
9	0	40
10	0	45
11	0	50
12	0	55
13	0	60
14	0	65
15	0	70
16	1	0.01
17	1	5
18	1	10
19	1	15
20	1	20
21	1	25

Setting Up the Baseline Test Points

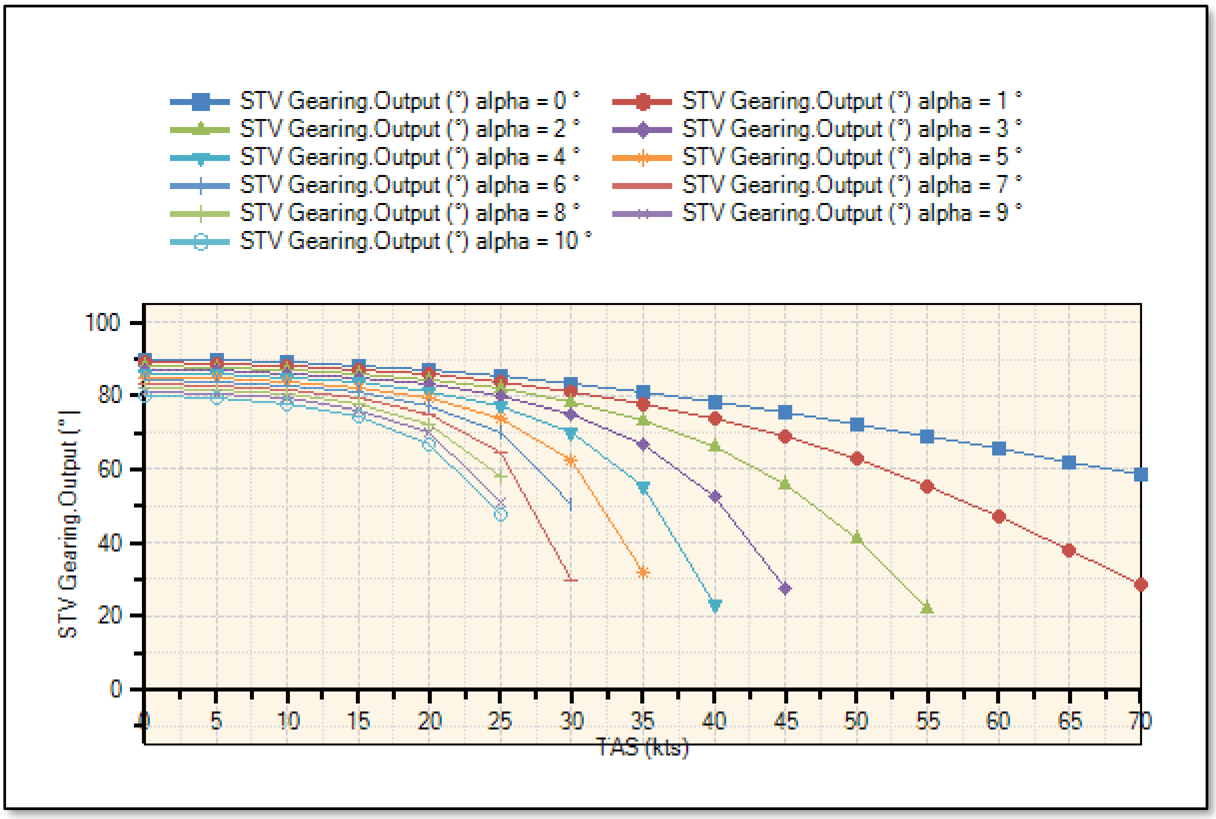
Once the test cases have been defined, they can then be combined with the Aircraft Model. When run, the integrated solver built into j2 Freedom runs through all the combinations finding the cases where the aircraft can satisfy the conditions and establishing all the inputs and control positions to do so. It will also identify those conditions where there is no solution.

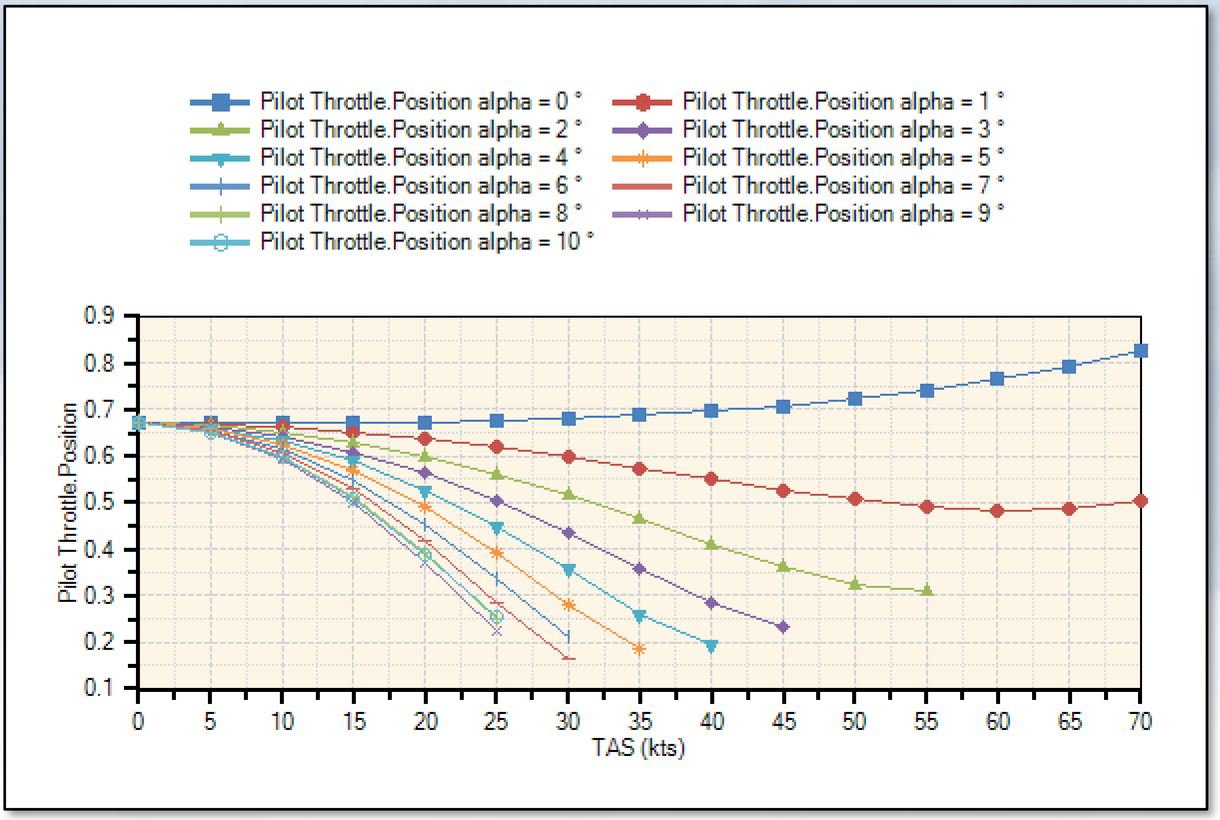


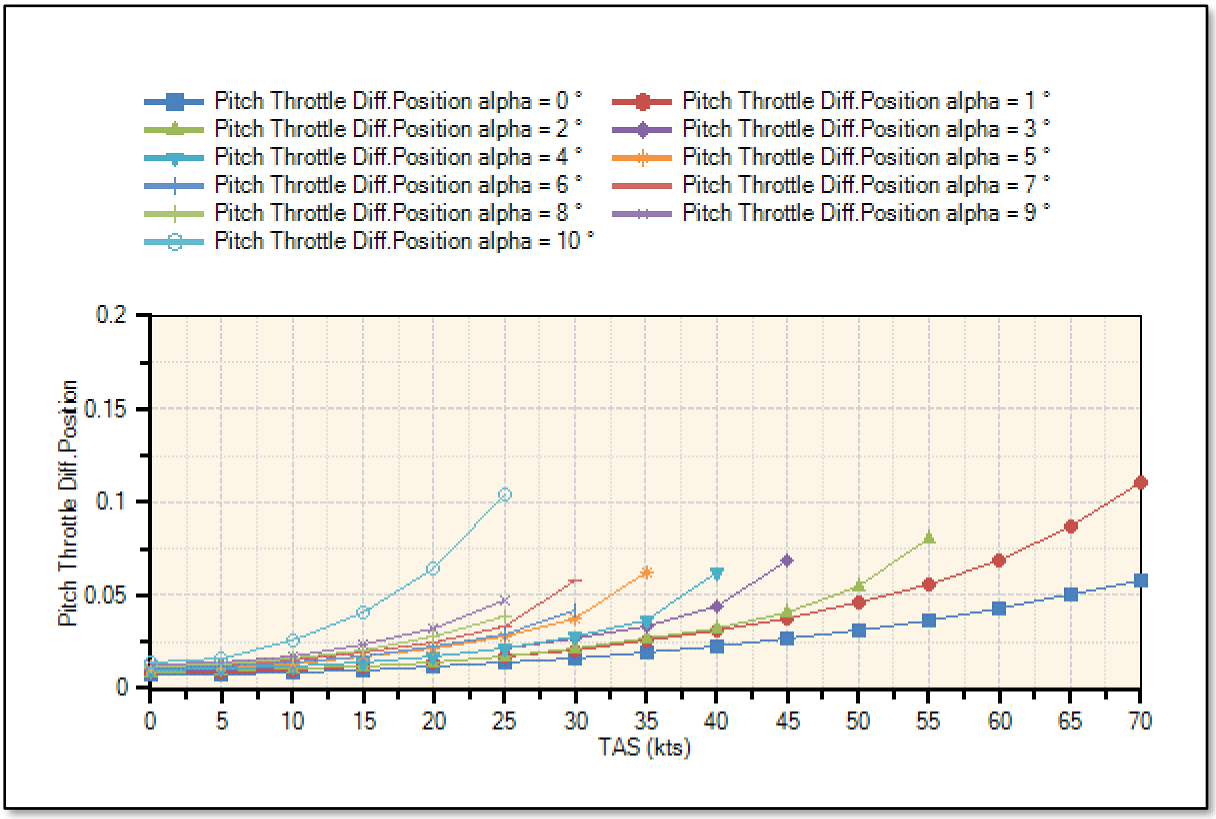
	Case Item 1	Case Item 2	Case Item 3	Case Item 4	Case Item 5	Case Item 6
:27:21	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 40 kts
:27:21	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 45 kts
:27:21	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 50 kts
:27:22	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 55 kts
:27:22	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 60 kts
:27:22	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 65 kts
:27:23	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 70 kts
:27:24	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 10 kts
:27:24	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 15 kts
:27:24	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 0.01 kts
:27:24	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 20 kts
:27:25	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 25 kts
:27:25	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 30 kts
:27:25	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 35 kts
:27:25	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 5 kts
:27:25	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 40 kts
:27:26	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 45 kts
:27:26	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 50 kts
:27:26	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 55 kts
:27:29	ALT-FX : H = 200 ft	ALP-TM : W' = 0 g	FLT-PTH : U' = 0 g : gamm...	PT-RT : Q' = 0 °/s^2	LON-TR-FX : STV.Position...	VEL-FX : TAS = 60 kts

Running the Baseline Analyses

From the analysis results we can establish the conditions necessary to trim the aircraft. As the speed increases so it becomes more difficult to trim the aircraft and thus it is possible to find the ranges of combinations and flight conditions.

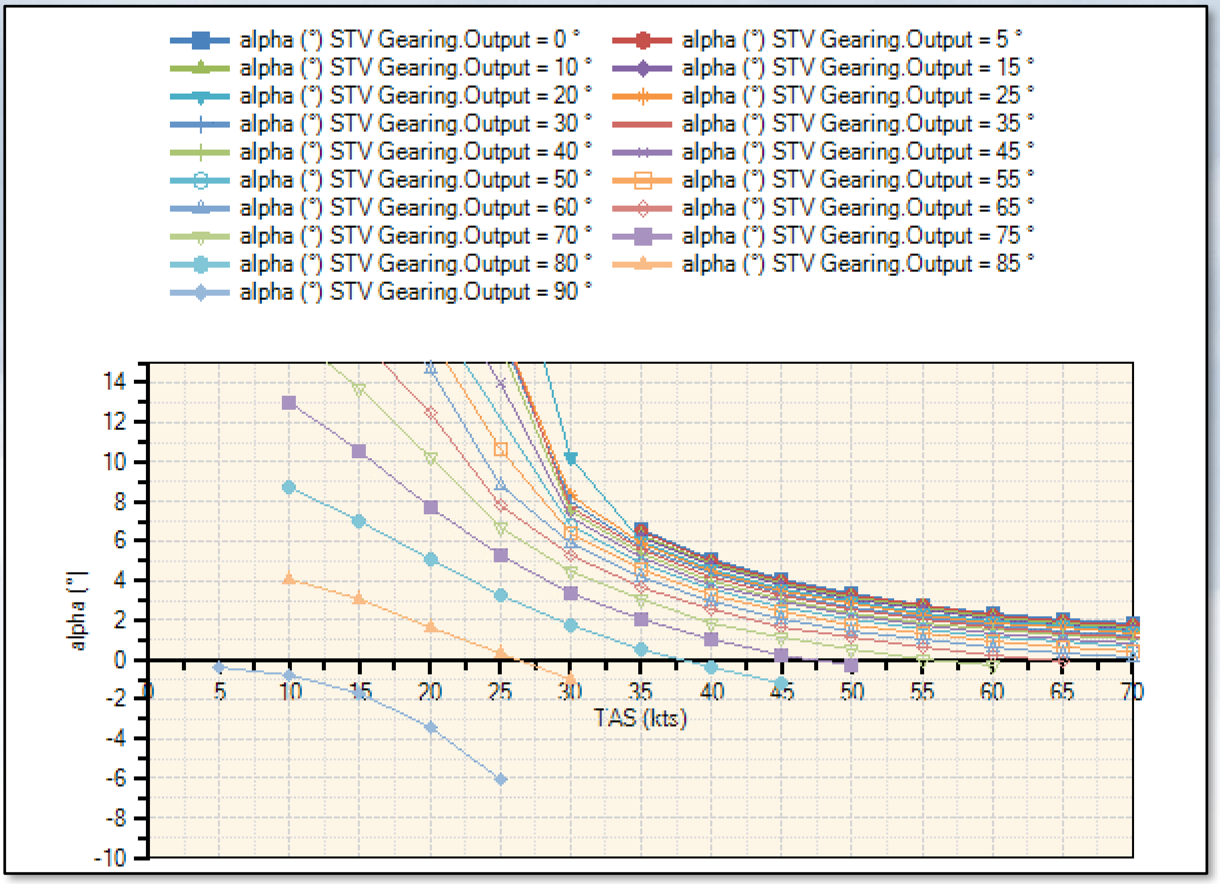


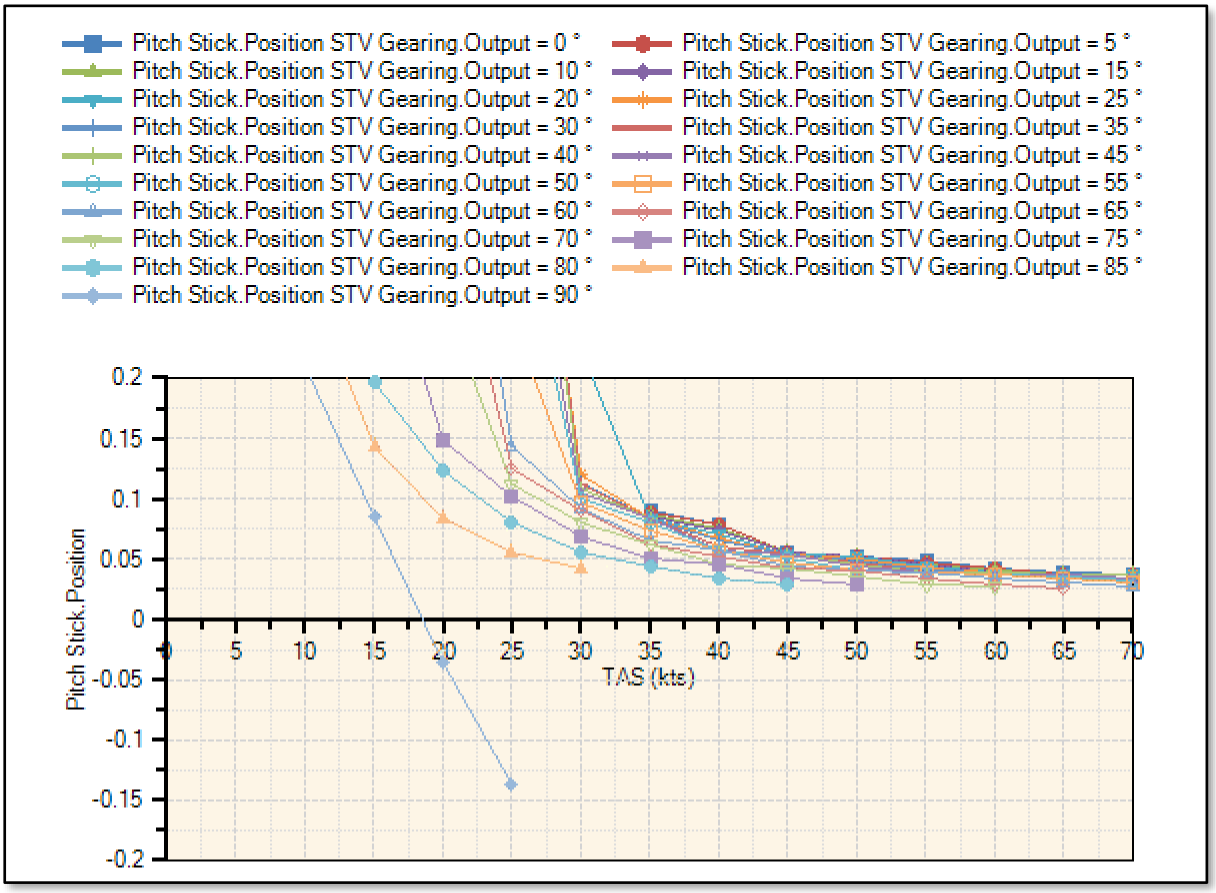




Control Settings for Baseline Tests

The next stage is to run a set of conventional trims where the angle of attack, elevon deflection and pilot throttle are used to trim the aircraft for a range of fixed STV angles.





Conventional Trimming over a Range of STV Angles

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A key finding identified here is that the aircraft starts to approach conventional flight at speeds above 35kts. This is where the aircraft can trim at an angle of attack less than 10° at 0° STV angle. At lower speeds, some STV angle is required to maintain flight. However, we want to be able to transition to lower angles of attack, so the full transition is considered to go up to 55kts whereby the aircraft is in fully conventional flight.

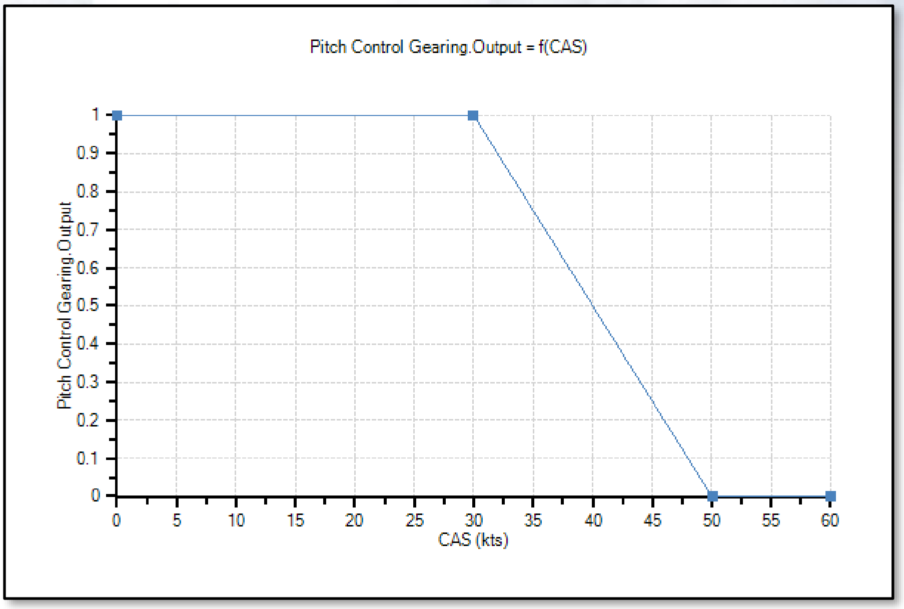
These analyses have helped to identify the regions of interest and the magnitude of the values involved.

Identifying Scheduling

Once we have established the magnitude and regions of interests, we can start to shape the values that can be used to control the aircraft through the transition. This means, what values of STV angle are likely to be required at what speeds and what values of the Pilots Pitch Stick are needed to trim the aircraft. From these we can schedule some feedforward information for the transition phase.

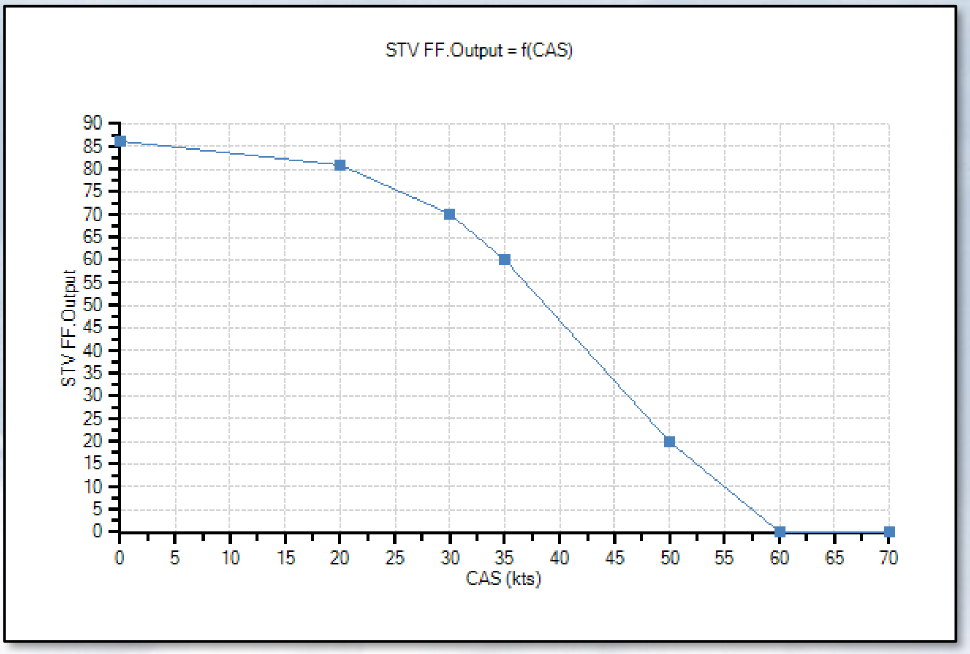
To establish a smooth transition, 2 sets of curves are to be created for testing purposes. The first is to provide a curve of approximate STV angles with airspeed and the second is to blend the differential throttle and flaps into a single pitch controller.

The initial approach was to have the pitch control come fully from the engines with the Pitch Stick position being translated directly into a Pitch Differential Throttle value at low speed and then swapping over to Pitch Stick driving the flap deflection only at higher speeds.



Transitioning the Pitch Control

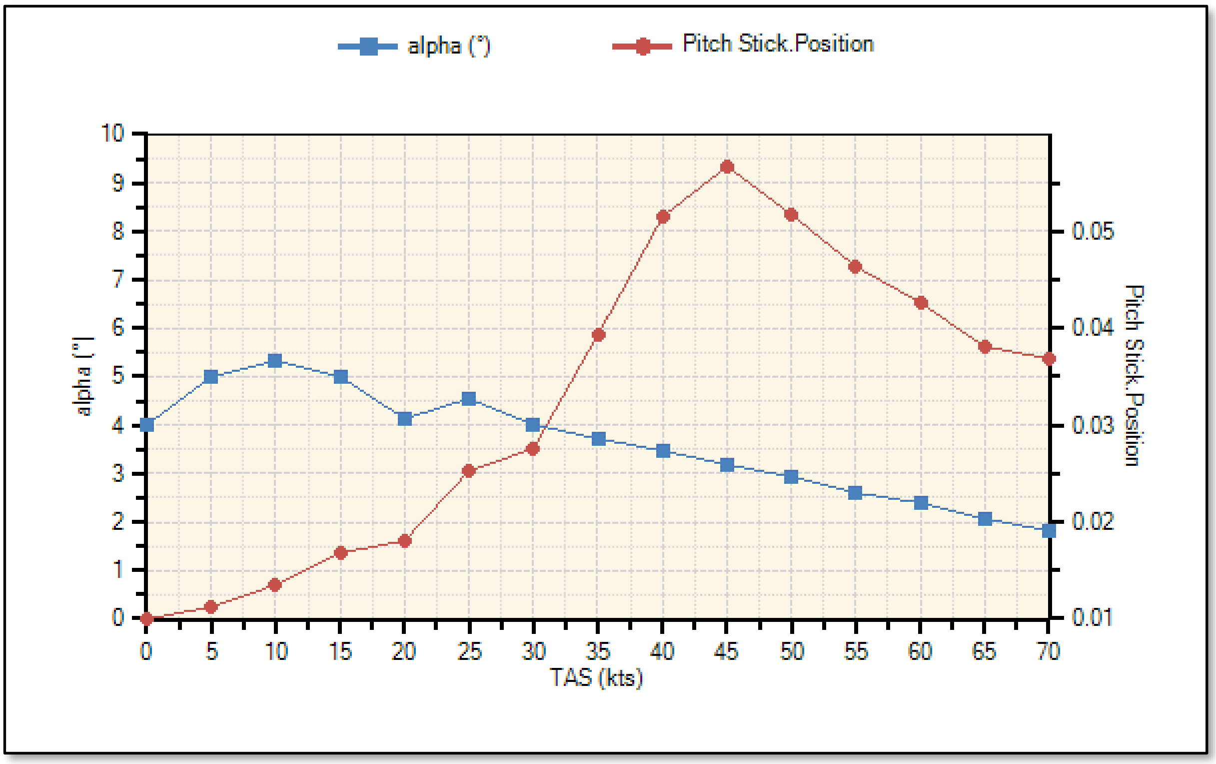
From the previous results, a suitable airspeed to STV progression was found.



Changes in STV Angle with Airspeed

The aircraft was now trimmed conventionally using angle of attack, pilot throttle and pitch stick over the full range of airspeeds where the STV angle was driven by the airspeed. The objective is to get a smooth transition through angle of attack and stick position as one might expect in a conventional aircraft.

From the initial values the response showed that the initial values were not suitable.

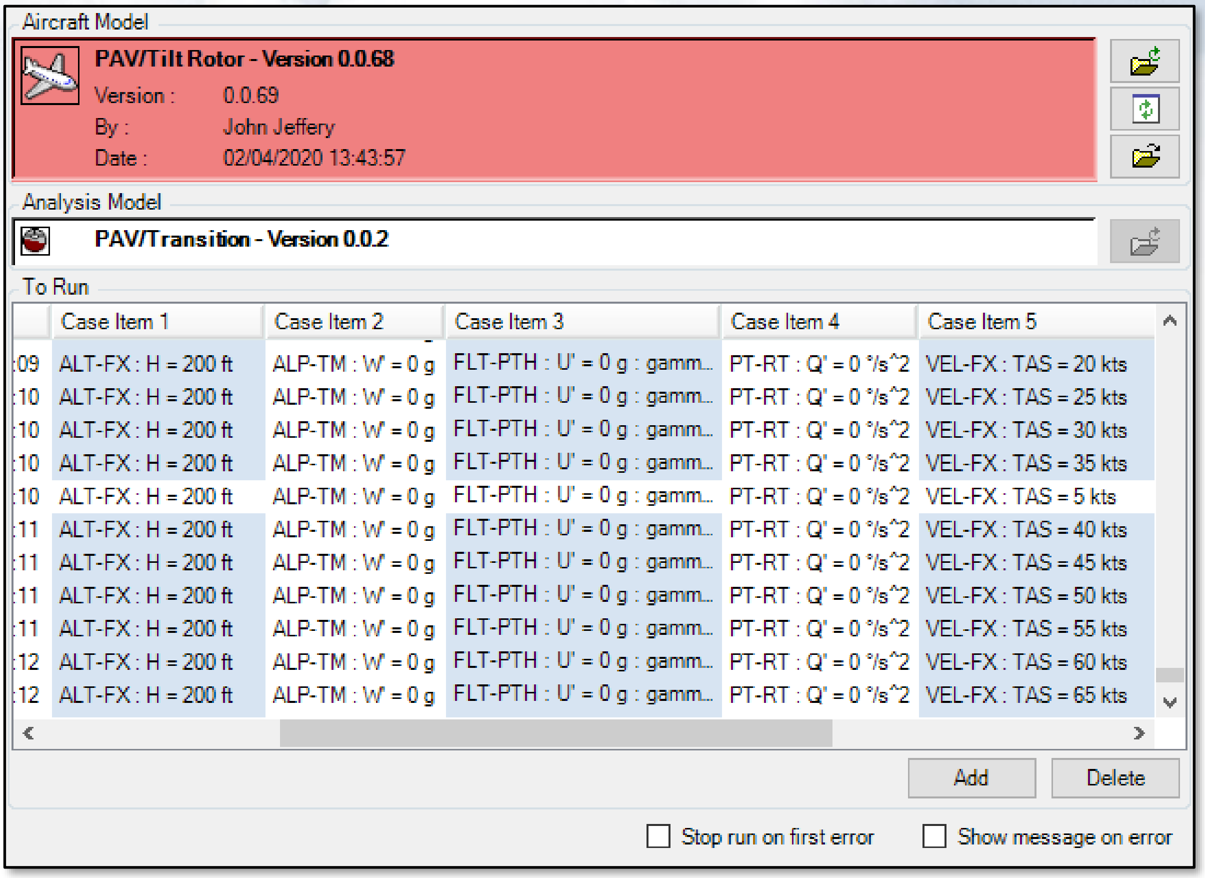


Trim Settings for Initial Transition Tables

In this case, the pilot would be required to pull back on the stick initially to increase speed until reaching conventional flight when it would then require pushing forwards on the stick. The first phase is counterintuitive and as such presents a controls challenge to be solved. The angle of attack trend is better, the first hump being due to the aircraft being rotated such that the thrust vector is almost vertically upwards whilst the STV angle is less than 90°.

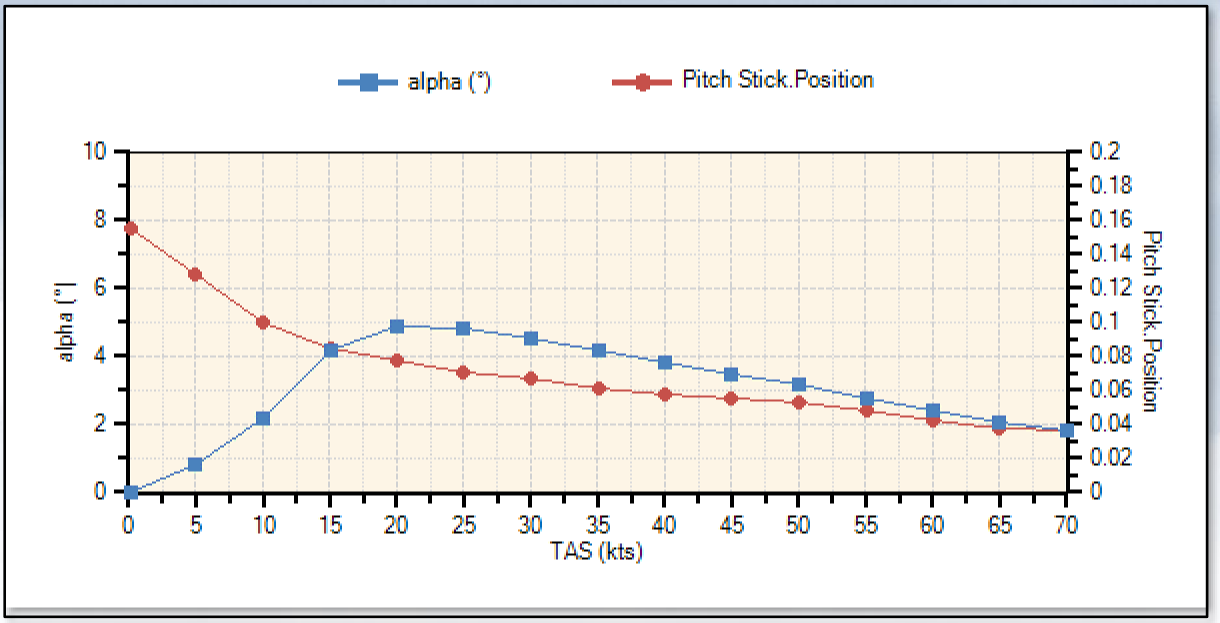
As the Pitch differential throttle values are smaller than the movement of the pitch stick for flap deflections so this needs to be scaled down. After some adjustment it was possible to establish a set of values to produce a smoother response.

Multiple tests were performed as the model was adjusted. As all the tests were already set up the integrated version control would identify that the model had changed and informs the user by highlighting in red.



Notifying the User the Model has been Updated

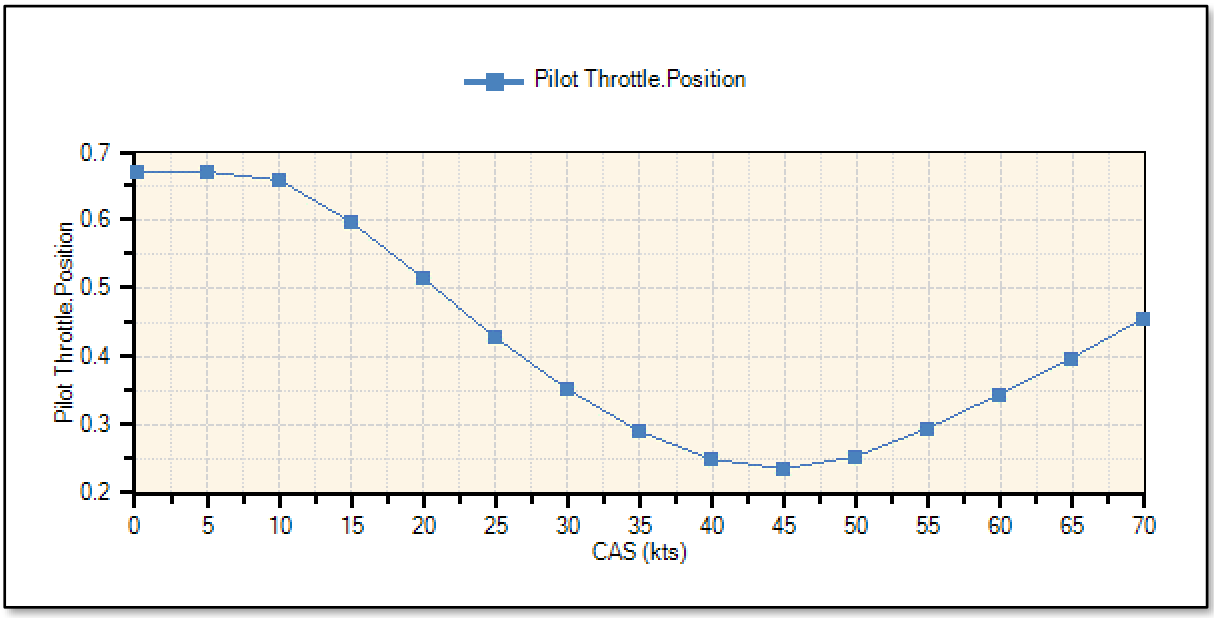
Following the adjustment of the variations of STV Angle with airspeed and the Pitch Control Transition with airspeed we can produce smooth and acceptable steady state conditions for Angle of Attack and Pitch Stick.



Finalised Trim Settings

The increase in angle of attack for the lower speed range may cause some instability issues but this has been left in for this example. If problems occur, this can be adjusted by reducing the STV Angle at the lower speeds and thus require a higher angle of attack to re-orient the thrust vector.

The analysis also provided the symmetric throttle settings (Pilot Throttle.Position) required to maintain the speeds.



Throttle Positions to Trim

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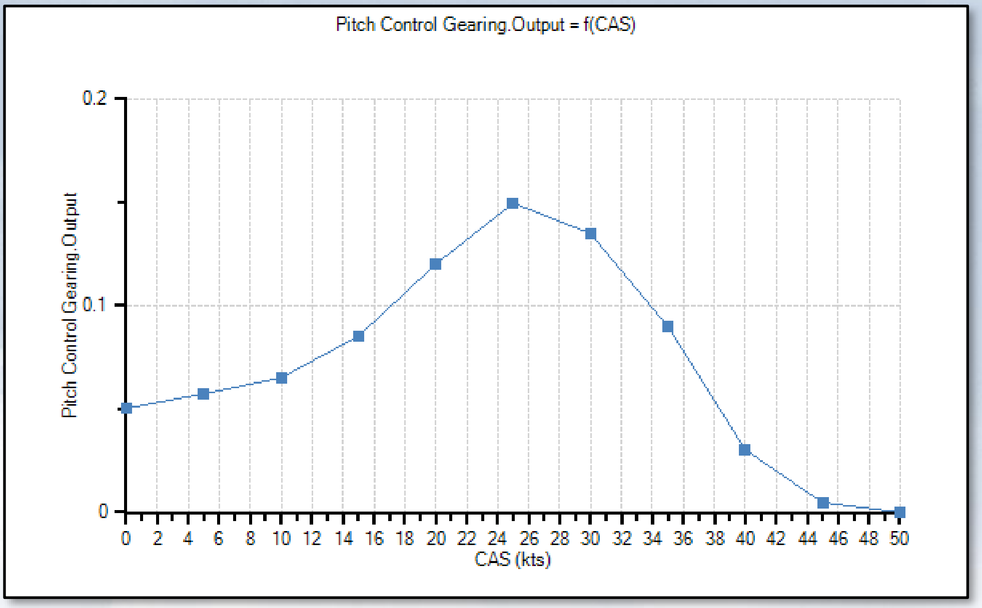
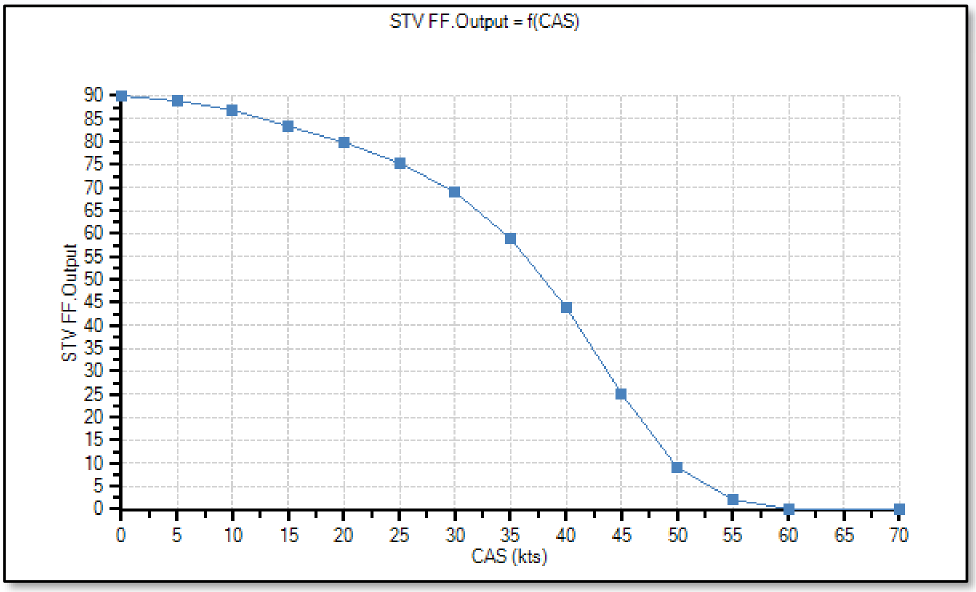
The resulting values of the STV Angle and Pitch Control Transition with airspeed can be found below.



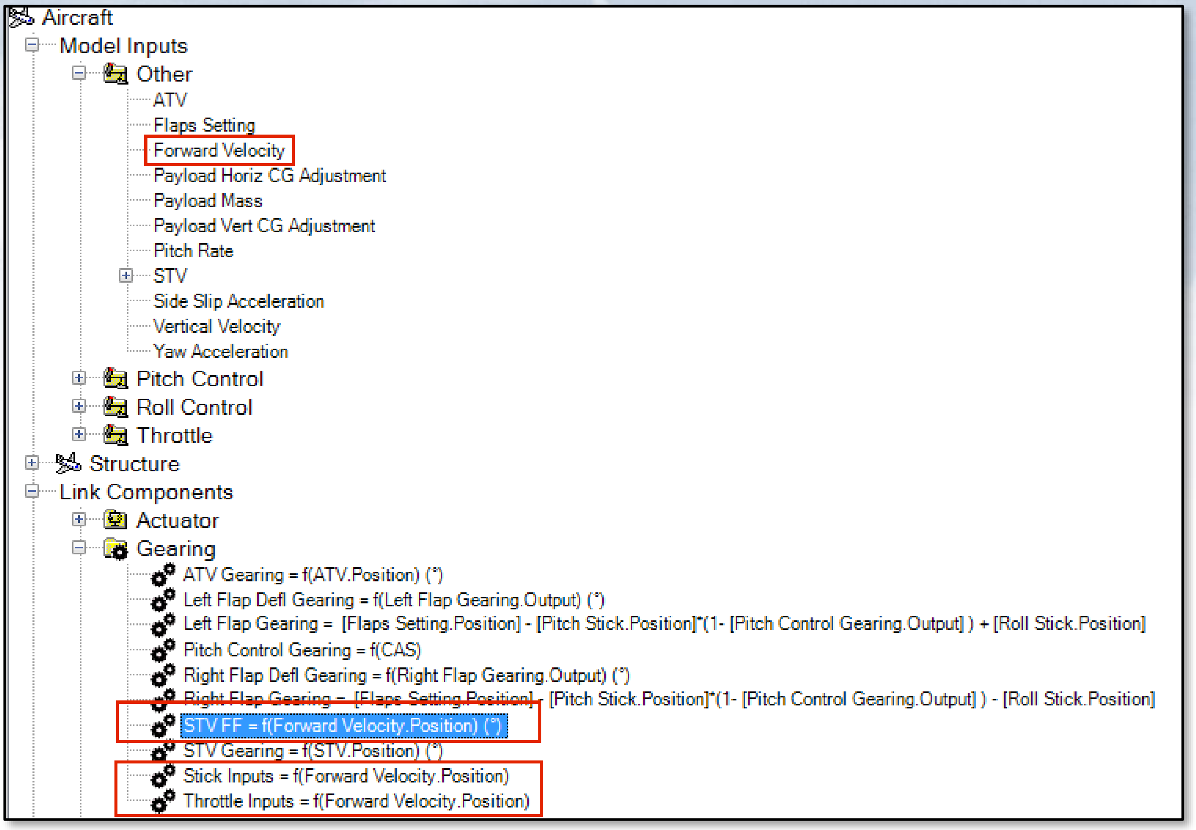
Resulting Transitioning the Pitch Control



Resultant Changes in STV Angle with Airspeed

Feed Forward Assessment

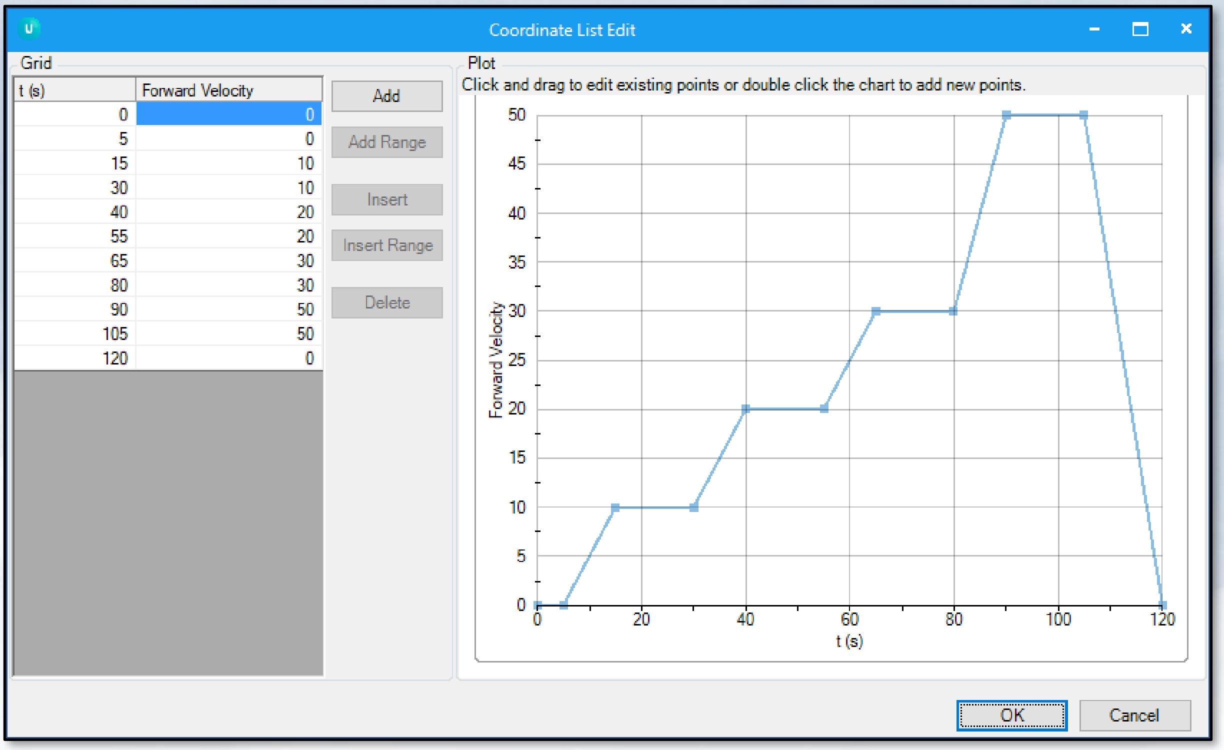
With the STV Angle, Throttle, and Pitch Stick position found for a given airspeed, these can now be used as Feedforward values to set the controls for a target airspeed. A new model input was added that set a target airspeed (Forward Velocity) and 3 new gearings that represent the Pitch Stick (Stick Inputs), Throttle (Throttle Inputs), and STV Angle (STV FF). These are lookup tables of the Forward Velocity.Position.



Adding the New Inputs and Gearings to the Model

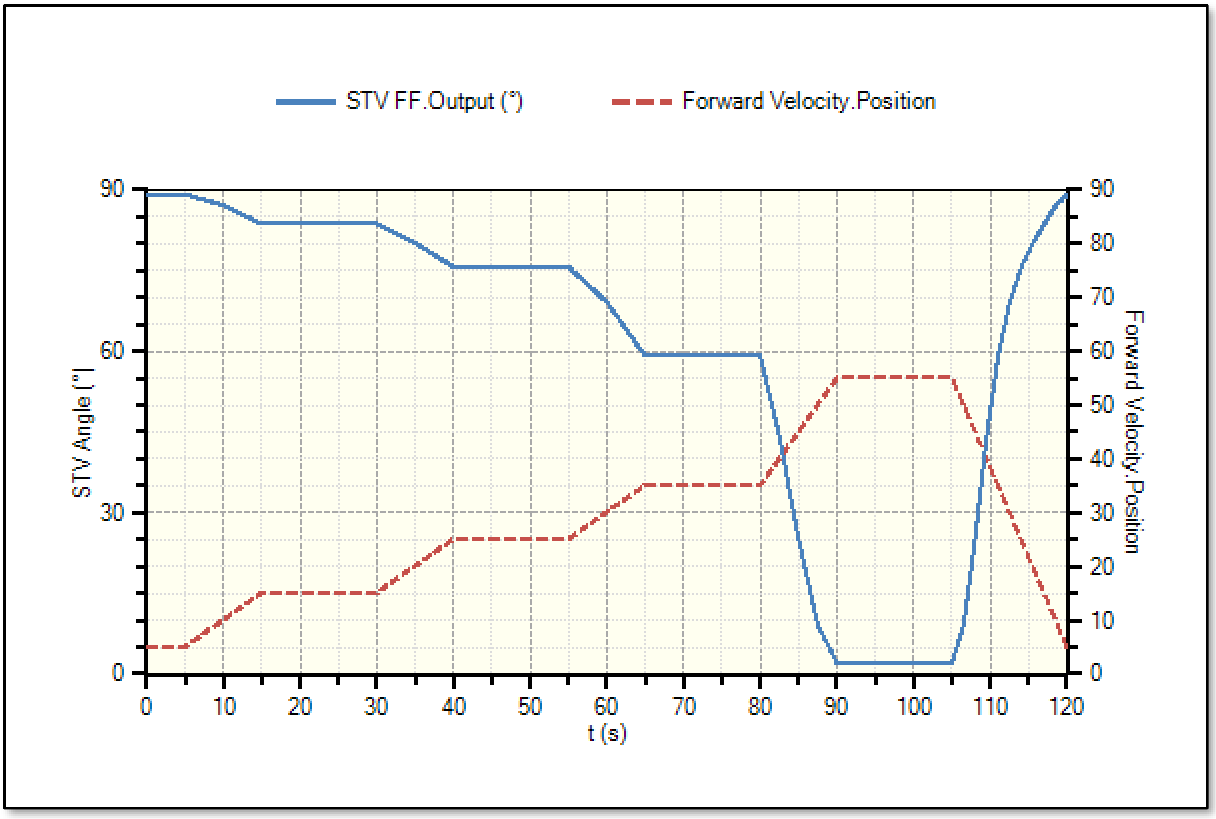
Thus, when the target velocity value is set, so the STV Angle Changes and the Throttles and Pitch Stick change along with it. If these values are correct, as the STV angle is changed, so a new Airspeed should be found.

The next step is to create a manoeuvre that would change the target velocity. This was performed by trimming the aircraft where the Forward Velocity.Position and the trimmed velocity are identical and then creating an input that changed the Forward Velocity.Position relative to the trimmed value. The Forward Velocity.Position was increased over a period of steps and then the aircraft allowed to settle and finally a large decrease in the Forward Velocity.Position.

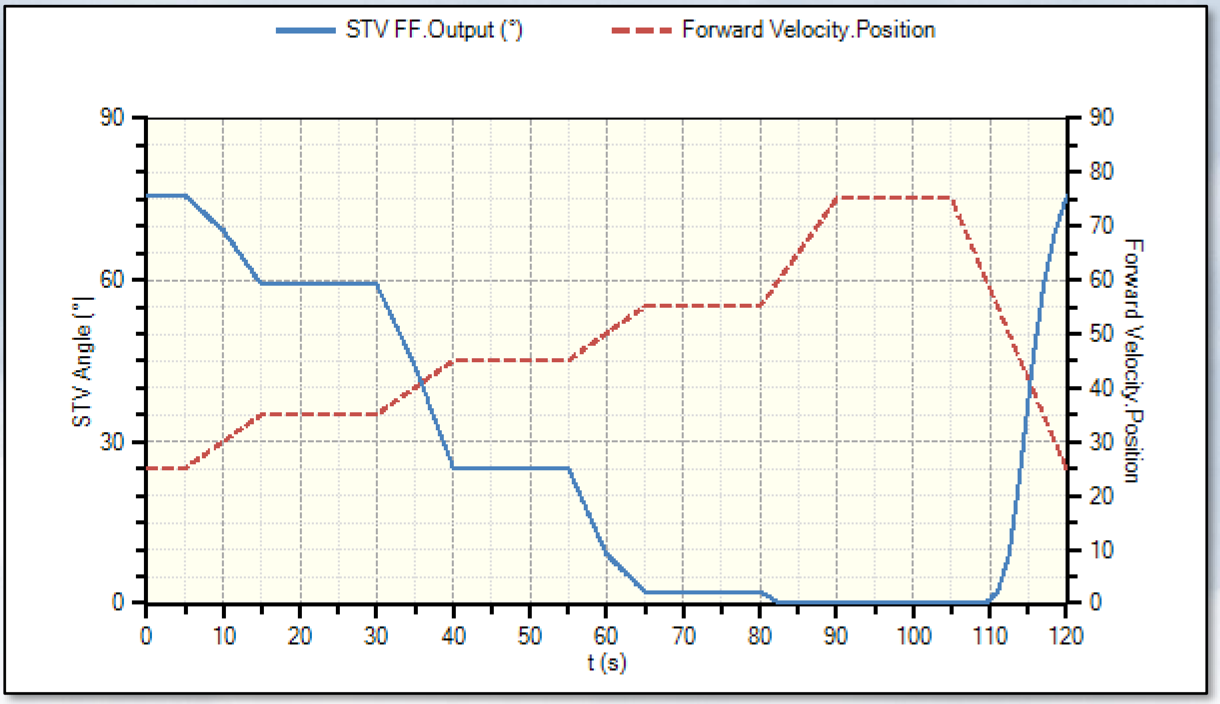


Setting the Time History of the Forward Velocity.Position

By running the above profile with 2 different initial velocities (5KTS and 25KTS), the aircraft is put through the full transition range of STV Angles and speeds.

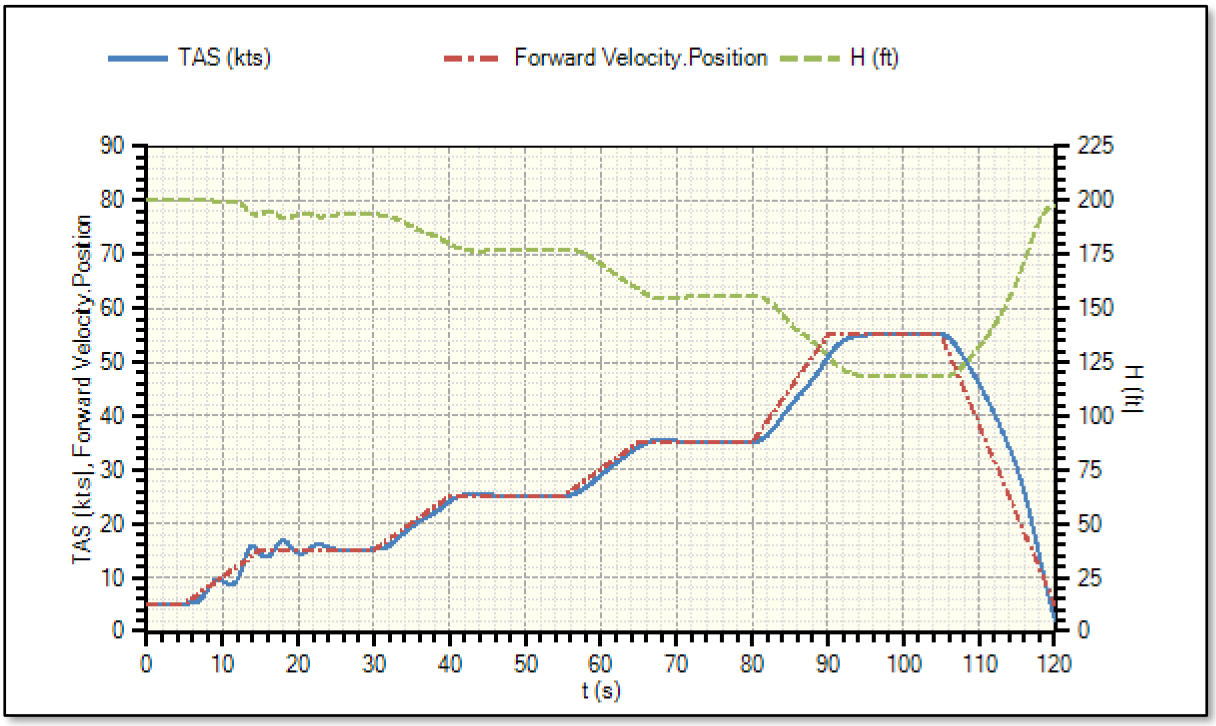


Range of STV Angles for Target Forward Velocity Profile with 5KTS initial Velocity



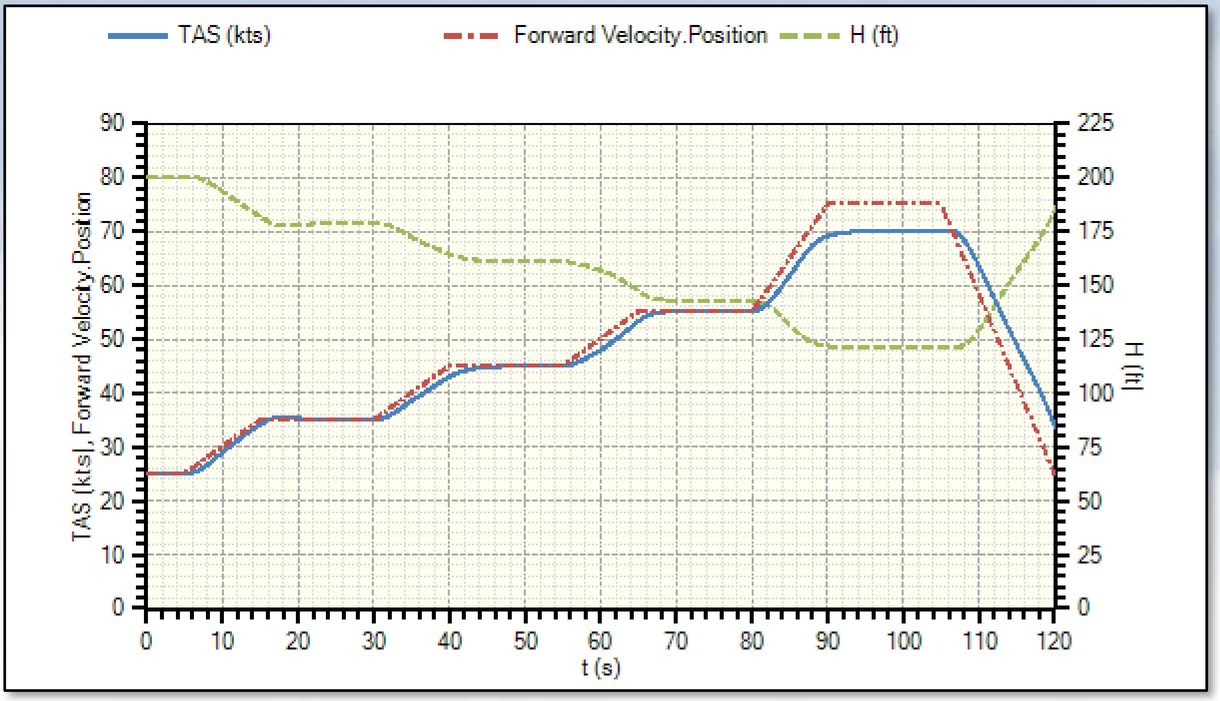
Range of STV Angles for Target Forward Velocity Profile with 25KTS initial Velocity

With the target Forward Velocity and the scheduling of the STV Angle, Pilot Throttle and Pitch Stick the dynamic analysis is performed.



Resulting Speed and Altitude Profiles for 5KTS Initial Velocity

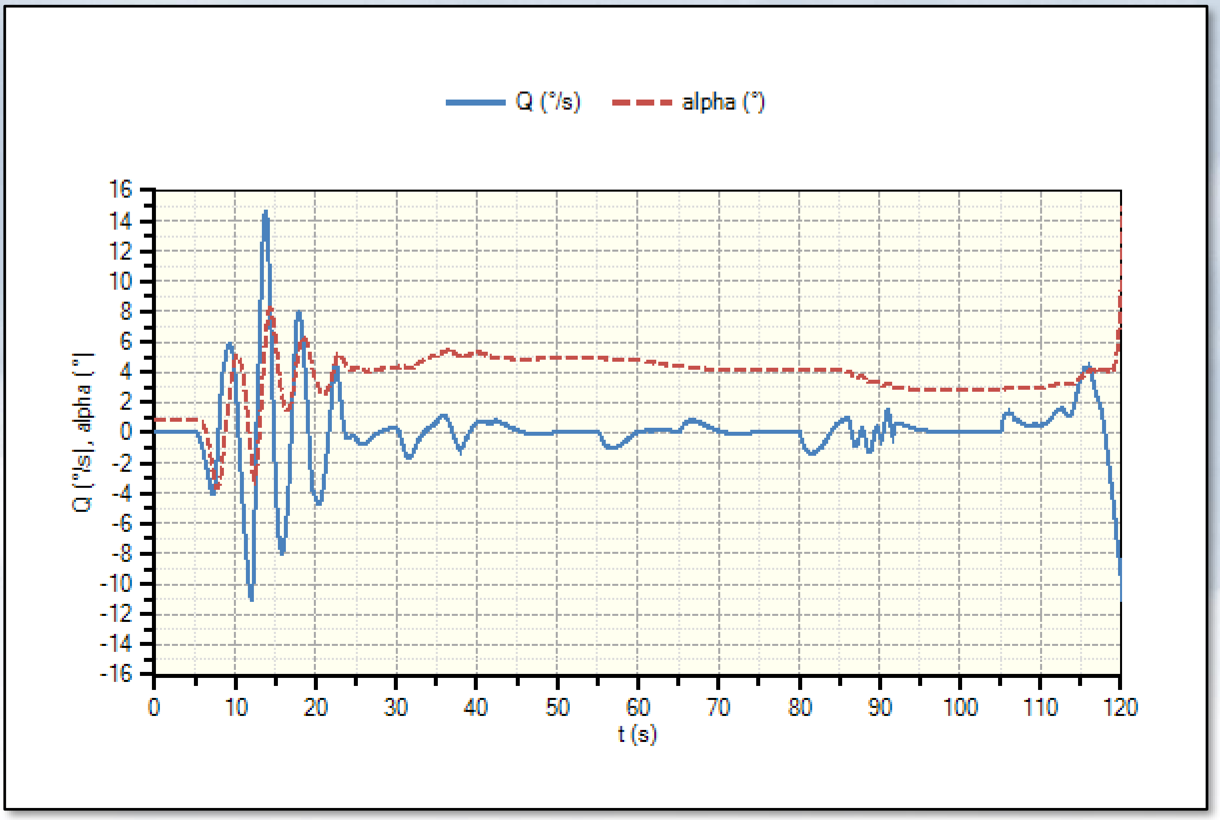
It can be seen that the actual Airspeed follows the Target value very well, although there is some oscillation at lower speed. As the aircraft accelerates to each new speed so it also descends but then stabilises when the speed is constant. This is because the trim conditions are for steady state and do not take into account the dynamic response. As the aircraft decelerates, so the altitude returns to the start point.



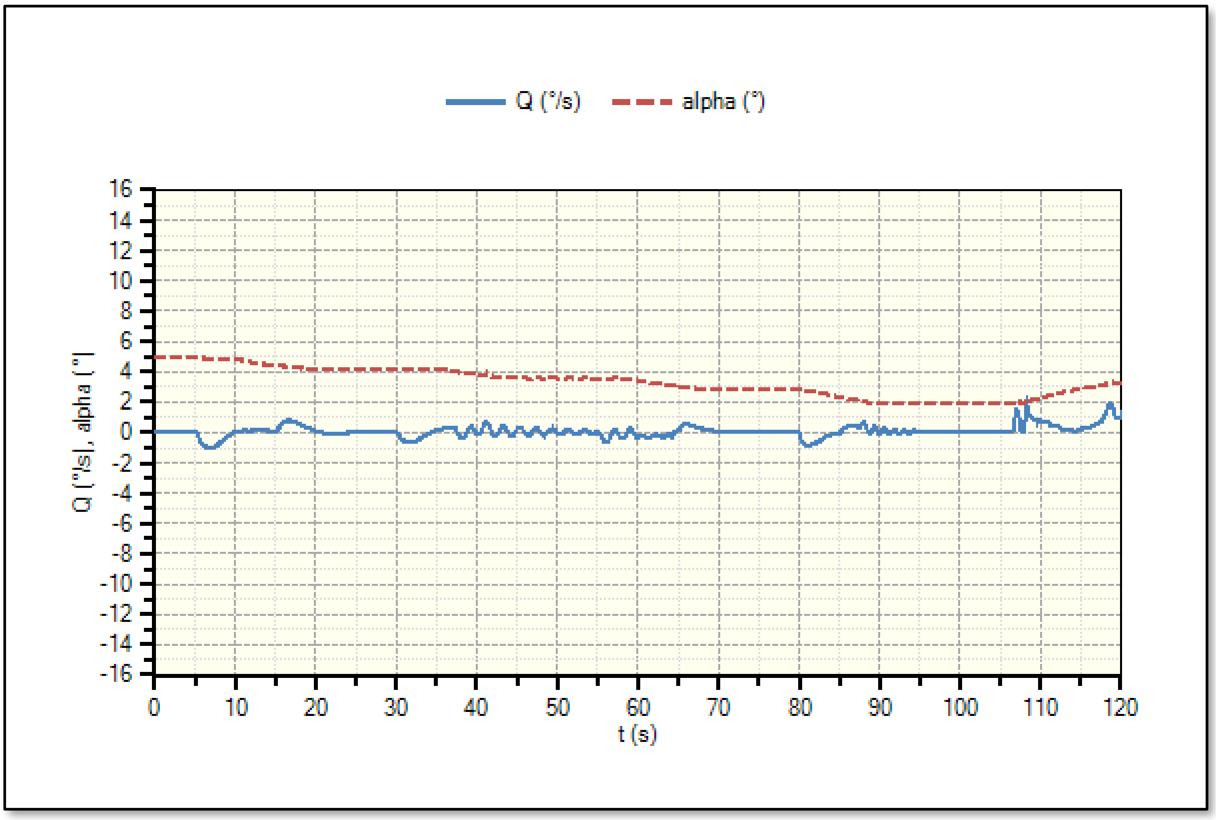
Resulting Speed and Altitude Profiles for 25KTS Initial Velocity

When starting at 25KTS, the aircraft responds much better with no oscillation. What can be seen is that the speed limits to 70kts which is the limit of the Pilot Throttle and Pitch Stick scheduling with the tables being limited. There is still the descent during acceleration and the ascent during deceleration but this is less pronounced.

When looking at the Pitch Rate and Angle of Attack for the two scenarios the oscillation is more obvious at the lower speeds. At the low speed there is very little inherent stability and so as the aircraft is disturbed from the initial condition it tends to oscillate. However, by the time the aircraft has reached 15KTS it has started to stabilise.



Pitch Rate (Q) and Angle of Attack (alpha) Profile for 5KTS Initial Velocity



Pitch Rate (Q) and Angle of Attack (alpha) Profile for 25KTS Initial Velocity

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What can be seen is that the aircraft naturally finds the Angle of Attack for the given speeds that were established in the Steady State Analysis, including the increase in Angle of Attack from 0 to 25KTS and then the steady decrease.

It should be noted in these tests, that the current aircraft has no AFCS other than the scheduling of the STV Angle, Pilot Throttle and Pitch Stick scheduling with target Forward Velocity.

CONCLUSIONS

Through the application and use of the j2 Universal Tool-Kit, it was possible to build a dynamic model of a Tilt Rotor UAV complete with variations in engine thrust location and centre of gravity.

The unique approach of the j2 Universal Tool-Kit of allowing trims to be defined through a set of rules meant that a series of static test cases could be set up to establish the trim conditions and settings necessary to maintain stable flight using the GUI.

From the trim conditions it was possible to put together a schedule for the Symmetric Tilt Angle for the Engines and the blending of the Pitch Thrust Differential and the Flaperon Deflection to control the aircraft. A feedforward Schedule for the Pitch Stick and Pilot Throttle was defined also which meant that the aircraft's speed could be controlled through the use of the Symmetric Tilt Angle and the Feed Forward values.

These schedules can then be used to manage the transition of the aircraft from thrust vectored to conventional flight.

There is now sufficient information to define the flight control system.